CONSTRUCTED WETLANDS TECHNOLOGY AS A NATURE-BASED SOLUTION FOR SUSTAINABLE MUNICIPAL WASTEWATER TREATMENT IN WESTERN INDIAN OCEAN REGION

Editors

Richard Joseph Kimwaga

Charles Buregeya Niwagaba

Damas Alfred Mashauri

FIRST EDITION

WIOMSA

Coasts Ocean and People

WESTERN INDIAN OCEAN MARINE SCIENCE ASSOCIATION

Nairobi Convention

CONSTRUCTED WETLANDS TECHNOLOGY AS A NATURE-BASED SOLUTION FOR SUSTAINABLE MUNICIPAL WASTEWATER TREATMENT IN WESTERN INDIAN OCEAN REGION

Editors
Richard Joseph Kimwaga
Charles Buregeya Niwagaba
Damas Alfred Mashauri

FIRST EDITION

September 2025

Published by: WIOMSA – Western Indian Ocean Marine Science Association

Contributed by: The University of Dar es Salaam (UDSM), WIOMSA, Nairobi Convention, University of Dodoma (UDOM) and Council for Scientific and Industrial Research (CSIR) of South Africa

Citation: Kimwaga, R.J., Niwagaba, B.C. and Mashauri, D.A. (2025). *Constructed Wetlands as a Nature Based Solution for Sustainable municipal Wastewater Treatment in Western Indian Ocean Region*, University of Dar es Salaam, WIOMSA and Nairobi Convention, xxx + 350p.

ISBN: ISBN 978-9976-56195-1

Cover photos: Constructed Wetlands at University of Dodoma (UDOM), Tanzania (Top) Photo credit: *Leah Marwa and Richard Kimwaga*; Shimo la Tewa Constructed Wetlands in Mombasa (Bottom) Photo credit: *Stephen Mwangi*

Design & layout: Gordon Arara

Printing firm: Jamana Printing

Contact Information:

Richard Joseph Kimwaga
P.O. Box 35131
Dar es Salaam, Tanzania
Phone: +255 754 265636
Email: rkimwaga2007@yahoo.com; rjkimwaga@udsm.ac.tz
Website: www.udsm.ac.tz

Table of Contents

THE EDITORS xvii

THE AUTHORS xix

FOREWORD xxiv

ACKNOWLEDGEMENTS xxv

PREFACE xxvi

LIST OF ACRONYMS xxix

Chapter 1: Coastal and Marine Pollution in Western Indian Ocean Region 1
By Susan Taljaard, Steven Weerts, Brent Newman, and Sumaiya Arabi

1.1 Description of the WIO Region 1

1.2 Hydrographic Features 2

1.3 Ecosystem Distribution and Key Threats 5
1.3.1 Mangrove Forests 5
1.3.2 Seagrasses 7
1.3.3 Coral Reefs 8
1.3.4 Saltmarsh 9

1.4 Sources of Land-based Pollution 10
1.4.1 Urban Development and Tourism 10
1.4.2 Agriculture and Forestry 14
1.4.3 Industry and Mining 16

1.5 Impact of Pollutants on Coastal and Marine Ecosystems 18
1.5.1 Microbiological Contamination 19
1.5.2 Suspended Sediment Loading 22
1.5.3 Nutrient Enrichment 23
1,5.4 Marine Litter 25
1,5.5 Toxic Pollution 27

1.6 Measures to Control Coastal and Marine Pollution 32

1.7 References 39

Chapter 2: Municipal Wastewater Treatment in Western Indian Ocean Region 51
By Zaina Mseli, Asumin Kantanga and Richard Kimwaga

2.1 Overview of Municipal Wastewater Treatment in the Western Indian Ocean Region 51

2.2 Types of Wastewater 53

2.2.1 Municipal Wastewater 53
2.2.2 Industrial Wastewater 55
2.2.3 Hospital Wastewater 57
2.2.4 Stormwater 58

2.3 Pollutants of Concern in Municipal Wastewater Treatment 58

2.4 Wastewater Management Systems in the Western Indian Ocean Region .. 59
2.4.1 Sewerage System 59
2.4.2 Faecal Sludge Management (FSM) 61
2.4.3 Storm Water Management System 62

2.5 Wastewater Treatment Technologies in WIO Region 63
2.5.1 Onsite Technology 63
2.5.2 Offsite Technology 64
2.5.3 Reuse Technology. 66

2.6 Wastewater Treatment Challenges and Impacts in WIO Region 67
2.6.1 Poor Urban Planning 67
2.6.2 Capital Investment Requirements 67
2.6.3 Attitude and Socio-cultural Barrier 68
2.6.4 Low Public Awareness 68
2.6.5 Insufficient Attention in Selecting the Appropriate Technology 68

2.7 Concluding Remarks 68

2.8 References 69

Chapter 3: Introduction to Constructed Wetlands 73
By Richard Kimwaga

3.1 Understanding the Paradigm Shift towards Constructed Wetland as a Nature-Based Solution. 73

3.2 Concept of Nature-Based Solution 76

3.3 Advantages of Constructed Wetland Systems 78

3.4 Limitations of Constructed Wetland Systems 79

3.5 Types of Constructed Wetlands 82
3.5.1 Types of CW Based on Wastewater Level and Flow Direction. 82
3.5.1.1 Horizontal Surface Flow (HSF) Wetlands 82
3.5.1.2 Free Water Surface (FWS) Wetlands 83
3.5.1.3 Subsurface Flow Constructed Wetlands 85
3.5.1.3.1 Horizontal Subsurface Flow 85
3.5.1.3.2 Vertical Subsurface Flow 87
3.5.2 Types of CW Based on Macrophytes (plants) Growth. 90
3.5.2.1 Free Floating Macrophytes 91

3.5.2.2 Submerged Macrophyte Systems 91
3.5.2.3 Rooted Emergent Macrophytes........ 91

3.6 Pollutants Removal Mechanisms in Constructed Wetlands 93
3.6.1 Chemical Processes........ 94
3.6.2 Biological Processes 95

3.7 Components of Constructed Treatment Wetlands........ 96
3.7.1 CW Vegetation/Macrophytes 96
3.7.2 Soil or Substrate (Media) Supporting Vegetation 101
3.7.3 Water Column (In and Above the Substrate) 102
3.7.4 Living Organisms........ 102

3.8 Types and Selection of Wetland Configuration 103

3.9 Where Can Wetland Find their Applications?........ 106

3.10 References 107

Chapter 4: Policies, Laws, and Institutions Related to Constructed Wetlands 115
By Deogratius Mulungu and Richard Kimwaga

4.1 Introduction 115

4.2 Key International and Regional Arrangements 116

4.3 Overview of National Arrangements........ 122
4.3.1 Comoros........ 122
4.3.2 Kenya 122
4.3.3 Madagascar 123
4.3.4 Mauritius........ 124
4.3.5 Mozambique........ 124
4.3.6 Reunion (France) 125
4.3.7 Seychelles 126
4.3.8 Somalia........ 127
4.3.9 South Africa 127
4.3.10 Tanzania........ 129

4.4 Conventions 130

4.5 International/Regional Strategies and Projects 133
4.5.1 Strategies........ 133
4.5.2 Projects........ 133

4.6 International and Regional Institutional Framework........ 135
4.6.1 Western Indian Ocean (WIO) Region........ 135

4.7 National Institutional Frameworks........ 136
4.7.1 Institutional Framework in Kenya........ 136

4.7.2 Institutional Framework in Mauritius ... 137
4.7.3 Institutional Framework in Seychelles ... 138
4.7.4 Institutional Framework in Tanzania ... 139

4.8 National Policies and Strategies ... 143
4.8.1 Policies and Strategies in Kenya ... 143
4.8.2 Policies and Strategies in Mauritius ... 146
4.8.3 Policies and Strategies in Seychelles ... 146
4.8.4 Policies and Strategies in Tanzania ... 149

4.9 National Legal Framework ... 151
4.9.1 Legal Framework in Kenya ... 151
4.9.2 Legal Framework in Mauritius ... 153
4.9.3 Legal Framework in Seychelles ... 155
4.9.4 Legal Framework in Tanzania ... 155

4.10 Status and Challenges on Policy, Laws and Institutions Related to Constructed Wetlands ... 157

4.11 References ... 158

Chapter 5: Planning for Constructed Wetlands ... 163
By Zai Mseli, Asumin Kantanga and Richard Kimwaga

5.1 General CW Planning Considerations ... 163

5.2 Assessment of Current and Future Land Use Plan Through Master Plan ... 165
5.2.1 Land Use and Land Use Plan ... 165
5.2.2 Land Use Master Plan ... 169
5.2.3 Future Land Use Plan ... 169
5.2.4 Reporting Assessment of Land Use Plan ... 171

5.3 Community Mobilization and Sensitization Campaigns ... 171

5.4 Definition of Treatment Objectives ... 173

5.5 Wastewater Characterization and Quantification ... 173

5.6 Selection of the Type of CW System ... 177

5.7 Selection of the CW Construction Site ... 177
5.7.1 Land Use and Accessibility ... 178
5.7.2 Topography ... 179
5.7.3 Hydrology ... 179
5.7.4 Geology ... 179
5.7.5 Permits and Regulations ... 180

5.8 Establishment of Vegetation and Substrate ... 180
5.8.1 Wetland Plants/Vegetation ... 180
5.8.1.1 Wetland Planting Stock ... 181

5.8.1.2 Condition of Planting Stock 183
5.8.1.3 Planting Wetland Vegetation 184
5.8.1.4 Successful Plant Establishment 186
5.8.1.5 Summary 187
5.8.2 Substrate 187
5.8.2.1 HF Wetland Substrate 187
5.8.2.2 VF Wetland Substrate 188

5.9 Planning Examples 190

5.10 References 191

Chapter 6: Design of Constructed Wetlands 195
By Richard Kimwaga

6.1 Design of Pre-treatment Units 195

6.2 Factors Affecting the Treatment Performance in Constructed Wetlands 197
6.2.1 Influent Wastewater Characteristics and Effluent Water Quality Requirements 198
6.2.2 Temperature 198
6.2.3 CW Wetland Type 200

6.3 Sizing of Constructed Wetland (FWS and SSF) 200

6.4 Determining the Design Approach 201

6.5 Design Procedures 201

6.6 Design Approaches for Sizing of Constructed Wetland 202
6.6.1 The UK Model for the Design of Constructed Wetlands 202
6.6.2 The First-Order Plug-Flow Biokinetic Model 203
6.6.3 Sizing Based on Specific Area Requirement per Population Equivalent (PE) 204

6.7 Design of Inlet Structure, Feeding Arrangements, and Outlet Structures 206
6.7.1 Inlet Structures 206
6.7.2 Outlet Structures 209

6.8 Worked Examples 212

6.9 Solution 213

6.10 References 216

Chapter 7: Construction of Constructed Wetlands 219
By Leah Marwa and Richard Kimwaga

7.1 Mobilization and Safety Precautions 219
7.1.1 Mobilization 219
7.1.2 Safety Precautions 220

7.2 Site Preparation 220
7.3 Excavation works 221
7.4 Construction of CW Walls 222
7.5 Lining of CW Bottom and Embankments 223
7.6 Installation of the Inlet and Outlet System 224
7.6.1 Inlet/Outlet Stonework 225
7.6.2 Inlet and Outlet Piping 225
7.7 Substrate Packing and Filling 227
7.7.1 General 227
7.7.2 Quality and size of substrate materials requirements 228
7.7.3 Size and Quality of Substrate Materials 229
7.8 Planting 229
7.8.1 Use of Seeds 230
7.8.2 Use of Propagated Seedlings 230
7.8.3 Use of Transplantation 230
7.8.4 Use of Rhizomes 230
7.8.5 Before Planting 231
7.9 Construction of Spillway 231
7.10 Constructed Wetland Commissioning 232
7.10.1 Before Planting 232
7.10.2 Leveling of Gravel 232
7.10.3 Water Level Control 232
7.10.4 Weed Control 233
7.10.5 Check-up of Wetland Structures 233
7.11 Fencing and Protection 233
7.12 General CW Construction Approval Tips/Steps 233
7.13 Bidding for Constructed Wetland Works 234
7.14 Concluding Remarks 234
7.15 References 234

Chapter 8: Operation and Maintenance Requirements for Constructed Wetlands 237
By Leah Marwa and Richard Kimwaga

8.1 General Requirements and Considerations 237
8.2 Start-up Considerations 239
8.2.1 CW Basin Weather Tightness Testing 239
8.2.2 Antecedent Conditions 240

8.2.3 Ecological Transition....240

8.3 Operation and Maintenance (O&M) of CWs 240
8.3.1 Operation of CWs....241
8.3.2 Maintenance of CWs....242

8.4 Management of the System 243
8.4.1 Monitoring and Evaluation (M&E)....243
8.4.2 Documentation and Recordkeeping....246
8.4.3 Plant Security and Safety 247
8.4.3.1 Health and Safety 247
8.4.3.2 Personal Protective Equipment 248
8.4.3.3 Infection Control 248
8.4.3.4 Emergency Contact Procedures....249
8.4.4 Asset Management 249
8.4.5 Management of Clogging....250
8.4.6 Management of Vegetation 250

8.5 Reuse and Recycling of CW End Products.... 252

8.6 Basic Troubleshooting.... 253

8.7 References.... 254

Chapter 9: Economics and Financing Options of Constructed Wetlands.......257
By Richard Kimwaga

9.1 Introduction 257

9.2 Various Cost Categories and Elements of CWs 258
9.2.1 Capital investment cost (Capex)....258
9.2.1.1 Project Planning and Design Costs....259
9.2.1.2 Excavation and Earthwork Cost....259
9.2.1.3 Liner Cost....260
9.2.1.4 Substrate Cost 262
9.2.1.5 Construction Material Costs 264
9.2.1.6 Plants and planting costs 264
9.2.2 Operation and Maintenance Cost 265

9.3 Benefit Evaluation 266
9.3.1 Economic Benefit....268
9.3.1.1 Hydrology/Water Quality 268
9.3.1.2 Increase of Surface Water Quality....269
9.3.1.3 Groundwater Recharge....270
9.3.1.4 Fish and Wildlife Habitat. 270
9.3.1.5 Existence and Bequest of Biodiversity and Biological Resources ..271
9.3.1.6 Recreational and Educational Activities....271

9.3.2 Environmental Benefit 272
9.3.3 Social Benefit 273

9.4 Cost Benefit Analysis 274

9.5 Financial Cost Benefit Analysis 275

9.6 Financing of CW 275
9.6.1 National Level 276
9.6.2 Local level 276
9.6.3 Communities and Civil Societies Level 276
9.6.4 Household Level 277
9.6.5 Entrepreneurship Level 277
9.6.6 Financial Institutions Level 277
9.6.7 International Organizations and External Funding Agencies Level 277

9.7 Cost and Benefit Analysis Example 277

9.8 References 281

Chapter 10: Constructed Wetlands Case Studies in Western Indian Ocean Region 285
By Richard Kimwaga

10.1 Ten Years Experiences of Using Engineered Wetlands Systems for Onsite Treatment of Wastewater by the Local Communities in Tanzania 286
10.1.1 Introduction and Rationale for Constructed Wetlands 287
10.1.2 CW System Description (size, type of CW, the design, and operating conditions) 288
10.1.3 CW System Pollutants Removal Performance 290
10.1.4 Observed and Documented Design and Operational Challenges Common CW Problems 292
10.1.5 Lessons Learnt (Worst Case and Best-Case Scenarios) 294
10.1.6 References 295

10.2 Treatment Constructed Wetlands in a Community Setting in Mombasa, Kenya 296
10.2.1 Introduction and Rationale for Constructed Wetlands 296
10.2.2 CW System Description (location size, type of CW, the design, and operating conditions) 299
10.2.2.1 Location 299
10.2.2.2 Constructed Wetland Design and Operation 299
10.2.3 CW System Pollutants Removal Performance 303
10.2.3.1 System Pollutants Removal Performance 303
10.2.3.2 Operation and Maintenance of the CW 303
10.2.3.3 Management and Regulation of the CW 305
10.2.4 Observed and Documented Design and Operational Challenges 307

10.2.4.1 Operational Issues ... 307
10.2.4.2 Societal Issues ... 309
10.2.5 Lessons Learnt ... 310
10.2.6 References ... 312

10.3 Performance of a Constructed Wetland Treating Synthetic Greywater in Mauritius ... 315
10.3.1 Introduction and Rationale for Constructed Wetlands ... 315
10.3.2 System Description (size, type of CW, the design, and operating conditions) ... 316
10.3.2.1 Synthetic Greywater Preparation ... 316
10.3.2.2 Set up of Experimental HSSFCW ... 317
10.3.2.3 Investigation of System Performance ... 318
10.3.2.4 First Order Plug Flow Model ... 319
10.3.2.5 Operating Parameters ... 319
10.3.2.6 Statistical Analysis ... 321
10.3.3 CW System Pollutants Removal Performance ... 321
10.3.3.1 Characteristics of Synthetic Greywater ... 321
10.3.3.2 Bed Performance ... 322
10.3.3.2.1 Inlet and Outlet BOD ... 322
10.3.3.2.2 .BOD Removal Efficiency ... 323
10.3.3.3 Effect of Operating Parameters on the System Performance ... 324
10.3.3.4 BOD Removal Reaction Rate Constant ... 326
10.3.3.5 The Value of kBOD ... 328
10.3.3.6 Reuse of Treated Greywater ... 330
10.3.4 Conclusion ... 331
10.3.5 References ... 331

10.4 Application of Municipal Wastewater Technology to Semi- arid Regions: "A Pilot Study using a Constructed Wetland in Toliara city, Madagascar" ... 335
10.4.1 Introduction and Rationale for CW ... 336
10.4.2 CW System Description (size, type of CW, the design and operating conditions) ... 337
10.4.2.1 CW System Pollutants Removal Performance ... 344
10.4.2.2 Removal Efficiency ... 348
10.4.3 Lessons Learnt (Worst Case and Best-Case Scenarios) ... 350
10.4.4 References ... 350

List of Figures

Figure 1.1: Schematic illustration of major surface current patterns in the Western Indian Ocean 2
Figure 1.2: Marine pollution hotspots (major coastal urban cities) in the WIO region 21
Figure 2.1: Stormwater bypassing the Kipevu wastewater treatment plant in Mombasa draining directly into the Indian Ocean. 60
Figure 3.1: Hotspots' of marine pollution (major coastal urban cities) in the WIO region 74
Figure 3.2: Horizontal free water surface 83
Figure 3.3: Basic elements of FWS wetland 83
Figure 3.4: Typical application of FWS wetland for municipal wastewater treatment 84
Figure 3.5: Horizontal flow subsurface CW 85
Figure 3.6: HSSF wetland schematic 86
Figure 3.7: Application of a HSSF wetland to domestic wastewater treatment 86
Figure 3.8:Vertical flow sub-surface CW 87
Figure 3.9: Typical arrangemet of a VF constructed wetland 88
Figure 3.10: A hybrid wetland system (VF + HSSF) 89
Figure 3.11: Schematic representation of a free-floating macrophyte-based wastewater treatment system 91
Figure 3.12: Schematic representation of a submerged macrophyte-based wastewater treatment system 91
Figure 3.13: Schematic representation of emergent macrophyte-based wastewater treatment systems: a) system with surface flow, b) system with horizontal subsurface water flow, c) system with vertical subsurface water flow 92
Figure 3.14: Oxygen transfer through root zone 99
Figure 3.15: Introduction to Constructed Wetlands-18: Configurations for CTW 105
Figure 4.1: A schematic representation of the institutional framework for the water sector under the Water Act 2002 136
Figure 4.2: Institutional Water Management Framework (IWMF) in Tanzania 140
Figure 4.3: Policies, Laws, and Institutions Related to Constructed Wetlands-21: The Organization structure of the Vice President's Office (VPO). 142
Figure 5.1: Example of healthy plant stock and root development. 183
Figure 5.2: Procedures for installing potted plants in a standard FWS wetland 184
Figure 5.3: Procedure for planting rhizomes in a standard VSB wetland 185

Figure 5.4: Procedure for installing potted plants in a mulch-insulated VSB wetland............ 185
Figure 5.5: Substrate configurations in an HF wetland.. 188
Figure 5.6: VF wetland substrate arrangement.. 189
Figure 5.7: Typical distribution of grain sizes (AKUT graph based on German guidelines ATV) 189
Figure 6.1: Various pre-treatment options with CW 196
Figure 6.2: Specific area requirement per PE for HF and VF wetland for different specific wastewater discharges 205
Figure 6.3: Inlet designs... 207
Figure 6.4: Image of sawtooth weir 208
Figure 6.5: Feeding arrangements for CTWs.. 209
Figure 6.6: Outlet structures.. 210
Figure 6.7: Outlet Screens (Drop board for water level control) 211
Figure 6.8: Wastewater level maintenance. Left: Outflow pipes hanging on a chain at CW Waikeria, New Zealand. Right: Swiveling elbow at CW Bouvron, France. 212
Figure 7.1: Site preparation of CW on sloped terrain.. 221
Figure 7.2: Excavation of constructed wetlands 221
Figure 7.3: Recommended angle for CWs walls.. 222
Figure 7.4: Collapsed embankment due to structural instability 222
Figure 7.5: Compaction or lining the bottom of wetland to avoid seepage...................................... 223
Figure 7.6: Typical clean stones used for inlet and outlet zones (50 – 100 mm) 224
Figure 7.7: Recommended arrangement and size of inlet and outlet stonework 225
Figure 7.8: Plan view to show the layout of the inlet and outlet piping.. 226
Figure 7.9: Position of inlet and outlet structures.. 226
Figure 7.10: Incorrect positioning of the inlet and outlet pipes.. 226
Figure 7.11: Correct positioning of the inlet and outlet pipes... 227
Figure 7.12: Construction of Constructed Wetlands-48: The required size and quality of wetland substrate material... 228
Figure 7.13: Subsurface flow constructed wetland showing spillway 231
Figure 7.14: Arrangement of different components of a constructed wetland 232
Figure 8.1: Safety posters and signs are good reminders to follow proper procedures............ 248
Figure 8.2: Effluent of the constructed wetland for visual appearance 254

Figure 9.1: Illustration of the scale dependency of the unit cost of wetland construction.............. 258

Figure 9.2: Total DALYs due to Diarrhoeal Diseases ('000) 280

Figure 10.1: Common Operational Problems in Constructed Wetlands in Tanzania. 292

Figure 10.2: Location of constructed wetland (CW) in Mombasa, Kenya 300

Figure 10.3: Constructed wetland layout.. 301

Figure 10.4: Comparison of the project site in 2008 309

Figure 10.5: Set up of the experimental bed.. 318

Figure 10.6: Inlet and outlet BOD and COD of the HSSFCW irrespective of the operating conditions 322

Figure 10.7: BOD removal efficiency of the bed since its start-up in 2015 323

Figure 10.8: Progression of BOD at HRT 20 h (n = 10), HRT 22 h (n = 5) and 24 h (n = 17) 326

Figure 10.9: The K-C model of observed mean BOD progression along the bed at HRT 20-24 h (n=32) 330

Figure 10.10: The K-C* model of observed mean BOD at HRT of 20-24 h (n=32) 330

Figure 10.11: The site of the pilot study of small scale of constructed wetland 337

Figure 10.12: Septic tank system (pretreatment).. 338

Figure 10.13: The territorial landscape... 339

Figure 10.14: A constructed wetland with 3 parallel cells.. 339

Figure 10.15: Schema of constructed wetland in the phase I period 341

Figure 10.16: Linearized BOD data for determination of reaction rates (k)... 343

Figure 10.17: pH values in the septic tank effluent and effluent from the wetland (pond D and pond G) (July 2010-August 2011).. 344

Figure 10.18: Variation of temperature (°C) from the septic tank effluent and effluent from the pond D and pond G (phase I, II and III, July 2010 – August 2011)... 345

Figure 10.19: Dissolved oxygen concentration profiles in the phase I, II and III from the septic tank effluent (influent to wetland) and from effluent of pond D and pond G (July 2010 – August 2011)... 346

Figure 10.20: Concentration trend of BOD from septic tank effluent and from pond D and pond G (as measured from July 2010 to August 2011) 347

Figure 10.21: Concentration trend of TSS from septic tank effluent and from pond D and pond G (as measured from July 2010 to August 2011) 348

List of Tables

Table 1.1: Summary of major sources of marine litter in the countries of the WIO region ... 13

Table 1.2: Overview of key impacts associated with the key problems linked to marine pollution in the WIO region ... 19

Table 1.3: Key reported impacts and proportion of plastic/synthetic litter in countries of the WIO region ... 26

Table 1.4: Key International and regional conventions/agreements applicable to coastal and marine pollution management, indicating signatory countries ... 33

Table 2.1: Wastewater and faecal sludge treatment systems in the WIO region ... 52

Table 2.2: Estimated volumes of municipal wastewater generated in coastal areas of the WIO region (and potentially entering the coastal and marine environment) ... 55

Table 3.1 : Effect of Pollutant Loading on Wetland Processes ... 80

Table 3.2: Pollutant Removal Processes ... 94

Table 3.3: Major roles of macrophytes in constructed wetlands ... 97

Table 3.4: Media characteristics ... 102

Table 4.1: Key International and regional conventions/agreements applicable to marine water quality management, indicating signatory countries ... 118

Table 5.1: Wastewater properties and their necessity for identification ... 174

Table 5.2: Wastewater discharge standards ... 175

Table 6.1: Temperature coefficients and rate constants ... 199

Table 6.2: Media characteristics for SSF systems ... 201

Table 6.3: Temperature coefficients and rate constants ... 204

Table 8.1: Typical minimum monitoring requirements for successful operation of wetland treatment systems ... 244

Table 8.2: Invasive plant species in WIOMSA Region Constructed Wetlands ... 252

Table 9.1: The cost of earthwork for constructed wetland systems ... 260

Table 9.2: Cost comparisons of design options for liner construction in medium-large scale wetlands 262

Table 9.3: Unit cost spent on substrate materials of SSF wetlands 263

Table 9.4: Frequency and duration of labour employed for routine operation and maintenance activities of an SSF constructed wetland (350 m^2 × 4 beds) in Masaya, Nicaragua 266

Table 9.5: Wetland functions good and services and valuation method 267

Table 10.1: Physico-chemical parameters at Three CW systems in Tanzania 290

Table 10.2: Water sampling parameters, limits and testing methodology 302

Table 10.3: Water sampling results (average values) 304

Table 10.4: Monthly operation and maintenance costs for the CW in USD 304

Table 10.5: HLR effect on performance of the bed 320

Table 10.6: Comparison of inlet and outlet BOD and COD 323

Table 10.7: Pearson, Kendall and Spearman correlation between HRT, HLR and OSLR on BOD removal efficiency 325

Table 10.8: Mathematical relationship derived for both K-C and K-C* models and their respective R2 values at three HRTs 328

Table 10.9: Calculated kT and kBOD values by method of fitting in the K-C* model 329

Table 10.10: Volumetric loadings and operational data applied 340

Table 10.11: Pond D and pond G systems characteristics 341

Table 10.12: Data ranged of the environmental parameters measured from July 2010 to August 2011, from the septic tank effluent, pond D and pond G effluent 345

Table 10.13: Summary of BOD, TSS, NH_4-N, NO_3-N and PO_4-P concentrations in the influent (septic tank effluent) and effluent (pond D and G) per month and removal efficiency during the phase I, II and III 349

THE EDITORS

Dr. Richard J. Kimwaga who is a Senior Lecturer at the University of Dar es Salaam is a distinguished figure in Water, Sanitation and Wastewater and Hygiene (WASH) as an academic, researcher, and practitioner. Holding a Ph.D in Environmental Engineering, Master's degrees in Environmental Studies and Water Resources Engineering, and a Bachelor's in Civil Engineering, Dr. Kimwaga is a Professional Engineer registered with the Engineers Registration Board (PEng No. 4862). He is also certified by the National Environmental Council (NEMC) for Environmental Impact Assessment (EIA) (Expert Registration No. NEMC/EIA 0375). Engaged with international and national professional institutions, networks, and associations such as Nile IWRM NET, GWP-Tanzania, and WaterNet, he contributes actively to his field. He's an active member of the Global Sanitation Graduate School (GSGS), funded by the Bill and Melinda Gates Foundation. He is also Academic Core-Lead Partner and Representative for Tanzania under GSGS Eastern and Southern Africa (ESA) Regional Hub. Dr Kimwaga has been the Principal Investigator for various international research projects the notable ones being Sustainable Sanitation in Theory and Action (SUSTAIN), Sustainable Water and Sanitation for All (SUWASAN) and Promoting Evidence-Based Investments in Sanitation for Health and Equity (PROMISE). Dr. Kimwaga has over 25 years of professional and research experience, spanning consultancy services in Constructed Wetlands, Wastewater and Faecal Sludge Engineering, Integrated Sanitation Management (ISM), Integrated Water Resources Management and Development (IWRMD), WASH, Solid Waste Management, and Stormwater Management. His achievements include managing stakeholder engagement processes, facilitating workshops, and moderating international conferences. Dr Kimwaga was the member of the National Core Technical Team for the preparation of Tanzania Development Vision 2050 (TDV2050) dubbed as DIRA 2050 and Long-Term Perspective Plan (LTPP) 2025 - 2050.

Dr. Charles B. Niwagaba is an Associate Professor of Civil Engineering at Makerere University. He holds BSc. Civil Engineering and MSc. from Makerere University; and Ph.D in Environmental Technology from the Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden. He has 24 years of experience in research, teaching and consultancy in Civil and Environmental Engineering. Dr. Charles B. Niwagaba has undertaken community outreach activities in the promotion and marketing of sanitation along the sanitation service chain, encompassing resources recovery and safe reuse of resources from sanitation and waste management. He has been involved in research and consultancies funded locally by Government of Uganda and by various multi-lateral agencies. Dr. Niwagaba has extensive knowledge in development of innovative practices in sanitation improvement (from Engineering, social marketing to financing); solid waste management with emphasis on recycling and re-use *e.g.* composting, biogas, grey water treatment and use, application of faecal sludge in industrial kilns and boilers, design of faecal sludge treatment plants. Prof. Niwagaba has published over 120 peer reviewed articles and book chapters.

Prof Damas Mashauri has his double degrees at Tampere University of Technology Finland (Dr Technology in June 1986 and a Master's in Water Supply and Sanitation Engineering in 1981). Prof Damas Mashauri is a bona fide alumna of the University of Dar es Salaam, Tanzania where he graduated with B Sc. (Civil Engineering) Honours in 1979. Prof Damas Mashauri is a is registered Member (1996) of Engineers Tanzania (IET) (No.622) since 1996. And he is Registered Professional Engineer Tanzania (No.1581) with ERB. Prof Mashauri is prominent member of Member of International Association for Hydraulic Research (IAHR) since 1986. Since 1990 he is a Member of the International Association on Water Quality (IAWQ). Prof Mashauri is a Registered Environmental Impact Assessor (Tanzania) registered with National Environment Management Council (NEMC). Prof Mashauri was UNESCO Chair Holder (UNESCO Chair on Flood and Drought Risks in the Southern Africa Region) at the University of Namibia till December 2022. Prof Mashauri was a full professor and SADC-WATERNET Professorial Chair holder at Namibia University of Science and Technology from February 2010 to December 2017. Professor Mashauri is one of the founding members of WATERNET in April 1999. Was a full Professor of Civil Engineering at the University of Namibia from January 2018 to December 2022 when he retired to Tanzania. Prof Mashauri has been teaching both Undergraduate and Postgraduate programmes at all institutions he has been involved with. He has taught courses like water supply transmission and distribution, wastewater and stormwater reticulation, water and wastewater treatment, infrastructure planning, management of solid waste and hazardous waste, and design as well as infrastructure development. Prof Mashauri has been involved in facilitating legal aspects of water resources management at post graduate levels. Prof Mashauri has undertaken short courses in environmental assessment, water and environmental laws and management of urban water, wastewater, and energy utilities among others. As such he has been offering short and modular courses in the topics mentioned above.

THE AUTHORS

Dr. Richard J. Kimwaga who is a Senior Lecturer at the University of Dar es Salaam is a distinguished figure in Water, Sanitation and Wastewater and Hygiene (WASH) as an academic, researcher, and practitioner. Holding a Ph.D in Environmental Engineering, Master's degrees in Environmental Studies and Water Resources Engineering, and a Bachelor's in Civil Engineering, Dr. Kimwaga is a Professional Engineer registered with the Engineers Registration Board (PEng No. 4862). He is also certified by the National Environmental Council (NEMC) for Environmental Impact Assessment (EIA) (Expert Registration No. NEMC/EIA 0375). Engaged with international and national professional institutions, networks, and associations such as Nile IWRM NET, GWP-Tanzania, and WaterNet, he contributes actively to his field. He's an active member of the Global Sanitation Graduate School (GSGS), funded by the Bill and Melinda Gates Foundation. He is also Academic Core-Lead Partner and Representative for Tanzania under GSGS Eastern and Southern Africa (ESA) Regional Hub. Dr Kimwaga has been the Principal Investigator for various international research projects the notable ones being Sustainable Sanitation in Theory and Action (SUSTAIN), Sustainable Water and Sanitation for All (SUWASAN) and Promoting Evidence-Based Investments in Sanitation for Health and Equity (PROMISE). Dr. Kimwaga has over 25 years of professional and research experience, spanning consultancy services in Constructed Wetlands, Wastewater and Faecal Sludge Engineering, Integrated Sanitation Management (ISM), Integrated Water Resources Management and Development (IWRMD), WASH, Solid Waste Management, and Stormwater Management. His achievements include managing stakeholder engagement processes, facilitating workshops, and moderating international conferences. Dr Kimwaga was the member of the National Core Technical Team for the preparation of Tanzania Development Vision 2050 (TDV2050) dubbed as DIRA 2050 and Long-Term Perspective Plan (LTPP) 2025 - 2050.

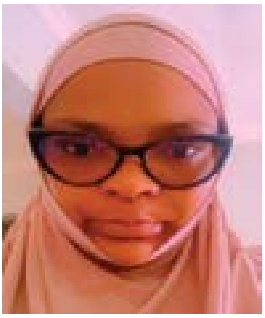
.**Prof. Deogratias M.M. Mulungu** is a renowned academic, researcher and consultant at the University of Dar es Salaam, holding a Ph.D in Engineering Hydrology, Masters in Water Resources Engineering and a Bachelor's in Civil Engineering. He is a Professional Engineer registered with the Engineers Registration Board, Tanzania. Prof Mulungu has deep expertise and experience in matters of climate downscaling and climate change impacts, hydrological processes, open channel hydraulics, computations in water resources engineering; groundwater hydrology, hydrological modelling, surface water hydrology, hydrological modelling, water governance, wetlands hydrology, constructed wetlands, Integrated Water Resources Management and Development Plan, and leadership. He has published widely both locally and internationally. Prof. Mulungu has been engaging in both local and international fronts, and has experience in providing professional advice to the Government or parastatals in advancing National visions and the sustainable development goals. He has participated and has membership in regional and international professional networks such as Alexander von Humboldt Foundation, FRIEND Nile, SADC WaternNet, NBCBN Foundation, Global Environmental Change consortium under the International Council for Science Regional Office for Africa (ICSU ROA), the African Research Universities Alliance (ARUA) and International Association of Hydrological Sciences. Prof. Mulungu has been the Secretary and member of the Special Audit Committee for implementation of rural water supply and sanitation projects, and the Secretary and member of the Special Committee to review and develop the design, construction supervision and operation and maintenance (DCOM) manual both for the Ministry of Water, Tanzania. Moreover, he holds a couple of coordination positions at the University of Dar es Salaam: The research and postgraduate studies coordinator at the Department of water resources; Projects coordinator of the Bureau for Industrial Cooperation (BICO). Also, serving as a management advisory committee member of the Technology Development and Transfer Centre.

Dr. Susan Taljaard is a Principal Researcher at the Council for Scientific and Industrial Research (CSIR) in South Africa and is a registered professional at South Africa's Council for Natural Scientific Professions. Over the past 40 years her research in marine, coastal and port systems focused on understanding biogeochemical characteristics and processes, responses to global change pressures, as well as development of science-based policy and best practice. This research has been largely shaped by the CSIR's mandate to foster science that contributes to the quality of life of South Africa's people, in collaboration with the private and public sectors. Her applied research outputs involved the development of environmental management frameworks, operational policies, guidelines, and toolkits in support of sustainable growth and development in marine, coastal and port environments. These included South Africa's 1st national coastal management framework (2014), as well as regional water quality management frameworks and guidelines, through the Benguela Current Large Marine Ecosystem Programme (2006), and for the Western Indian Ocean on commission of UNEP's Nairobi Convention Secretariat (2022). Her appointment as Honorary Professor at Nelson Mandela University and previously as Professor Extraordinary at University of Stellenbosch (South Africa), offers her the opportunity to share her transdisciplinary insights and learn from the next generation of marine and coastal scientists.

Steven Weerts works at South Africa's Council for Scientific and Industrial Research, as Principal Scientist and Research Group Leader. He is a marine and estuarine ecologist with 30 years' experience providing science support to a wide variety coastal and marine sector. He has worked extensively on coastal plain rivers, lakes, estuaries and marine continental shelves of South Africa and the wider West Indian Ocean Region. This work has been in the applied biophysical fields of water quality- and biological monitoring, ecological health, environmental flow allocations, assessment of impacts of anthropogenic activities, development and climate change, strategic environmental assessment, design of environmental offsets, State of Environment reporting and development of water quality guidelines at national and regional scales.

Dr Brent Newman is a Principal Scientist at the Council for Scientific and Industrial Research (CSIR) in South Africa and is a registered and is a registered professional at South Africa's Council for Natural Scientific Professions. The focus of his research is environmental chemistry and ecotoxicology in the coastal and marine environment. This includes water and sediment quality, the toxicity testing of wastewater, water, and sediment, and human health risks through exposure to chemicals in fish and shellfish. Through his research he has developed baseline metal concentration models for the South African coastline that assist authorities in reaching a decision on whether sediment is metal contaminated, and the magnitude of contamination. He also performs research in the broader field of chemical contamination, including studies on various organic pollutants (*e.g.* polycyclic aromatic hydrocarbons, pesticides, flame retardants) in sediment and seafood. He is involved in the use of toxicity testing as a tool for investigating the impact of toxicants in wastewater, ambient water, and sediment, and is involved in developing toxicity tests using indigenous South African organisms. His other research areas include investigating the chemical/contaminant footprint of large cities on coastal ecosystems and the impact of pharmaceutically active compounds and personal care products on coastal ecosystems.

Ms Sumaiya Arabi has over 15 years of professional and research experience as a scientist, working in the fields of marine pollution and coastal pollution management. Holding a Master's degree in Marine and Coastal Management, she is a Professional Natural Scientist registered with The South African Council for Natural Scientific Professions (SACNASP). Ms Arabi has worked as a Researcher for the Council of Scientific and Industrial Research (CSIR), focusing on the impacts of marine pollution discharges, port environmental management and impacts of marine plastic litter. Currently she works for the National Department of Forestry, Fisheries & the Environment responsible for the management of land-based sources of marine pollution in South Africa. She facilitates and implements measures to address land-based marine pollution and is actively involved in the development of the United Nations international legally binding instrument on plastic pollution.



Zaina Hussein Mseli is an accomplished Environmental Engineer and Technologist, as well as a dedicated academician and researcher at the University of Dodoma in Tanzania. She is holding a Master's degree in Environmental Technology and Management from Ardhi University, and a Bachelor of Science in Environmental Engineering from the University of Dar es Salaam. In her professional career, Zaina has gained extensive experience in the field of water supply, sanitation, and groundwater management. She has worked as a Water Supply and Sewerage Engineer at Consultant Company as a Project Engineer in several Tanzanian towns. She also worked as an Environmental and Social Expert in different project in Tanzania. She had experience on Resettlement Action Plans (RAP) for major projects including the East Africa Crude Oil Pipeline (EACOP). In addition to her professional and research activities, Zaina is also actively involved in community engagement, environmental conservation, and climate change adaptation efforts. She has experience in stakeholder engagement processes, facilitating workshops, and moderating international conferences. Zaina's diverse expertise, combined with her strong academic credentials and passion for her field, make her a valuable asset in the water and environmental engineering sector in Tanzania and beyond. Further, Zaina enjoys exploring new adventures, engaging in basketball games, and spending quality time with kids. She also takes pleasure in leisurely walks to stay physically fit and enjoy the outdoors.

Ms. Asumin Selemani Kantinga is a distinguished Chemical and Process Engineer, esteemed academician, and dedicated researcher at the University of Dodoma, Tanzania. She holds a Bachelor Degree in Chemical and Process Engineering, and Master's degree in Renewable Energy Engineering from the University of Dar es Salaam. Throughout her professional career, Asumin has amassed extensive experience in chemical and process engineering, environmental and energy management. Asumin has contributed significantly to various environmental and social projects as an environmental consultant at Paulsam Geo-engineering Company. She has played pivotal roles in Resettlement Action Plans (RAP) for major projects including the East Africa Crude Oil Pipeline (EACOP), Nyanzaga Gold Mine, and the Bulyanhulu Gold Mine extension. Her expertise in stakeholder engagement, workshop facilitation, and seminar conduction underscores her commitment to effective environmental and community engagement. In addition to her professional endeavors, Asumin is actively involved in social and community activities, environmental auditing, and climate change adaptation initiatives. Her diverse expertise, coupled with her strong academic background and passion for her field, makes her a valuable asset in the energy and environmental sectors both in Tanzania and internationally. Outside of her professional life, Asumin enjoys exploring new adventures, watching technological movies, and spending quality time with her family.

Eng. Leah Marwa is a laboratory engineer at the Water Resources Department, University of Dar es Salaam, and a registered professional engineer with the Engineers Registration Board (P.Eng. No. 6112). She holds a B.Sc. in Civil and Water Resources Engineering and a MSc. in Water Resources Engineering from the University of Dar es Salaam. She has nine (9) years research experience in areas of water resources, engineering, environment, and sanitation. Eng. Leah Marwa has been undertaking research activities in areas of water quality, solid waste, wastewater, and faecal sludge. Leah has worked extensively on faecal sludge characterization and quantification as a means of developing potential predictors for faecal sludge characterization at the community scale. This work has been quite beneficial for other researchers working in the field of faecal sludge. Her accomplishments in this line of work include serving as a stakeholder in reviewing drafts of faecal sludge management guidelines, serving as a technical team member in reviewing waste water standards, and developing curricula for the Ordinary Diploma and Bachelor degree in Water Supply and Sanitation Engineering.

FOREWORD

Pollution of any kind including that of marine and coastal ecosystems together with biodiversity loss and climate change are the three planetary crises which present one of the biggest challenges of our time. Certainly, they present one of the biggest threats to humanity. Additionally, in the face of resource scarcity the world is grappling with, there is transformative shift towards a circular society where waste is considered a valuable resource rather than a waste. To ensure a sustainable world, various approaches to addressing the grand global challenges should be grounded on the sustainable principles. Nature based solutions including constructed wetland technologies have been proven to provide the promising solutions to even marine and coastal ecosystems pollution from land-based sources and activities like those of Western Indian Ocean (WIO) region. In WIO region, the application of constructed wetland technology has been in existence for around three decades now, however its wide spread application in terms of uptake and adaptation at a scale has rather been limited due to various reasons. Stories on the success of Constructed Wetlands (CW) for wastewater treatment have not been told to a wider audience because they have not been well organized and documented. On the other hand, given the gravity and magnitude of the coastal and marine ecosystem pollution challenges, there is a need to device a counteract solution. There have been experiences of design, construction and use of the CW technologies for wastewater treatment in the WIO region but they have not been widely shared. Thus, an attempt has been made to structurally organize and present CWs for wastewater treatment with the view of sharing good and bad operational experiences of this promising technology in the WIO region. It is the expectation of the authors that this book will be a useful resource for those interested in applying this nature-based solution to address the pollution challenges in the ecosystems particularly those of the WIO region.

Richard Joseph Kimwaga, Ph.D

Lead Author and Editor

University of Dar es Salaam

ACKNOWLEDGEMENTS

I wish to sincerely and gratefully acknowledge and appreciate the various individuals whose remarkable moral and material contributions and support made this work a success. First and foremost, thanks are to the Almighty God of heaven for generously granting me good physical and mental health and also, for making my dream realized since my early academic years. I had a dream of sharing my academic and practical knowledge that would contribute to addressing some of the development challenges including ever increasing devastating environmental pollution leading to biodiversity loss. Appreciation goes to the Western Indian Ocean Marine Science Association (WIOMSA) for financially supporting this endeavour in collaboration with the Nairobi Convention. Nairobi Convention Secretariat is also thanked for their valuable input and contribution. My sincere thanks also go to the Regional Task Force Members of Western Indian Strategic Action Plan (WIOMSAP) Programme for their constructive comments on the case studies. I owe a very big appreciation to the University of Dar es Salaam and the University of Dodoma for providing effective enabling environment to facilitate the book writing process.

Richard Joseph Kimwaga, Ph.D

Lead Author and Editor

University of Dar es Salaam

PREFACE

In recent years, the poor and an inadequate municipal wastewater and faecal sludge management have escalated environmental challenges which are threatening the coastal and marine ecosystems' health of most of the Western Indian Ocean (WIO) region. This situation, if unabated, is likely to worse, thereby threatening the environment and ecosystem and thereby, the millions of people living in the area. The discharge of untreated and partially treated wastewater and faecal sludge into ocean has resulted into the marine and coastal ecosystems' pollution with consequential progressive degradation of the quality of the seafood which is the dominant main livelihood, contributing to the economic and wellbeing of the most of the coastal communities of the WIO region. Wastewater and faecal sludge treatment technologies can be a viable option to tackle these challenges. The conventional wastewater and faecal sludge treatment technologies which have been in use for the past decades are energy-intensive and highly mechanized technologies, a characteristic which doesn't favor their wide and intensive application, particularly in the WIO region communities. Contrary to the conventional technologies, nature-based technologies that utilize solar energy and living organisms offer a promising and sustainable solution to wastewater and faecal sludge problems in the region. In this era, where the sustainable principles are promoted and embraced in any development endeavors, constructed wetland (CW) treatment technology is a game changer in the paradigm shift towards the use of the less energy intensive treatment technologies. Currently, CWs are being utilized for effective removal of a wide range of pollutants from various wastewater sources including domestic, industry, agriculture worldwide.

Worldwide, CWs are increasingly being recognized as the green solution to addressing the wastewater and faecal sludge management challenges. Encouragingly, CW technology has presented another layer of wastewater and faecal sludge treatment technology options. Although, CW technology, in some of WIO region countries, e.g. Tanzania and Kenya, has been comprehensively developed, the effective and considerable application/uptake of this technology at scale is discouragingly still low. This may be partly attributed to an inadequate presence of robust guidelines for supporting the effective and smooth adaptation and proper use of this technology. Important elements and aspects in guidelines for the proper development and subsequent application of CW technology include understanding and knowledge of design, construction supervision and operation and maintenance (O&M) of CW. Specifically, there is no credibly published CW technology book that is tailored and customized to the WIO region needs and context. This book is an attempt and effort to address the pollution of coastal and marine ecosystems in the WIO region using CW technology as a nature-based solution (NBS). Globally, Nature Based Solutions have been widely accepted and have gained attention as one of the approaches to tackle the ever-increasing urban wastewater and fecal sludge problems. The book is the result of a lot of data gathered and analyzed; and compiled cases from various research and practical experiences using the latest approaches and concepts. One example of these concepts includes circular economy as an incentive for the sustainable sanitation services.

The objective of this book is to provide a comprehensive latest and advance understanding and knowledge of the CW technology compiled through various research works around the world and to present the pollutant removal performance experiences through the application of this technology in the WIO region. Further, the knowledge on pollutant removal mechanisms, design, construction and operation and maintenance of this technology is presented.

Generally, the broad goal of this book is to compile and objectively summarize the knowledge on CW technology generated under various conditions and its reflection to WIO region. The book provides an extensive overview of this treatment technology around the world, including examples from WIO region. As such, the book's intention is to provide a broad base of knowledge, including: 1) basic information about processes occurring in wetland soils as well as the overlying and underlying water, 2) general information about various types of constructed wetlands for wastewater treatment, 3) detailed information about functioning, performance, operation and maintenance, and costs of subsurface horizontal flow constructed wetlands, 4) information on the use of CW technology in the various climatic regions around the world. The book is not intended as design manual and therefore it does not contain detailed guidelines for the design and construction of these systems.

The pivotal to the discussion of CW technology presented in this book is on the technical underpinnings/principles and practical application and implementation experience of the CW in the WIO region and the world over. The structure of this edition of the book reflects ten chapters. Chapter one which deals with coastal and marine pollution in WIO region, has found the direct major coastal and marine pollution contribution sectors to be urban development and tourism, agriculture and forestry, fisheries and aquaculture, industry and mining, marine transportation and energy production. Key problems associated with marine pollution in the WIO region have been identified as microbiological contamination, nutrient enrichment (eutrophication), marine litter, suspended sediment loading and toxic pollution. Chapter two presents the existing municipal wastewater treatment methods in the WIO region. Key issues reported in this chapter include ineffective and inadequacy and high operating costs of conventional wastewater treatment technologies due to high intensity of energy they utilize. Also, the chapter presents the weakness and time inferiority of the existing wastewater and faecal sludge treatment technologies. Chapter three provides the general introduction to CW technology including its definition, types and the underlying major pollutant removal mechanisms. Chapter four highlights the enablers for mainstreaming and ultimate adaptation and application of the CW technology. Several WIO region countries have existent and appropriate policies, laws and institutions related to CW technology. Issues needing attention are harmonization, reviewing and updating of these enablers to keep pace with the rapidly changing world in various fronts of development challenges. Chapter five deals with the planning processes for the CW technology. Factors to be considered for CW technology planning are comprehensively discussed in this chapter. Chapter six presents the various design approaches and methods for CW where the mostly used design approach in WIO region is the first-order plug-flow bio-kinetic model. Chapter seven deals with the construction procedures and techniques where it was found out that construction procedure for CW technology are similar to other civil engineering infrastructure with focus on flow and substrate packing and macrophye planting. Chapter eight highlights and emphasizes the needs and importance of CW system operation and maintenance (O&M). Evidently, most of the implemented CW facilities have fallen into disarray and became malfunctioned largely due to poor and inadequate operation and maintenance. Thus, the chapter presents the operation and maintenance requirements and protocols for the proper functioning of the CW technology. Chapter nine gives information on assessment and analysis of the economics and financing of the CW. Examples on cost benefit analysis are also presented in this chapter. Chapter ten presents the various CW case studies in the WIO region with the view of documenting the lessons learnt as well as success and failure factors pertaining to effective and smooth operation of the CW.

We believe that the experiences and the case studies which are articulately discussed in this book can serve as useful reference materials for wastewater and faecal sludge professionals, practitioners, researchers, and academicians in the WIO region. We hope that this book will become a major resource for the widespread dissemination and further uptake of this successful eco-technology in the WIO region. The book is a huge accelerator towards contributing to the achievement of the Agenda 2030 and its Sustainable Development Goals (SDGs) specifically, SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development. This goal is relevant to marine pollution where target 14.1 is aimed at preventing and significantly reducing marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution.

Evidently, this book stands out as the only available document from the compilation of CW research findings and case studies to address and control pollution from the ever-increasing wastewater and faecal sludge challenges and problem significantly originating from land-based activities in the WIO region..

LIST OF ACRONYMS

ACP	African, Caribbean, and Pacific
AMCOW	African Ministers' Council on Water
ANN	Artificial Neural Network
ASCLME	Agulhas and Somali Current Large Marine Ecosystems Project
BCC	Behavior Change and Communication
BGI	Blue-Green Infrastructure
CA	Cellular Automata
CAACs	Catchment Areas Advisory Committee
CBA	Cost Benefit Analysis
CBD	Convention on Biological Diversity
CBD	Central Business District
CCIC	Climate Change Information Centre
CE	Circular Economy
COBWSOs	Community Based Water Supply Organizations
COP	Conference of Parties
CPM	Commission on Phytosanitary Measures
CW	Constructed Wetland
CWA	Central Water Authority
CWB	Central Water Board
CWCs	Catchment Water Committees
CZMC	Coastal Zone Management Centre
DDT	Dichlorodiphenyl Trichloroethane
EbA	Ecosystem-based Adaptation
EC	European Commission
ECMA	Environmental Management and Coordination Act
EIA	Environmental Impact Assessment
ESS	Ecosystem Services
ESSAPs	Environmental Sanitation Strategy and Action Plans
EWURA	Energy and Water Utilities Regulatory Authority
FAO	Food and Agriculture Organization
FARI	Forum for Academic and Research Institutes
FML	Flexible Membrane Liners
FSM	Faecal Sludge Management
GSGS	Global Sanitation Graduate School
HAB	Harmful Algal Bloom
HCB	Hexachlorobenzene
IAPSC	Inter-African Phytosanitary Council
ICM	Integrated Coastal Management
IMO	International Maritime Organization
IPPC	International Plant Protection Convention
IRR	Internal Rate of Return
ISM	Integrated Sanitation Management
IWMF	Institutional Water Management Framework
IWRM	Integrated Water Resources Management
IWRMD	Integrated Water Resources Management and Development
KMFRI	Kenya Marine Fisheries Research Institute
LBSA	Land Based Sources and Activities
LGA	Local Government Act
LGAs	Local Government Authorities
LWMA	Landscape and Waste Management Agency
MEAs	Multilateral Environmental Agreements
MOLUSCE	Module for Land Use Change Evaluation
MOWASSCO	Mombasa Water Supply and Sanitation Company
MoW	Ministry of Water
NAWAPO	National Water Policy
NBS	Nature Based Solution

NEMA	National Environment Management Authority
NEMC	National Environment Management Council
NEP	National Environment Policy
NPV	Net Present Value
NSMP	National Sanitation Management Policy
NWB	National Water Board
NWMP	National Water Master Plan
NWSS	National Water Services Strategy
OCPs	Organochlorine Pesticides
OCPs	Octacalcium Phosphates
OHMSCP	Oil and Hazardous Materials Spill Contingency Plans
OPRC	Oil Pollution Preparedness, Response and Co-operation
PAHs	Poly-aromatic hydrocarbons
PBDEs	Polybrominated Diphenyl Ethers
PBP	Pay Back Period
PCBs	Polychlorinated Biphenyls
PCDD	Polychlorinated Dibenzo-p-Dioxins
PCDF	Polychlorinated Dibenzofurans
PCPs	Pharmaceuticals and Personal Care Products
PCs	Pollutants of Concern
PFAs	Perfluorooctanesulfonic Acids
POPs	Persistent Organic Pollutants
PUC	Public Utilities Corporation
PVC	Polyvinyl Chloride
RBC	Rotating Biological Contactor
RBO	River Basin Organization
RNP	Ruaha National Park
RPPO	Regional Plant Protection Organizations
RUWASA	Rural Water Supply and Sanitation Agency
SACCO	Savings and Credit Cooperative Organisations
SADC	Southern African Development Community
SAMSA	South African Maritime Safety Authority
SAP	Strategic Action Programme
SAPPHIRE	Strategic Action Programme Policy Harmonisation and Institutional Reforms
SBR	Sequencing Batch Reactor
SCWCs	Sub-Catchment Water Committees
SMSA	Seychelles Maritime Safety Authority
SSDS	Seychelles Sustainable Development Strategy
SST	Sustainable Seas Trust
SWIOFP	Southwest Indian Ocean Fisheries Project
UESHSAPs	Urban Environmental Sanitation and Hygiene Strategic and Action Plans
UNEP	United Nations Environment Program
URA	Utility Regulatory Authority
USESIFP	Urban Strategic Environmental Sanitation Investment and Financing Plan
WASH	Water, Sanitation and Hygiene
WIO	Western Indian Ocean
WIO-LME	Western Indian Ocean Large Marine Ecosystems
WIOMSA	Western Indian Ocean Marine Science Association
WIOSAP	Western Indian Ocean Strategic Action Plan
WIOSEA	Western Indian Ocean Sustainable Ecosystem Alliance
WIOSMA	Western Indian Ocean Marine Science Association
WMA	Wastewater Management Authority
WRA	Water Resources Authority
WSP	Water and Sanitation Programme
WSP-AF	Water and Sanitation Programme Africa Region
WSSAs	Water Supply and Sanitation Authorities
WSSP	Water Sector Strategic Plan
WSSP	Water Sector Strategic Plan
WTO	World Trade Organization
WUAs	Water User Associations

Chapter 1: Coastal and Marine Pollution in Western Indian Ocean Region

By Susan Taljaard, Steven Weerts, Brent Newman, and Sumaiya Arabi CSIR, South Africa

HIGHLIGHTS

The coastal and marine pollution in WIO region is increasingly becoming the environmental management challenge of concern. It threatens and deprives all the services and functions accorded to the local communities' wellbeing and livelihoods. As such efforts have to be put in place to address the environmental challenge at hand. This chapter provides an overview of the extent, magnitude and nature of the coastal and marine pollution in the WIO region. The chapter sets the stage and tone for the need to use nature-based solutions to address the ever-increasing pollution of coastal and marine ecosystems largely from land-based activities.

1.1 Description of the WIO Region

The WIO region along with a combined coastline of more than 15,000 km spans the mainland countries of Somalia, Kenya, Tanzania, Mozambique, South Africa, Madagascar, Comoros, Reunion, Mauritius and Seychelles (UNEP *et al.*, 2015). Globally, at least 40 percent of the world's population lives in coastal areas and coastal cities have expanded rapidly over the past decade. The WIO region has been no exception. All countries in the region have experienced rapid population growth and urbanization in coastal areas, particularly the larger coastal centres. Opportunities created by urbanization, availability of ports and harbours, and various coast specific developments have attracted high concentrations of people in these areas. By 2014, countries in the region had a combined population of 212.6 million, with as much as 50 percent of the population in mainland countries living in the coastal zone (UNEP *et al.*, 2015).

The socio-economic setting of the WIO region is largely dictated by availability and state of natural resources. A significant proportion of coastal communities in the region depend directly upon coastal and marine resources for food and building materials. They rely heavily on small scale fisheries for livelihoods, together with agriculture, subsistence forestry, marine aquaculture, small-scale mining, localized trading, small livestock husbandry, trade in handicrafts, employment in services industries and other sectors related to coastal or coastal and marine systems, such as oil and gas production, and shipping (UNEP *et al*, 2021a). Extractive industries, construction, and service sectors, including tourism, are significant drivers of growth. Potential growth is predicted in investments in infrastructure, stabilization of power generation, fiscal reforms, and natural gas reserves (UNEP *et al*., 2015). Such rapid urbanization and extensive utilization of coastal and marine resources are posing serious threats to these, often sensitive environmental areas, including threats from pollution.

1.2 Hydrographic Features

Ocean surface circulation in the WIO region (as shown in the Figure 1.1) is primarily wind driven and is an important factor influencing temperature and salinity distribution, availability of nutrients, distribution and abundance of phytoplankton, fisheries, and the transport and fate of pollutants (UNEP *et al*, 2021a).

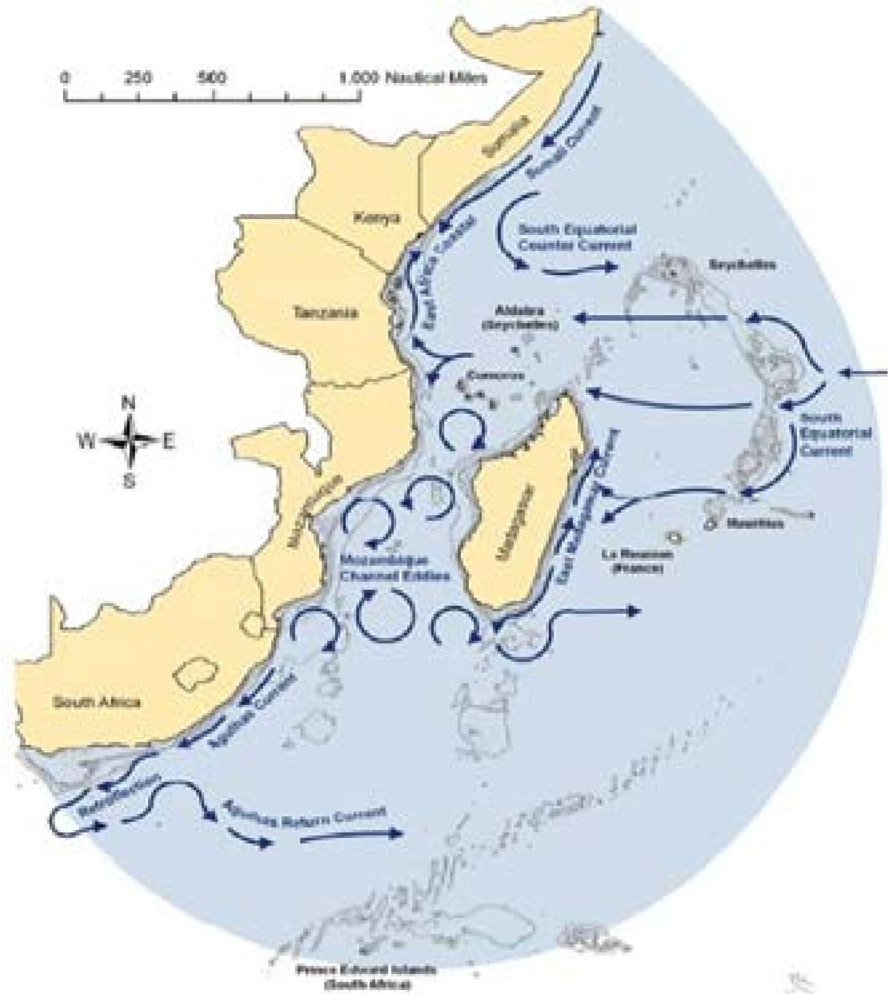


Figure 1.1: Schematic illustration of major surface current patterns in the Western Indian Ocean (Source: UNEP et al. 2009a)

The prevailing wind regimes can be divided into two distinct systems; the monsoon regime that dominates the Somali Current Large Marine Ecosystem and the subtropical high-pressure system that dominates the southern region's Agulhas Current Large Marine Ecosystem (Beckley, 1993; Okemwa, 1998; UNEP *et al*., 2015). Large-scale climatic phenomena, such as the El Niño Southern Oscillation and the Indian Ocean Dipole, influence the meteorology of the WIO region (UNEP *et al*., 2015).

The prevailing wind regimes can be divided into two distinct systems; the monsoon regime that dominates the Somali Current Large Marine Ecosystem and the subtropical high-pressure system that dominates the southern region's Agulhas Current Large Marine Ecosystem (Beckley, 1993; Okemwa, 1998; UNEP *et al*., 2015). Large-scale climatic phenomena, such as the El Niño Southern Oscillation and the Indian Ocean Dipole, influence the meteorology of the WIO region (UNEP *et al*., 2015).

The Northeast Monsoon affects the climate of the Northwest Indian Ocean from November to March and is characterized by north-easterly winds over the tropics and northern subtropics (Ngusaru, 1997). It has winds of moderate strength, with dry terrestrially derived air blowing from Arabia to Madagascar (Weller *et al*., 1998). In contrast, during the Southwest Monsoon (June to October) wind direction reverses and winds tend to be much stronger, with an intense wind stream developing along the high Eastern African highlands (*e.g*. Ethiopian highlands, Kenya highlands, highlands of northern and southern Tanzania) (Ngusaru, 1997; Slingo *et al*., 2005).

During the Northeast Monsoon, the North Equatorial Current flows westward, turns south at the coast of Somalia, and returns east as the Equatorial Counter current between 2° and 10° S (UNEP *et al*., 2021a). During the Southwest Monsoon, the North Equatorial Current reverses its flow and becomes the strong east-flowing Monsoon Current. Part of the South Equatorial Current turns north along the coast of Somalia to become the Somali Current. A pronounced front, a phenomenon unique to the Indian Ocean at 10° S, marks the limit of the monsoon influence (Kanayev *et al*., 2009). The Somali Current reverses direction with season (American Meteorological Society, 2000) and is the western boundary current of the Northwest Indian Ocean when flowing northwards along the East African coast. During the Northeast Monsoon, the Somali Current flows south, meeting the north-flowing East African Coastal Current which originates from the South Equatorial Current (Okemwa, 1998; Horrill *et al*., 2000; American Meteorological Society, 2000).

The East African Coastal Current's geographical extent is seasonally determined. It's interaction with the Somali Current shifts southward as the monsoon progresses (Horrill *et al*., 2000). By the time the Southwest Monsoon peaks in August, the Somali Current is established as a continuous current running from the East African Coastal Current to the East Arabian Current (American Meteorological Society, 2000). South of the monsoon region, there is a steady subtropical anti-cyclonic gyre, consisting of the west-flowing South Equatorial Current between 10° and 20° S, which divides as it reaches Madagascar (Kanayev *et al*., 2009; Lutjeharms, 2006). One branch passes to the north of Madagascar and turns south as a series of slow-moving gyres or eddies that constitute the Mozambique Current between mainland Africa and Madagascar (Lutjeharms, 2006). These drift southward along the shelf edge (Schouten *et al*., 2002) and can cause minor upwelling. The other branch, the East Madagascar Current, turns south to the east of Madagascar and then curves back to the east as the South Indian Current at about 40° to 45° S (Kanayev *et al*., 2009; Lutjeharms, 2006).

A strong, narrow, western boundary current, the Agulhas Current, is generated by the current described above and the Southwest Indian Ocean subgyre, with little inflow from the Mozambique Current (Lutjeharms, 2006). The Agulhas Current flows along South Africa before turning east and joining the Antarctic Circumpolar Current south of 45° S. It generates periodic gyres between its western boundary and mainland which are responsible for minor upwelling (Lutjeharms, 2006). The current system at the eastern boundary of the ocean is not as developed, but the West Australian Current flowing north from the South Indian Current closes the gyre to a certain extent (Figure 1). The Agulhas Current extends to a depth of about 1,200 m and the Somali Current to about 800 m. Other currents do not penetrate beyond 300 m. Below the influence of the surface currents, water movement is sluggish and irregular, and is derived from several oceanic sources apart from the Indian Ocean. These cold, dense layers, creep slowly northward from their source in the Antarctic Circumpolar region, becoming nearly anoxic (oxygen-deficient) en route.

The WIO region displays all three tidal types, namely diurnal, semi-diurnal and mixed, with semi-diurnal (*i.e.* twice daily) being most widespread. Semi-diurnal tides prevail on the coast of eastern Africa as far north as the Equator (Hamilton and Brakel, 1984). Tides are mixed in the northern region, particularly towards the Arabian Sea (Sheppard, 2000). Tidal ranges vary considerably. Mauritius, for example, has a spring tidal range of only 0.5 m, while along the eastern Africa coast the spring tidal range is of the order of 3-4 m (Alusa and Ogallo, 1992; Hamilton and Brakel, 1984; Kanayev *et al*., 2009).

Air temperature in the WIO region at sea level rarely falls below 20°C and seawater temperature is usually between 20-30°C. Upwelling is a seasonal phenomenon in some parts of the region. During the Southwest Monsoon, upwelling occurs off the Somali and Arabian coasts (Bakun *et al.*, 1998; Kanayev *et al.*, 2009). It is most intense between 5° and 11° N, with replacement of warmer surface water by water of about 14 °C. It modifies the salinity, temperature, and nutrient of the surface water (Vinayachandran *et al*., 2002).

As a result of high seasonal and annual variability in rainfall and evaporation rates, the region is subject to large variations in salinity. Sea surface salinity is also affected by anomalous anticyclonic winds blowing in the Southeast Indian Ocean, which prevent the export of saltier water from the WIO region. Overall, the salinity of WIO surface waters varies between 32 and 37 parts per thousands, but with large local differences. High surface salinity (greater than 35 parts per thousands) is also found in the Southern Hemisphere subtropical zone between 25° and 35°S, while a low salinity zone stretches along the hydrological boundary of 10° S from Indonesia to Madagascar.

In general, marine waters in the WIO region are oligotrophic, characterized by low nutrient concentrations and low phytoplankton biomass. For example, nutrients and primary productivity in surface waters of the Somali Current were found to be generally low except during seasonal upwelling (during the Southwest Monsoon), when colder nutrient rich waters are introduced to the Somali and Arabian coasts (McClanahan, 1988; Mengesha *et al.,* 1999). The flow of the South Equatorial Current delivers higher concentrations of nutrients to the central and northern Mascarene Plateau, resulting in higher levels of productivity in these areas (New *et al.,* 2005).

1.3 Ecosystem Distribution and Key Threats

The WIO region supports over 11,000 species of plants and animals in numerous ecosystem types. Ecosystems that are particularly sensitive to marine pollution are mangrove forests, seagrass beds, coral reefs, and salt marsh ecosystems (UNEP *et al.,* 2009a). These highly productive ecosystems are vital to the ecology and socio-economy of the region but are negatively impacted by human activity (UNEP *et al.,* 2015). A detailed explanation of these is provided as under: -

1.3.1 Mangrove Forests

Mangroves grow along sheltered shores of tropical and subtropical regions (UNEP *et al.*, 2015), thriving in sedimentary lagoons, bays, estuaries, and tidal creeks (Alongi, 2002; UNEP *et al.*, 2015). In the WIO region these ecosystems are found in all countries except Reunion (France), covering areas of about 1,000,000 ha. However, 90 percent of the coverage occurs in estuaries and deltas in Mozambique, Madagascar, Tanzania, and Kenya (UNEP *et al.*, 2009a; 2015). The most dominant species found throughout the region are *Bruguiera gymnorrhiza*, *Ceriops tagal* and *Rhizophora mucronata* (UNEP *et al.*, 2004), but others include *Avicennia marina*, *Avicennia officionalis*, *Heritiera littolaris*, *Lumnitzera racemosa*, *Sonneratia alba*, *Xylocarpus granatum* and *Xylocarpus moluccensis* (UNEP *et al.*, 2015).

Mangrove forests are extremely productive ecosystems that support complex food webs consisting of both terrestrial and aquatic organisms. Key fauna that typically associate with mangroves are polychaetes, bivalves, gastropods, crustaceans, birds, fish, marine turtles, and dugongs. They are vital spawning and nursery grounds for numerous invertebrate and fish species. Within the WIO region these habitats support major fisheries. Additionally, they provide visual aesthetics, shoreline protection from storms and severe wave action and erosion, trap sediments reducing turbidity of coastal waters, and fix, trap, and turnover nutrients (UNEP *et al.*, 2021a).

Despite their ecological value, mangrove ecosystems face severe degradation from various human activities such as inappropriate harvesting, clearing for forestation and agriculture, reduction in freshwater flows and marine pollution. Pest infestation, El Niño events and climate change also are impacting mangroves (UNEP *et al.*, 2015). The effects of marine pollution on mangrove ecosystems stem from various activities, including inappropriate disposal of waste and wastewater and oil spills associated with harbour activities and shipping. Mangroves act as sinks for pollutants from municipal and industrial discharges, as well as agricultural return flows. Mangrove swamps are commonly targeted for sewage and industrial discharge as the trees uptake nutrients and other pollutants are reduced or removed (*e.g.* heavy metals, organic compounds) by mangrove soils, algae, and microbes (Wong *et al.*, 1997). However, continuous pollution loading can eventually overwhelm a mangrove system's absorptive capacity. Excess nutrients promote the over-growth of algae, smothering and destroying the aerial roots of mangroves. Excessive organic loading also contributes to disease outbreaks, retardation of growth, mangrove mortality and a decline in mangrove biodiversity (UNEP *et al.*, 2009a). This is especially a concern in the larger coastal cities that do not have adequate wastewater treatment facilities, resulting in pollutants being discharged into estuarine waters and mangrove habitats (Richmond, 2002).

Many countries still use pit latrines and septic tanks, which contaminate the groundwater that drains into mangrove ecosystems, causing localized algal proliferation and eutrophication (Mmochi and Francis, 2003). Consequently, this practice contributes to the pollution of marine and coastal ecosystems of WIO region (UNEP *et al.*, 2021a). Toxic pollutants including heavy metals of zinc, lead and mercury (*e.g.* from industrial discharges) tend to accumulate in mangrove areas, polluting plants and soils, and affecting mangrove growth (Yim and Tam, 1999). Herbicides and pesticides leach into groundwater and surface water runoff causing mangrove defoliation and dieback (Mmochi and Francis, 2003; Schaffelke *et al.*, 2005). Oil spills can also be disastrous for mangrove forests (Munga, 1993; Richmond, 2002). Oiling causes mangrove defoliation, chlorophyll-deficient mutations, as well as seedling and tree mortality. Spillage from ships has caused considerable damage and destruction of mangrove forests in Mombasa (Kenya), resulting in mangrove dieback and the effects are still evident ten years after the last oil spill (Abuodha and Kairo, 2001).

1.3.2 Seagrasses

Seagrasses are highly productive ecosystems that cover approximately 0.1-0.2 percent of the global ocean (Duarte, 2002), with at least 45 species distributed mainly in tropical and subtropical regions. Seagrass beds are a common feature in shallow waters of the WIO region, with 12 species from three different families identified: *Cymodocea rotundata*, *C. serrulata*, *Enhalus acoroides*, *Halodule uninervis*, *Halophila ovalis*, *Halophila stipulacae*, *Halophila decipiens*, *Halophila beccarii*, *Thalassia hemprichii*, *Thalassodendron ciliatum*, *Syringgodium isoetifolium* and *Zostera capensis*. The most dominant genera are *Thalassia*, *Halodule*, *Syringgodium*, *Halophila* and *Cymodocea* (UNEP *et al*., 2015; Adams *et al*., 2016). Seagrass beds occur on soft substrates (sandy or muddy sediments), usually in estuarine and sheltered marine waters (den Hartog, 1979; Richmond, 2002). They fulfil important ecosystem functions. They are important habitats and nursery areas for numerous organisms, including crustaceans (crabs, shrimp, and lobster), echinoderms (sea urchins and sea cucumbers), molluscs (bivalves and gastropods) and fish. Seagrasses are a food source for invertebrates, fishes, marine turtles, and dugongs (Orth *et al*., 1984; Duarte, 2002; UNEP *et al*., 2015). They provide oxygen to waters and sediments, stabilize sediment, protect shorelines, and trap and re-cycle nutrients (Duarte 2002; UNEP *et al*., 2015).

In the WIO, seagrass ecosystems are degraded by trampling, direct removal, or indirect impacts of land-based activities. Globally, seagrass beds are listed as vulnerable, although in South Africa these ecosystems are already endangered due to a marked reduction in extent (Van Niekerk *et al*., 2019). Key threats to seagrasses include climate change, sedimentation, physical destruction of beds (*e.g.* dredging, trampling, and trawling), reduction in water levels (*e.g.* extended periods of mouth closure of inlets or extended periods of low tide), sedimentation and marine pollution (UNEP *et al*., 2015). Marine pollution because of inappropriate disposal of waste and wastewater, and oil pollution from harbour activities and shipping, is a major contributor to the decline of seagrass ecosystems (UNEP, 2021). Excessive nutrient inputs from sewage and domestic wastewater discharge stimulate phytoplankton, epiphytes and macroalgae growth, decreasing light availability to seagrass beds (Lapointe and Clark, 1992; Schaffelke *et al*., 2005; Duarte, 2002). Seagrass sediments also trap and accumulate organic compounds, resulting in organic-rich sediments that promote microbial activity (Duarte, 2002) leading to oxygen depletion and the release of toxic metabolic by-products like hydrogen sulphide and methane (Schaffelke *et al*., 2005). Agrochemicals, such as pesticides and herbicides, leaching into nearshore waters have been found to inhibit photosynthesis, reproduction, and growth in seagrasses (Duarte, 2002). Toxic pollutants, such as metals, accumulate in seagrass tissue through foliar uptake (Schaffelke *et al.*, 2005). The main consequence of oil pollution on seagrass beds is smothering (Abuodha and Kairo, 2001), and to exacerbate problems, dispersants commonly used to clean up oil spills contain toxic solvents that penetrate the protective waxy cuticles of seagrass blades, causing plant loss and harmful effects on associated biota (Ellison and Farnsworth, 1996; Abuodha and Kairo, 2001).

1.3.3 Coral Reefs

Coral reefs are shallow subtidal ecosystems found in tropical and subtropical oceans and are among the most biodiverse and productive ecosystems in the world (McClanahan, 2002; UNEP *et al.*, 2015). These living structures thrive in shallow, nutrient limited waters up to depths of 20-30 m (McClanahan, 2002). Highly productive coral reefs fringe over 1,500 km of the WIO region coastline. There are four main types of reefs. Fringing reefs are most common, generally associated with shallow lagoons. The other three classes include patch reefs, atolls, and barrier reefs (UNEP *et al.*, 2015).

Corals of the genus *Acropora* are the most abundant and diverse genus found in the WIO region, although since the 1998 bleaching event, the geographic range of *Acropora* has become limited to southern Tanzania and northern Mozambique. *Millepora*, once dominant in shallow coral communities, have also experienced a decline and are now represented in some regions by dead skeletons only. Previously dominant genera are being replaced by those that are less vulnerable to bleaching, such as *Porites* (Obura, 2005).

Other genera commonly found throughout the WIO region include *Astreopora*, *Alveopora*, *Cyphastrea*, *Echinopora*, *Favia*, *Favites*, *Galaxea*, *Goniastrea*, *Goniopora*, *Hydnophora*, *Leptoria*, *Montipora*, *Oxypora*, *Pavona*, *Platygyra* and *Pocillopora* (Fagoonee, 1990; Obura, 2005). Coral ecosystems support an array of fauna and flora, including macro- and micro-algae, tunicates, sponges, polychaetes, bivalves, gastropods, echinoderms (urchins, star fish and sea cucumbers), crustaceans (prawns, crabs, lobsters, isopods, amphipods), fish, microbes, and turtles (UNEP *et al.*, 2015). Corals provide unique habitat that supports local subsistence fisheries and tourism. They provide local communities construction materials and reefs protect shorelines from strong wave action and erosion.

As with most sensitive ecosystems in the WIO region, coral reefs are seriously threatened by climate change and human pressures including over-exploitation, inappropriate fishing techniques (poison and dynamite), and marine pollution. Corals subject to anthropogenic impacts, including pollution, are prone to increased risk from diseases. Numerous studies have reported high occurrences of diseases, blemishes and dead patches of coral reefs situated near urban outfalls (McClanahan, 2002).

Nutrient loading from inappropriate disposal of sewage and domestic wastewater increases the productivity and biomass of phytoplankton and opportunistic algae, inhibiting light penetration and severely affecting the growth and survival of coral reefs. Algae may overgrow and smother corals, promoting increased productivity of other opportunist organisms such as sponges and tunicates, which out-compete corals for habitat (Pastorok and Bilyard, 1985; Ramessur, 2002). Reef invertebrates and fish are vulnerable to toxic pollution (*e.g.* metals), accumulating these contaminants within soft body tissues and displaying distinct physiological and cytological responses to varying levels of pollutant exposure (Rainbow, 1995).

In addition, metals are easily absorbed by the tissue of coral skeletons, altering various chemically mediated processes such as reproduction and recruitment. Consequently, such pollutant exposure causes severe modifications in reef productivity and mortality rates (Peters *et al.*, 1997). Similar phenomenon has been reported in WIO region (UNEP *et al.*, 2021a). Studies have shown that corals exposed to oil pollution undergo a variety of negative impacts that include coral tissue death, bleaching and impairment of biological processes such as photosynthesis, reproduction, and growth (McClanahan, 2002). In addition, dispersants used to clean-up oil leaks contain toxic chemicals that exacerbate the effects of the oil spill and can prolong coral reef recovery by years (Peters *et al.*, 1997).

1.3.4 Saltmarsh

Saltmarshes in the WIO region occur in the south and are found almost entirely in South Africa (UNEP *et al.*, 2015; Adams, 2020). Here, intertidal, and supratidal saltmarshes cover about 5,870 ha and 6,190 ha, respectively. Intertidal saltmarsh typically occurs in permanently open estuaries distributed along the entire coastline of South Africa, but predominantly in warm temperate regions. Supratidal saltmarshes occur at elevations greater than 1.5 m above mean sea level and are dominant in the cool temperate region along the western and south-western coastlines (Adams, 2020).

Salt marshes also are important in mitigating threats from land, trapping excessive sediments, nutrients and other pollutants before they enter the marine environment. Common saltmarsh genera are *Sarcocornia*, *Salicornia*, *Triglochin*, *Limonium* and *Juncus*. Halophytic grasses such as *Sporobolus virginicus* and *Paspalum spp*. are also present. *Sarcocorniapillansii* is common in the supratidal zone (Adams *et al.*, 2016). Saltmarshes are poorly studied elsewhere in the WIO, but small patches are believed to be associated with mangroves and marshlands in the wider region (a small area of saltmarsh has been recorded in Maputo Bay) (UNEP *et al.*, 2015).

Saltmarsh ecosystems are threatened by climate change and various human activities, including changes in water abstraction (reduced river flows), flood plain development, and agriculture (resulting in nutrient enrichment through the introduction of fertilizers) (Adams, 2020). Approximately 43 percent of saltmarsh habitat has been lost due to encroaching development and agriculture from the 1930's to 2018 (Adams, 2020). Loss of intertidal saltmarsh habitat is usually due to inappropriate developments, such as causeways, bridges or encroaching housing and business developments.

Agricultural impacts are largely responsible for the loss of supratidal salt marshes associated with crop production and cattle grazing. Reduction in freshwater flows also impacts saltmarsh vegetation, causing salinization and desiccation. In temporarily open/closed estuaries, extended periods of mouth closure result in inundation and flooding of saltmarshes. Smothering of saltmarshes as a result of eutrophication (*e.g.* macroalgal blooms) caused by nutrient enriched sewage discharges and agriculture return flows is a growing concern (Adams, 2020).

1.4 Sources of Land-based Pollution

At the core of coastal and marine pollution management is the protection of valuable natural resources, not only to protect biodiversity, but also to safeguard ecosystem services that provide social and economic benefits to coastal communities. Ironically, as is the case elsewhere in the world, root causes in the socio-economic system itself contribute to deterioration and mismanagement of coastal and marine resources. These include population growth, poverty and inequality, inappropriate governance, inadequate knowledge, low awareness, and limited financial resources (UNEP *et al.***,** 2009a).

Root causes are deeply rooted in the social system demanding considerable commitment and effort over time to change. Their influence in hampering effective coastal and marine water quality management can be significant, and it is crucially important to acknowledge and create awareness of the importance and urgency of tackling these causes for long-term sustainability. While root causes typically characterize the indirect influences, underpinning societal dynamics contributing to the deterioration of coastal and marine ecosystems, the major land-based sectors that contribute directly to marine pollution in the WIO region include urban development and tourism, agriculture and forestry, industry and mining. Other sea-based sectors include fisheries and aquaculture, marine transportation, and energy production (UNEP *et al.*, 2021a).

1.4.1 Urban Development and Tourism

Of increasing concern in countries of the WIO region is the rapid and often uncontrolled coastal urbanization and tourism development, resulting in inappropriate management and control of waste. Key activities that contribute to marine pollution include municipal wastewater disposal (including faecal sludge), diffuse urban runoff and solid waste disposal. In many cases, basic infrastructure cannot cope with the increased volume of sewage. Sewage from sanitary facilities (septic tanks, pit latrines) and inadequately designed and operated wastewater treatment plants is a major source of marine pollution, with the type and level of treatment differing from country to country (UNEP *et al.*, 2009a, 2021a).

Non-centralized sewer systems, such as pit latrines and septic tanks, produce significant quantities of faecal sludge. As a result of inadequate sludge management, this has become a major source of pollution in parts of the region. While centralized wastewater treatment works are found in some areas, the rapid growth in the coastal zone has led to a marked increase in effluent volumes, challenging infrastructure maintenance and upgrades (UNEP *et al.*, 2009a). Microbial contaminants, nutrients, biodegradable organic matter and suspended solids are the main pollutants in untreated municipal sanitary wastewater. The highest concentrations of these pollutants are therefore found close to major cities in the region, although in many rural coastal areas contamination from open defecation on beaches is common. Urban stormwater can also introduce toxicants, such as metals and petroleum hydrocarbons, associated with storm runoff. Municipal solid waste is a major source of marine litter in coastal areas and inadequately treated wastewater is a major route by which microplastics enter water bodies (Ubomba-Jaswa and Kalebaila, 2020).

In the Comoros, increase in the population and urbanization has led to an increase in household waste production, untreated hospital waste and emissions associated with transport activity. There are no formal waste collection and processing structures in place. Garbage is disposed along the roads, into the ocean/sea or rivers, and in the vicinity of where people live. There is no sewerage, drainage, and evacuation of wastewater treatment networks in the Comoros (ASCLME, 2012a).

In Kenya, most urban centres, such as Mombasa, Kilifi, Lamu and Malindi, are not able to effectively dispose of sewage. Increased developments in river basins have also contributed significantly to suspended sediment loading into the coastal environment (ASCLME, 2012b). Parts of Madagascar do not have sewage treatment facilities prior to disposal and wastes are discharged into estuarine and shallow waters (UNEP *et al.*, 2009a; ASCLME, 2012c). In Mozambique, the capital Maputo is the only city with a sewage infrastructure, but this treats only about 50 percent of the city's sewage and sewage contamination occurs in Maputo Bay. Sewage contamination has also been recorded in Beira Bay and Nacala Bay. The rest of Mozambique mainly relies on pit latrines and septic tanks, which contaminate groundwater systems (ASCLME, 2012d).

In the Seychelles, effluent from wastewater treatment works discharging directly to coastal waters was found to contain unacceptable levels of faecal contamination (Antoine *et al.,* 2008; ASCLME, 2012e). At Beau Vallon Bay, run-off from non-point sources, such as rivers and small streams, contributes to high microbial loads during the rainy season (Radegonde, 1997; Antoine *et al.,* 2008). Outbreaks of water borne diseases usually occur during the rainy season, associated with defective wastewater disposal systems. Septic tanks are the most common human waste disposal option in Somalia with only a small section of Mogadishu having sewage systems (ASCLME, 2012f).

Since about 1985 the design of offshore sewage outfalls in South Africa has followed the receiving water quality objectives approach, where effluent quantities and composition must be within limits that meet receiving water quality objectives. Generally, long-term environmental monitoring programmes at these outfalls have indicated no marked or widespread detrimental impact on the marine environment or its beneficial uses (in terms of chemical and microbiological contamination). Of greater concern is the rapid increase in discharges to less dynamic and sensitive areas such as surf zones and estuaries, where effluents from malfunctioning or overloaded treatment facilities are adversely affecting the ecosystems and their beneficial uses (RSA DEA, 2016).

Estuaries in particular are increasingly negatively impacted, to the extent that eutrophication and fish kills are now recurring problems in some urban systems (Van Niekerk *et al.,* 2019). Many smaller coastal towns still rely on conservancy or septic tanks for sewage disposal. Overflows and seepage from these tanks can cause nutrient enrichment in estuaries and the coastal environment, while untreated sewage from bucket toilets, pit latrines and septic tanks also poses a risk to coastal water quality in rural areas (ASCLME, 2012g).

In Tanzania, the growth in coastal populations has resulted in increased quantities of wastewater (including faecal sludge) and solid waste especially in cities such as Dar es Salaam, Tanga and Mtwara. In these cities more than 90 percent of the population rely on pit latrines and septic tanks. Sludge management has become a major challenge. In some areas damage to sewer pipes has led to discharge of untreated sewage onto sand- and mudflats near the harbour (ASCLME, 2012h). On the island of Zanzibar sewage runoff from Zanzibar Town contributes to nutrient and microbiological contamination of adjacent coastal waters (Nyanda *et al.,* 2016).

A feature common to all countries is that most land-based sources of solid waste are associated with urban centres, particularly informal settlements and industrial and commercial areas, and runoff is the main distributor via rivers, streams and stormwater drains (Lane,2007). The major sources of solid waste contributing to marine litter in each of the countries of the WIO region are presented in Table1.1.

Table 1.1: Summary of major sources of marine litter in the countries of the WIO region (Lane, 2007, unless otherwise referenced)

COUNTRY	MAJOR SOURCES
Comoros	Of concern is waste from hospitals, including compresses, syringes, braiding, packaging, plastic, glass and human waste discharged in open dumpsites, usually in the vicinity of the hospitals (Abdallah *et al.*, 2006). Direct dumping of garbage onto the beach or the sea/ocean, wrecked vehicles, ships, and appliances (UNEP and WIOMSA, 2008; UNEP, 2018).
Kenya	The major sources of marine litter are reported to be beach recreation (66%), shipping (14%), dumping and surface runoff from urban areas.
Madagascar	Marine litter mostly comes from land-based sources such as discharge from stormwater drains and untreated municipal sewerage consisting mainly of plastic wrappers, bottles, bottle caps, plastic bags, cigarette butts and plastic containers.
Mauritius	Marine litter arises chiefly from beach recreation, surface runoff from urban areas and from rivers. The volume of ship-generated garbage is far smaller than land-generated volumes.
Mozambique	Beach users, garbage from shipping, fishing gear, road users and urban stormwater runoff are the major sources of litter.
Reunion	Major source of marine litter includes residential, fishing "ghost net" and shipping. Waste from shipping arrives by ocean currents from countries such as Hawaii, Indonesia, Australia and Mauritius. Plastic bottles and plastic bags dominate the waste, and cause hazards to marine turtles (UNEP, 2018).
Seychelles	Most litter is from water runoff from rivers and storm drains (despite daily cleaning) from port wastes and particularly from public eating spots or picnic areas. Data are not available for litter generated by the fishing industry.
South Africa	The major source of marine litter is surface runoff from urban areas (via rivers and storm drains), confirmed by (a) litter deposition being greatest in the rainy season with higher levels close to urban areas; and (b) the high proportion of locally made articles (96%) in stranded litter. Commercial, industrial and low-income residential areas produce most litter. Ship-generated waste is trivial compared to land-based litter sources. Some litter comes across the South Atlantic in the West Wind Drift from Argentina, Uruguay and Brazil. Marine litter on uninhabited oceanic islands derives from local and foreign fisheries, and distant continents. Litter mostly consists of single–use items and packaging such as paper and plastic food wrapping, cans, plastic bottles, cigarette packets and cigarette butts. These items accumulate in public places such as public parks and gardens, shopping centres, car parks, railway and bus stations, public bins, landfill sites and recycling depots. Despite its small proportion (~6%) compared to total land area, urban areas produce most of the solid debris found in river catchments (UNEP, 2018).
Tanzania	The major source of marine litter arises from uncontrolled disposal of solid wastes in unplanned settlements where, for example, about 70% of Dar es Salaam's population live. Most litter is from surface runoff, illegal dumping into river valleys and drainage from crude, open dump sites located near the beach and rivers. Marine litter also arises from fishing and shipping, as the important economic city of Dar es Salaam has a moderate-sized port and fishing is a major activity amongst the coastal communities. The latter are presumed to contribute a significant quantity of gear, boats, traps and plastic bottles in marine litter.

Mauritius has shown the ability to contain solid waste from the island. Mozambique, despite poverty and governance challenges, similarly contributes very little to the marine litter load. This is because it has a very poor transport infrastructure, and most of the population lives in rural poverty with limited access to products with plastic packaging. Additionally, informal recycling of most salvageable products is commonplace. These factors have kept solid waste loads, that may contribute to marine litter, under control thus far but this situation may change (Lane, 2007).

Marine litter has been researched in South Africa for over two decades and there is information on the abundance, distribution, and trends of different types of litter found around the coast. Studies by the City of Cape Town have shown that the primary origin of waste was from informal settlements on the banks of canals. There seems to be an increase in plastic litter during rainy seasons (Verster and Bouwman, 2020).

Seychelles has a good waste management system in place and has almost no marine litter generated from the islands. There is relatively little information on the quantities, types and characteristics of solid waste that contribute to marine litter in Tanzania, Madagascar, and Kenya. It is, however, known that large quantities of litter from urban areas reach the seas and oceans. The main reason for the littering is that none of these countries has an adequate solid waste management system (Lane, 2007).

Also, a concern is that most of the marine litter in the small island states comes from the eastern Indian Ocean, where the challenge is not only to reduce local pollution, but how to clean up litter from elsewhere. However, in Madagascar, NGOs (*e.g.* Manaomanga) are taking initiatives to collect and reduce marine litter by sensitizing local communities and recycle plastic waste into furniture, thereby contributing to blue economy initiatives. Another option for dealing with plastic is to ban its use. A good example of this is Rwanda, which successfully banned the use of plastics in their country (Danielsson, 2017).

1.4.2 Agriculture and Forestry

Agriculture is the backbone of the economies in most countries in the WIO region and central to the alleviation of poverty. Agriculture contributes to marine pollution primarily through return flows from agricultural areas in adjacent catchments, introducing pollutants such as suspended solids (the result of erosion due to inappropriate land-use practices), inorganic nutrients (excessive use of fertilizers), pesticides (persistent organic pollutants) and microbial contaminants (typically associated with runoff from livestock rearing areas). Slashing and burning as a way of bush clearing for subsistence agriculture adds to the atmospheric pollution in some countries. Pollutants from agricultural activities usually enter the marine environment through river discharges, although agricultural activities adjacent to coastal areas can directly contaminate coastal waters through surface or sub-surface runoff (UNEP *et al*., 2009a).

In the Comoros, agricultural production occupies approximately 67 percent of land and accounts for 98 percent of export revenue. Vanilla, ylang-ylang and cloves are mainly grown for the export market, with cereals, rice, potatoes, fruits and legumes grown for local consumption. Steep slopes and continuous cultivation without provision of fallow fields has led to the impoverishment of the soil and incidents of serious soil erosion, and subsequent siltation of coral reefs. Pesticides and fertilizers are often used sparingly while growing crops for export.Almost all organic waste coming from agricultural practices is reintroduced into the soil to improve fertility (Abdallah *et al*., 2006).

Agricultural activities in Kenya's coastal region are mostly subsistence, although commercial farming occurs in the proximity of coastal areas near Mombasa, Kilifi, and Lamu, as well as inland from where agricultural pollutants are transported to the coast by rivers, particularly during the rainy season (Barasa *et al*., 2008). For example, the Tana and Athi rivers drain hinterland agricultural areas, carrying significant quantities of nutrients into their estuaries. Livestock rearing is another major source of pollution from agricultural activities in Kenya with some of the busiest slaughterhouses also located on the farms (UNEP *et al*., 2009a). Siltation has been found to cause shadowing and/or smothering of coral reefs and seagrass beds along adjacent coasts (Munga *et al*., 2006). Coastal forest degradation also has contributed to increased erosion and sediment loading to coastal areas, for example in Malindi-Ungwana Bay (ASCLME, 2012b) and Mwache Creek in Mombasa (Bosire *et al*., 2014) precipitating extensive mangrove die-back.

In Madagascar, agriculture contributes significantly to the GDP and employs more than 70 percent of working people, who are involved especially in the cultivation of rice and cattle rearing (ASCLME, 2012c). Small areas of intensive production of sugarcane and cotton are in the southwest and northwest of the country, where the greatest quantities of fertilizers and pesticides are applied. Bushfires, harvesting of forests for production of charcoal and clear-felling for agricultural purposes contribute to serious erosion and subsequent sediment loading to coastal and marine environments (UNEP *et al*., 2009a).

In Mauritius, cultivated land covers almost 50 percent of the island, mostly sugarcane, tea, tobacco and food crops. The island has a long history of pesticide use, importing significant amounts of agrochemicals, which point to potential impacts on the coastal environment. Most the country's small-scale farmers use hand sprayers, resulting in wastage and spillage of the pesticides. However, over the past decade there has been a systematic conversion of agricultural lands to land for industrial and urban development, thereby reducing the land onto which agrochemicals are applied (UNEP *et al.*, 2009a). Most agricultural activity in Mozambique occurs along rivers, and these are the main pathways of agrochemicals to the coastal areas. Dichlorodiphenyltrichloroethane (DDT) is officially banned in Mozambique, but it is still being used in the country and neighbouring regions (ASCLME, 2012d).

Pollution from agricultural activities has not been properly assessed in the Seychelles. However, as agriculture does not represent a significant proportion of land-use, it is not considered to be a major source of marine pollution. Agriculture takes place on a local scale, often for own use only (UNEP *et al.*, 2009a). In South Africa, river discharges draining intensive agricultural areas are considered a major pathway of pollution. Nutrient enrichment has resulted in large scale eutrophication in estuarine systems (Adams *et al.*, 2020). Of concern is the potential impact from agrochemical inputs that have not been properly monitored (Van Niekerk *et al.*, 2019).

Most of the agricultural activities in Tanzania occur in river valleys and floodplains where agrochemicals are known to be used to control pests and diseases and to improve yields (UNEP *et al.*, 2009a). In Zanzibar, agricultural activities are still artisanal in nature, dominated by the cultivation of food crops rather than cash crops, with sugarcane being cultivated in the northern district. The use of fertilizers and pesticides has remained relatively low, mainly used in rice and sugarcane cultivation. Poor management of livestock also contributes to coastal pollution. The destruction of coastal forests contributes to high suspended solids loading in coastal areas, although no quantitative data are available to confirm this (UNEP *et al.*, 2009a).

Even without substantial scientific evidence of existing impacts, it can be expected that marine pollution associated with agricultural activities will increase in the coming years and will require environmentally sustainable interventions, especially in the large river basins discharging into the coastal areas..

1.4.3 Industry and Mining

Industries and mining activities are becoming sources of marine pollution, for example, through the inappropriate disposal of wastewater and solid waste. Most of the economies of WIO countries, in addition to depending on agriculture, also rely on food processing industries such as breweries, distilleries, fish processing plants and sugar mills. Other significant industries include textiles, tanning and paint manufacture. These industries dispose large amounts of toxic contaminants into estuaries and shallow coastal regions (UNEP *et al.*, 2009a).

In the Comoros, industries are mainly associated with the processing of agricultural and livestock products (including food processing), although their contribution to coastal pollution (in terms of biodegradable organic matter, suspended solids and solid waste) is small in comparison to waste from domestic sources.

On the Kenyan coast, most industries are situated in Mombasa, Kilifi and Lamu districts. Few of these industries treat their wastewater, and either discharge effluents to municipal sewers or stormwater drains. Large quantities of solid waste are produced by cashew nut and sisal processing factories (Mwaguni and Munga, 1997). The highly productive food processing, metal and textile industries in Kenya directly discharge untreated wastes into the Kilindini Harbour and Port Reitz, negatively affecting the health and productivity of sensitive ecosystems such as coral reefs (Mmochi and Francis, 2003). Titanium mining along Kenya's south coast poses potential pollution threats to coastal ecosystems (Abuodha and Hayombe, 2006).

In Madagascar, most industries are situated in coastal urban centres, mainly near the ports of Antsiranana, Ambilobe, Mahajanga, Tolagnaro and Toamasina, focusing mainly on seafood processing, sugar extraction, oil and soap production, breweries, tanneries and sisal production (ASCLME, 2012c). Most of these industries do not treat their waste, and where there is some treatment, it is limited to coagulation and decanting, or to decanting only prior to discharge into a treatment system or directly into the ocean (UNEP *et al.*, 2009a). While larger mining concerns in Madagascar are required to treat and monitor their effluents in accordance with agreed environmental management plans, the expansion of small-scale mining, particularly gold mining using mercury, is becoming a much larger threat to pollution of the rivers discharging into the ocean. Plaine Lauzun, Vacoas-Phoenix and Coromandel are the main industrial zones in Mauritius. Sugar processing plants (the largest contributor), textiles (*e.g.* dye houses), breweries and food processing plants mostly discharge to municipal treatment works (UNEP *et al.*, 2009a).

However, some sugar processing plants release waste products directly into rivers and canals that empty into shallow coastal areas (Mmochi and Francis, 2003). Various other industries on the island, such as steel mills, galvanising, electroplating and battery factories, discharge their wastes directly into rivers (Grand River Northwest and St. Louis River) which empty into marine systems (Ramessur, 2002). Most industrial facilities in Mozambique are in the coastal cities of Maputo, Matola and Beira and include textile, paper and tyre factories as well as a brewery. Most of those in Maputo discharge untreated wastewater into the Influent River that drains into Maputo Bay (ASCLME, 2012d).

Industries potentially contributing to marine pollution in the Seychelles mainly comprise food processing and chemical industries (Radegonde, 1997). Industries such as canning and brewing also discharge considerable amounts of waste into estuarine waters of the island (Mmochi and Francis, 2003; ASCLME, 2012e).

In Somalia, untreated waste from tanneries, slaughterhouses and fish markets are discharged into the ocean (ASCLME, 2012f). Toxic chemicals and solid wastes are dumped into the ocean on a regular basis. Contamination from dumpsite leachate is also a source of pollution, especially during the rainy season (ASCLME, 2012f).

In South Africa, the disposal of industrial wastewater to sea occurs mainly in the larger urban coastal centres (*e.g.* Durban and Richards Bay) with an estimated 722,151 m^3 being discharged daily into marine or estuarine waters (RSA DEA, 2016; Van Niekerk *et al.*, 2019). Most of this effluent is discharged to the offshore environment through properly designed marine outfalls that are subjected to the regular environmental monitoring and assessment studies. Mining of sand, diamonds and heavy minerals also occur along the South African coast, contributing to suspended and settleable matter, and other potential pollutants.

Most of the larger industries along the coast in Tanzania are located in Dar-es-Salaam, with some growth also occurring in Tanga around the country's second largest seaport. Industries include food processing (agro industries), chemical factories, breweries, soap and steel manufacturing plants. Most of these industries discharge wastewater into the Msimbazi and Mzinga Creeks (Mgana and Mahongo, 1997; 2002). Various other industries contribute to the untreated waste loads entering estuaries and shallow coastal environments (Mmochi and Francis, 2003). Industrial activities in Zanzibar are mainly located in the Saateni, Maruhubi and Mtoni areas, and include food processing (slaughterhouses, dairy products and beverages) and chemical (soap production) industries, generating significant biodegradable wastes and suspended solid loads.

1.5 Impact of Pollutants on Coastal and Marine Ecosystems

Key problems associated with marine pollution in the WIO region have been grouped into microbiological contamination, nutrient enrichment (eutrophication), marine litter, suspended sediment loading, and toxic pollution (UNEP *et al.*, 2009a). An overview of typical environmental impacts and socio-economic consequences of these problems is summarized in Table 1.2.

Table 1.2: Overview of key impacts associated with the key problems linked to marine pollution in the WIO region (Source: UNEP et al. (2021))

PROBLEM					ENVIRONMENTAL IMPACTS
Microbial contamination	Nutrient-enrichment	Marine litter	Suspended sediments	Toxic pollution	
	•		•	•	Modification in species composition in marine biological communities
	•		•		Smothering of benthic communities
		•	•		Entanglement/suffocation of marine organisms
			•	•	Chronic effects on marine biota
	•		•	•	Mortality (acute effects) on marine biota
	•				Opportunistic/nuisance/harmful/toxic algal blooms
	•		•	•	Discoloration of coastal waters
	•				Anoxic conditions/bad odours
•					Water contamination/pollution with pathogens
					SOCIO-ECONOMIC CONSEQUENCES
	•	•	•		Loss of aesthetic value
•	•	•		•	Human health risk through contact recreation
•	•			•	Human health risk through ingestion of contaminated seafood
•	•		•	•	Loss in quality and value of seafood products
	•		•	•	Loss of fisheries resources and revenue

1.5.1 Microbiological Contamination

Microbial contamination refers to the presence of pathogenic microorganisms (protozoa, bacteria, algae, fungi and viruses) of either human or animal origin in the aquatic environment. These pathogens can pose health risks to human beings. Many human diseases in coastal areas are water-borne and directly associated with poor water quality. These include diseases such as dysentery, cholera and diarrhoea. In coastal waters, infection during recreation activities, consumption of contaminated seafood and diseases in marine organisms are the main pathways of impacts from microbiological contamination.

In the WIO region, microbial contamination of coastal waters is typically associated with inappropriate disposal of municipal wastewater (including sewage and faecal sludge), contaminated runoff from urban areas, contaminated runoff from agricultural areas used for livestock rearing, and industrial effluents (*e.g.* from food processing industries). The loss of the recreational value of coastal waters due to microbiological contamination is evident throughout the coastal zone of the WIO region. In many areas the situation is exacerbated by poor aesthetics and bad odours (UNEP *et al.*, 2009a).

Studies conducted around Taolagnaro (Madagascar) reported high bacteriological contamination in coastal waters, attributed to the defecation on beaches as well as inappropriate treatment of municipal wastewater. Although untreated municipal wastewater associated with urban runoff remains a concern, NGO-guided sanitation initiatives have led to the construction of public toilets and the cleaning of beaches has been occurring, combined with the sensitization of local populations to change their behaviours. Human illnesses associated with the consumption of contaminated seafood such as molluscs have been reported (UNEP *et al.*, 2021a). Studies in Mahajanga and Nosy confirmed microbial pollution in some waters along these parts of the coast (UNEP *et al.***,** 2009a). In Maputo Bay (Mozambique), microbial contamination has been recorded in shellfish and ***Vibrio*** *spp*. These species have been identified as the main cause of severe gastro-intestinal illnesses in Matola (Fernandes, 1996).

Areas in Maputo Bay near sewage discharges, such as Miramar near the entrance of the Maputo Estuary, are not considered safe for swimming (ASCLME, 2012d). Faecal contamination has been reported in Beira Bay and Nacala Bay, although not as severe as in Maputo Bay (Fernandes, 1995). In Mauritius, microbiological parameters are monitored regularly (monthly) at several public beaches, including Flic enFlac, Albion, Pointe aux Sables, Trou aux Biches, Mon Choisy, Le Goulet, Grand Baie and Blue Bay. Most areas complied with Mauritius' guidelines for contact recreation, although exceptions have been recorded in Pointe aux Sables near Port Louis (UNEP *et al.***,** 2009a). Microbial pollution has been detected in urban areas along the Kenyan coast *e.g.* Mombasa (Mwaguni, 2002), as well as in the Kilindini/ Port Reitz creek area and, to a lesser extent, the Sabaki estuary/ Malindi Bay complex (UNEP *et al.***,** 2009a).

Figure 1.2 shows the location of marine pollution hotspots identified in the WIO region (UNEP *et al.*, 2021a). Not surprisingly, hotspots are primarily located at the coastal cities and larger towns, where most of the key sources of marine pollution are concentrated.

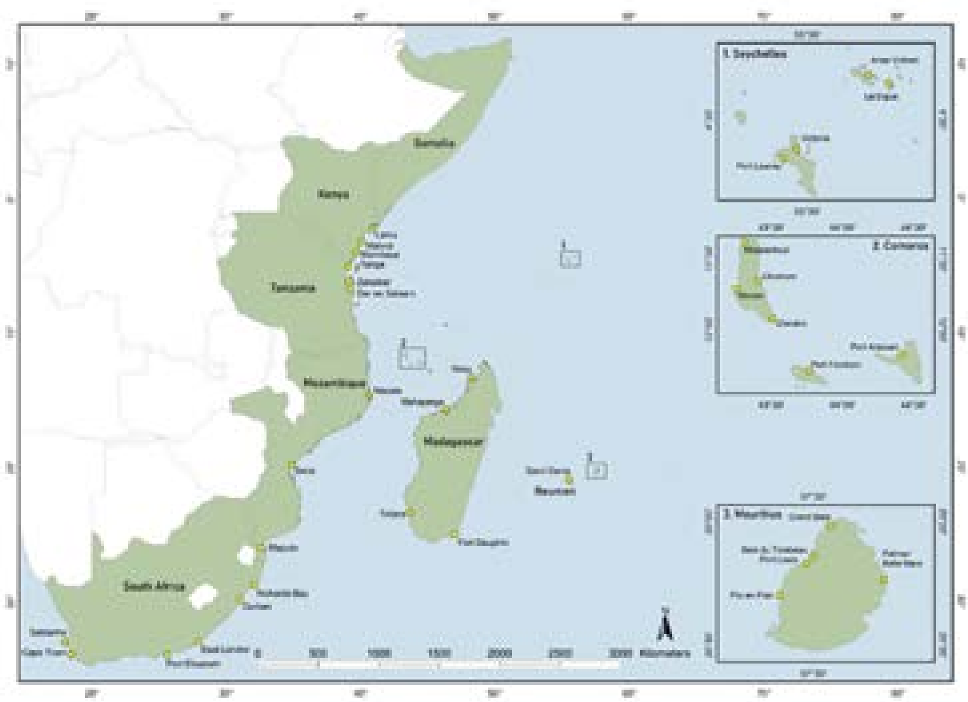


Figure 1.2: Marine pollution hotspots (major coastal urban cities) in the WIO region (Source: UNEP et al., 2021a)

In the Seychelles, high microbial counts were recorded at Beau Vallon Bay during the rainy season in 2007. These were mostly associated with run-off from non-point sources such as rivers and small streams (Antoine *et al.*, 2008). Outbreaks of water borne diseases usually occur during the rainy season and are mainly associated with defective wastewater disposal systems (UNEP *et al.*, 2009a). Microbiological contamination of recreational coastal water is also a concern in South Africa, especially along urban coasts. Regular (bi-weekly) monitoring of beach water quality in Cape Town revealed that contaminated stormwater runoff and malfunctioning wastewater treatment facilities were the root causes of microbiological contamination at some of its beaches (City of Cape Town, 2020).

Studies conducted in urban centres on the east coast (Durban) also observed areas where microbiological contamination was evident, especially during the rainy season (Mardon and Stretch, 2004). These patterns are also expected to occur along other urbanized coastal areas in South Africa which receive large volumes of wastewater or heavily contaminated urban runoff. Along Tanzania's coast, including Zanzibar, some beaches in Dar es Salaam (*e.g.* Ocean road and Banda beaches) have been closed for swimming and other recreational activities due to microbial contamination (ASCLME, 2012h). Levels of microbial contamination were found to be especially high during the rainy season, showing the influence of urban run-off and sewage contamination on microbial pollution on coastal beaches linked to urban areas (Lyimo, 2009; Mwakalobo *et al.*, 2013; Mushi, 2020).

1.5.2 Suspended Sediment Loading

Inappropriate catchment and urban practices have contributed significantly to sediment loading occurring at the coastal areas and in the marine environments across the WIO region, impacting sensitive ecosystems as well as coastal development (*e.g.* port) and tourism. Excessive sedimentation smothers coral reefs and results in a decrease of light available for benthic macrophytes and photosynthetic algae that support coral reefs (Schaffelke *et al.*, 2005). Discoloration of coral reef waters also reduces their aesthetic value, rendering them less attractive for tourism.

In Kenya, increased development in river basins has caused negative impacts on the depth of photic zone, and reduced primary production (ASCLME, 2012b). The Tana and Sabaki rivers deposit large volumes of sediment in coastal and marine environments, increasing turbidity in coastal waters in Ungwana Bay and Malindi Bay (Mmochi and Francis, 2003; Kitheka *et al.*, 2003a; b; Kitheka *et al.*, 2005) Sedimentation resulted in significant impacts on mangrove areas, smothering the root systems of trees and causing die-back of the forests on the River Tana estuary (Kitheka *et al.*, 2005), as well as in Lamu (Abuodha and Kairo, 2001) and Mwache Estuary (Kitheka *et al.*, 2003b). Sediment loading affects the coral reefs in the Malindi National Marine Park and Reserve in Kenya (McClanahan and Obura, 1997; Kazungu *et al.*, 2002; Kitheka *et al.*, 2003a), as well as the seagrass beds (Wakibia, 1995; Kazungu *et al.*, 2002).

Pollution as a result of suspended solids is a major issue for Madagascar, mainly as a result of soil erosion in catchments due to bushfires and deforestation. The River Betsiboka (also known as the Red River) owes its distinctive orange-red colour to the vast amount of silt that it carries and drains into the sea near Mahajanga. Coral reefs in the Toliara region receive large amounts of sediment carried by the Onilahy and Fiherenana rivers, reducing water transparency and smothering coral and mangrove areas. Sedimentation has changed sandy beaches, impacting the sea turtle nesting grounds, *e.g.* in the Masoala region (ASCLME, 2012c).

In Mauritius, high sedimentation and associated high turbidity occur in the lagoon at Rodrigues and in Grand Baie, resulting in the modification of these ecosystems. In Rodriques, this was mainly caused by the soil erosion from agricultural areas in the highlands. Besides, Grand Baie domestic wastewater discharge is the major source of suspended solids. Sedimentation causes damage to the coral ecosystem (*e.g.* by smothering), thereby affecting artisanal fishing (UNEP *et al.*, 2009a).

In Mozambique, poor land-use practices, including deforestation of coastal and hinterland areas, are the main contributors to sedimentation in coastal environments (UNEP *et al.*, 2009a). In Seychelles, sediment discharge has contributed significantly to coral losses around the main islands of Mahe, Praslin, and La Digue, together with other factors such as global warming (Jones *et al.*, 2002). Along the Tanzanian coast poor agricultural practices have been known to play a leading role in water quality deterioration due to sedimentation, resulting in the smothering of coastal ecosystems (*e.g.* coral reefs), reducing the aesthetic value and making the coast less attractive for tourism (Mohammed, 2002).

1.5.3 Nutrient Enrichment

Nutrient enrichment of coastal waters commonly stimulates algal production and may lead to eutrophication with detrimental effects on sensitive ecosystems (Lapointe and Clark, 1992; Schaffelke *et al.*, 2005). Excessive nutrient loading drastically increases the productivity and biomass of phytoplankton and opportunistic algae. Such algae tend to overgrow, smothering coral reefs and promoting the growth of other opportunist organisms such as sponges and tunicates (Pastorok and Bilyard, 1985). High concentrations of certain inorganic nutrients, such as nitrogen and phosphorus, inhibit coral calcification processes (Fabricius, 2005, Schaffelke *et al.*, 2005).

Decaying excess algal matter can radically reduce dissolved oxygen levels, especially in sheltered coastal waters, often resulting in the mass mortality of fish and invertebrates (Forbes and Demetriades, 2008). Nutrient loading in shallow waters results in localized eutrophication. In addition, decaying algal matter can cause negative impacts on coral health by causing diseases, blemishes, and causing dead patches (McClanahan, 2002). Nutrients reach elevated levels in sheltered environments, such as estuaries and creeks, compared with oceanic waters (*e.g.* Tudor Creek, Mombasa) (Okuku *et al.*, 2019). In 2001, a harmful algal bloom (HAB) in the Kiunga National Marine Reserve (Kenya) lasted for ten days and caused mortality of marine life associated with hypoxia. Studies near Mombasa showed that terrestrial nutrient loading from the city affected primary producers in onshore reefs at Nyali and Bamburi, especially during periods of low water exchange (Mwaura *et al.*, 2017).

Rivers draining the Madagascan Highlands are an important source of nutrients for the coast. The use of fertilizers causes nutrient enrichment leading towards eutrophication and HABs (ASCLME, 2012c). In Mauritius, eutrophication, algal blooms, and smothering of corals in shallow lagoons are common, particularly in Port Louis where coral mortality is prevalent (Ramessur, 2002).

Nuisance algal growth, affecting the recreational (aesthetic) value of coastal resources has been reported. For example, high nitrate concentrations introduced into lagoon systems through agricultural return flows have been associated with algal proliferation in the lagoons of Belle Mare/Palmar. As a result, many hotels have had to remove algal deposits from the shoreline every week (Dulymamode *et al.*, 2002). At Flic en Flac, black anoxic sands are observed and foul hydrogen sulphide smell is felt at the low water mark and these occurrences are associated with organic enrichment from wastewater discharges (Prayag *et al.*, 1995). Algal blooms are observed annually at Trou aux Biches and isolated cases have been reported at Bain des Dames near Port Louis (Prayag *et al.*, 1995, Botte, 2001).

In Seychelles, high nutrient loading in areas such as Port Victoria leads to eutrophication and HABs during certain periods of the year, resulting in oxygen depletion and mortalities of fish and benthic crustaceans. Such losses can ultimately affect fisheries and livelihoods (ASCLME, 2012e). Along the South African coast, estuarine systems typically act as nutrient-purifying systems where nutrients from catchments are absorbed, resulting in cleaner water entering the ocean (Adams *et al.*, 2020). Urban estuaries on the KwaZulu-Natal coast are increasingly showing signs of excess nutrient and organic loading from surface drainage and possibly malfunctioning sewage reticulation systems. This has contributed to fish kills in several estuaries in the eThekwini municipality and the Port of Durban (Forbes and Demetriades, 2008).

In the Tanga area of Tanzania, the proliferation of macroalgae has been reported in coastal waters due to nutrient loading from untreated municipal wastewater and industrial discharges, particularly from a fertilizer factory. Excessive growth of *Ulva spp*. and *Enteromorpha spp*. are associated with nutrient input from sewage pipes (ASCLME, 2012h). A study along the Tanzanian coasts also found that although seagrass beds themselves did not show major changes because of nutrient enrichment, the associated organisms were affected (Daudi *et al.*, 2012).

In Zanzibar, eutrophication, associated with the release of inorganic nutrients from domestic sewage, has been identified as one of the main causes of decrease in coral-reef-building algae (Björk *et al.*, 1995). Coralline algae are sensitive to phosphate and are disappearing from phosphate-rich areas (Björk *et al.*, 1996). Nutrient-rich waters from Zanzibar town flowing in a southwestern direction during the NE monsoon season stimulate phytoplankton production impacting areas around Bawe and Chumbe islands (Peter *et al.*, 2018).

1,5.4 Marine Litter

Marine litter pollution refers to the introduction of solid waste material, manufactured or processed by humans, into coasts and oceans and their surroundings (where it either floats or sinks) (Barnardo and Ribbink, 2020). Inappropriate disposal of solid waste is a serious problem in most of the coastal urban centres in the WIO region. However, it is a major drawback that the quantitative data available on this aspect is extremely limited. Important land-based sources of litter are wastes from urban centres (particularly ports, industrial and commercial areas, and informal settlements) that are discharged into marine environments via rivers (that also transport solid waste from adjacent catchments).

With growing awareness of its detrimental effects, marine litter, especially plastics and microplastics, has become increasingly important amongst scientists, members of the public, and governments. However, data on litter production, litter loads, location and composition, flow from the source, amounts entering the ocean and waste mismanagement is not available for most African countries, making effective management of waste difficult (Barnardo and Ribbink, 2020).

Litter also travels large distances from its origin, increasing the risk of organisms attaching to the litter and invading new regions, with both biological and commercial impacts. Litter that sinks to the ocean floor can affect gas exchange in bottom sediments (UNEP and WIOMSA, 2008). The economic impacts of litter result from decreased amenity value, increased costs of clean-up operations, increased flood risks, and damage to fishing and recreational vessels. The economies of Seychelles and Mauritius rely on the tourism industry and, therefore, waste management in these countries is well-resourced compared with other WIO countries (UNEP and WIOMSA, 2008).

Impacts of marine litter have been observed across the region. In Kenya, animals are entangled in marine litter and they may also ingest, resulting in serious cuts, suffocation, hampered mobility, drowning, strangulation, and starvation (Ochiewo, 2006). Increased development of villages in Madagascar has resulted in the garbage and other waste being dumped in mangrove forests. In Mahajanga, turtles have been found feeding on plastic bags, presumably mistaken as jellyfish. Abandoned cast nets can trap and drown turtles while seabirds become entangled in nets and other discharged fishing gear. Levels of ingestion of marine litter by animals off South Africa are one of the highest in the world and several threatened species are affected (UNEP and WIOMSA, 2008; ASCLME, 2012c; 2012g). A summary of key reported impacts in different countries is provided in Table 1.3.

Table 1.3: Key reported impacts and proportion of plastic/synthetic litter in countries of the WIO region (Source: UNEP and WIOMSA, 2008; unless specified)

COUNTRY	REPORTED IMPACTS	PROPORTION OF PLASTIC/SYNTHETIC LITTER
Comoros	Impacts on coral reefs and associated ecosystems (seagrasses, mangroves, beaches), and on ocean turtles and fish near urban areas.	In 1996 plastics were estimated to make up 3% by weight of household refuse More than 60,000 tonnes of garbage were produced by households in 2000, excluding markets and commercial areas.
Kenya	Impacts on human health, tourism and marine mammals are inferred but not quantified especially along urban areas and in the northern-most coastal areas.	The percentage of plastics in the waste stream is not specified. It appears that about 40% of items recovered on beaches are synthetics.
Madagascar	Impacts on human health particularly, and on aesthetics and tourism. Impacts on marine animals, particularly sea turtles (UNEP, 2018).	No quantification of marine litter has been made but there is evidence that 100 m^3 of plastics per day are collected in one coastal city's garbage stream.
Mauritius	Degradation of aesthetics and potential threat to public health. Solid waste in ports damage propellers of boats for transport and fishing. Litter blocks drainage systems and causes back-flooding. Lost anchors and fishing materials damage corals (UNEP, 2018).	Large quantities of solid waste are collected daily from beach and port areas of which about 70% is plastics, mainly polyethylene terphthalate (PET) bottles.
Mozambique	Negative impacts on human health, aesthetics and tourism associated with popular beaches	Although no marine litter quantification has been done, plastics are reported to be one of the most common litter items observed on beaches.
Seychelles	Very little impact reported as litter are kept very low on islands	Approximately 56% of litter items in a waste analysis done at the Old Port were plastics.
South Africa	Threats to marine organisms and birdlife, with several threatened species affected, entanglement, and negative impacts on tourism.	Plastics comprise up to 89% of litter items (60% by mass) found on beaches; 80% of the litter items found on an ocean bottom survey were plastic.
Tanzania	Smothering of marine organisms, including coral, and negative influence on future tourism and fisheries developments.	Plastics make up 6% by weight of non-food wastes in Zanzibar, and 3.4% in Dar es Salaam.

In South Africa, studies have been conducted on the effect of marine litter on aesthetics and tourism, and the costs of beach and harbour clean-ups, but economic impacts and impacts on ecosystem services such as fisheries, aquaculture, and shipping are lacking. Non-market costs of impacts on cultural and spiritual values are also lacking (Arabi and Nahman, 2020). The most common waste type causing the entanglement of sharks is plastic straps from bait boxes and other plastic packaging material (entanglement found with 53 sharks caught in shark nets between 1978 and 2000) (Cliff *et al.*,2002). In estuaries, gill nets are a common source of litter, for example in the Mlalazi Estuary, 51 monofilament gill nets were removed in 2018/2019 (Naidoo *et al.*,, 2020).

Reported entanglements have involved turtles, birds, Cape fur seals (usually caught in the rope, string, fishing line, and plastic straps), and whales (Naidoo *et al.*, 2020). On the remote island of Marion (a territory of South Africa), entanglements of 101 sub-Antarctic and Antarctic fur seals and five elephant seals were recorded over ten years and are likely to be associated with a discarded tackle from the longline fishery. Some turtle and bird species have been reported to consume plastic, resulting in intestinal obstruction and malnutrition. According to research, seabirds consume mesoplastics based on their color and foraging techniques. Brown mussels and juvenile fish from KwaZulu-Natal's mangrove forests were found to have ingested fibers and fragments of rayon, polyester, nylon, and polyvinylchloride. Plastic ingestion by seabirds in South Africa and the African sector of the Southern Ocean has been recorded in 36 species (Naidoo *et al.*, 2020).

1,5.5 Toxic Pollution

Toxic pollution refers to threats from chemical contaminants released into the coastal and marine environment being toxic in nature, persistent, and/or bio-accumulating. For the purposes of this assessment, these can be grouped into three broad categories, namely metals, petrochemicals (hydrocarbons), and other persistent organic compounds (*e.g.* pesticides).

Heavy Metals

Heavy metal pollution originates from various sources and affects the sensitive coastal ecosystems in varying ways. As heavy metals are not biodegradable, they may accumulate in plant tissue, affecting their growth. Mangroves act as pollution sinks (Wong *et al.***,** 1997; Yim and Tam, 1999) and numerous countries utilize these ecosystems as secondary waste treatment facilities. However, with the increasing disturbance to mangrove ecosystems, mangrove soils reach their maximum absorptive capacity for binding toxic metals, resulting in adverse effects on mangrove leaf numbers, stem basal diameter and biomass production (Wong *et al.***,** 1997; Yim and Tam, 1999).

Coral reef invertebrates and fish are vulnerable to metal contamination and accumulate these contaminants within soft body tissues and display distinct physiological and cytological responses to varying levels of pollutant exposure (Rainbow, 1995). In addition, heavy metals are easily absorbed by the tissue of coral skeletons, thereby altering various chemically mediated processes such as reproduction and recruitment. Consequently, such pollutant exposure causes severe modifications to reef productivity and mortality rates (Peters *et al.*, 1997). The human health risks associated with the consumption of heavy metal contaminated seafood are also well documented (*e.g.* Bosch, 2015). Some heavy metals, such as chromium (Cr), cadmium (Cd), nickel (Ni), and arsenic (As), are linked to human cancer (ATSDR, 2007), while others, such as mercury (Hg) and lead (Pb), are repeatedly shown to harm developing fetuses and children when exposed above the permissible limit (Jeevanaraj *et al.*, 2019).

Signs of metal pollution have been recorded in various coastal areas in the WIO region. A serious case of lead poisoning in Mombasa (Kenya), associated with an emission from a lead smelter, has also been reported (CNN, 2020). Elevated metal concentrations (cadmium, copper, lead, and zinc) were previously detected in sediments of the Sabaki estuary/Malindi Bay complex and Kilindini/Port Reitz Creek (UNEP *et al.*, 2009a).

Studies conducted previously in Kilindini and Makupa Creeks in Mombasa revealed elevated levels of metals (copper, cadmium, iron, and zinc), although the levels were considered to be substantially lower than those recorded in other polluted coastal areas (Kamau, 2001). Recent studies conducted along the estuarine areas of Ramisi-Vanga system, along Kenya's south coast, in peri-urban creeks of Mombasa, and in estuarine areas along the north coast showed metal concentrations within acceptable limits, except in the Kilindini Harbour that had elevated levels of chromium (Okuku *et al.*, 2019).

In Madagascar, monitoring at Mahajanga and Nosy-Be provided evidence of elevated metal concentrations in sediments, generally near sewage outfalls (UNEP *et al.*, 2009a). Metals, particularly chromium (from dye factories), zinc and lead (from industrial effluent and land runoff) are prevalent in Mauritian coastal waters. Estuarine habitats, such as Tombeau Bay and Poudre d'Or Estuary, have been exposed to untreated industrial wastes since the 1980s. Metals, particularly chromium (from textile industries), zinc and lead (from industrial effluent, sewage sludge and landfill ate) are potentially problematic (Ramessur, 2002; 2004). Studies conducted in Mozambique have detected the presence of metals, particularly lead, in the Port of Maputo from discharges of the Matola and Maputo Rivers, as well as in Nacala Bay (Fernandes, 1995, UNEP *et al.*, 2009a).

In South Africa, the sediment in estuaries and ports of many coastal cities are often severely contaminated by metals (Newman *et al.*, 2015; Harris *et al.*, 2019). However, in ports heavy contamination is usually limited to surface sediments in sheltered depositional areas due to frequent maintenance dredging (CSIR, 2009b). A first report of metals in corals of the WIO region found higher concentrations of most metals in reefs close to urban areas, although less contaminated than in other parts of the world (*e.g.* the Red Sea). Nickel concentration in corals of the genus *Sinularia* in South Africa was found to be the highest since ever reported (Van der Schyff *et al.*, 2020). Also, it co-occurred with concentrations of persistent chemicals such as polychlorinated biphenyls (PCBs), whose production was banned decades ago because of toxicity concerns. These and other chemicals pose a toxic risk to aquatic fauna and flora (Vogt *et al.*, 2018).

In Tanzania, several studies on heavy metals in coastal ecosystems have been undertaken. Mangrove sediments near Dar es Salaam (Msimbazi, Mtoni and Mzinga Creek) showed elevated levels compared with more remote mangrove areas (Mbweni) (Mremi and Machiwa, 2003; ASCLME, 2012h). An analysis of metals in sediments in the inner area of Dar es Salaam harbour (Machiwa, 2000) also revealed an accumulation of certain metals, notably chromium and copper. Some metal accumulation was also detected in mud crabs. Although the levels did not pose a risk in terms of average per capita consumption in Tanzania, potential risks (from arsenic and copper) were flagged if average per capita consumption is exceeded (Rumisha *et al.*, 2016; 2017a). Accumulation of some heavy metals has also been observed in some invertebrates and in sediments in mangroves off the coast of Dar e Salaam (Rumisha *et al.*, 2012; 2016) while heavy metals were also found to limit the gene flow in giant tiger prawns along the Tanzanian coast (Rumisha *et al.*, 2017b). A first study reporting metallic elements in dolphin tissue from Tanzania found concentrations to be low compared to other studies, but cadmium increased significantly with age in kidneys and lungs (Mapunda *et al.*, 2017).

Petrochemicals

Common sources of petrochemicals include urban runoff, shipping, port activities, illegal disposal, and accidental spillage of oil. The impacts of oil and petrochemicals are numerous. The main consequence of oiling on seagrass beds is complete smothering of these benthic plants, as well as their associated organisms (Abuodha and Kairo, 2001). To exacerbate the problem, dispersants which are commonly used to clean up oil spills contain toxic solvents which penetrate the protective waxy cuticles of seagrass blades. Studies have shown such actions affect the biological functioning of cellular membranes and chloroplasts, thereby causing plant loss as well as harmful effects in other benthic biota (Ellison and Farnsworth, 1996; Abuodha and Kairo, 2001).

Oiling also smothers mangrove ecosystems and their organisms (Abuodha and Kairo, 2001). Petroleum compounds persist in mangrove soils. Consequently toxic derivatives of oil are continuously re-released into the environment which causes the sub-lethal effects to mangroves. Oiling causes massive mangrove defoliation, chlorophyll-deficient mutations as well as seedling and tree mortality. Furthermore, the recovery of mangrove ecosystems from impacts of hydrocarbons can take several years (Abuodha and Kairo, 2001).

Oil pollutants often float above coral reefs (Peters *et al.*, 1997) and even if petroleum does not encounter the reef, the pollutant contains toxic substances that are water soluble and are taken up by corals. Studies have shown that corals exposed to oil undergo a variety of negative impacts that include tissue death, bleaching, and impairment of biological processes such as photosynthesis, reproduction, and growth (McClanahan, 2002). In addition, dispersants used to clean-up oil leaks contain toxic chemicals that exacerbate the effects of the oil spill and can prolong coral recovery by years (Peters *et al.*, 1997).

Studies in Kenya have indicated cases of complete smothering of seagrass beds and their associated organisms because of oiling. This is also the case for beds in Maputo Bay (Mozambique) which have been destroyed by oiling (Munga, 1993; Abuodha and Kairo, 2001; Richmond, 2002). Extensive mangrove forests in Mombasa and Maputo have been destroyed by soil spills (Munga, 1993, Richmond, 2002). In Mida Creek in Kenya, effects of oil spills on mangroves were still evident ten years after the incident (Abuodha and Kairo, 2001).

High levels of poly-aromatic hydrocarbons (PAHs) in Kilindini Harbour (Kenya) were attributed to the petroleum sources present in the area (Okuku *et al.*, 2019). Studies in Kenya also highlighted motor vehicle washing facilities as sources of PAHs (Kwach and Lalah, 2009). It was also found that pollution from oil spills tend to concentrate in areas within the Mozambique Channel due to eddy circulation from the north to the south (ASCLME, 2012d). In South Africa, there is evidence of accumulation of PAHs in some commercial ports (Newman *et al.*, 2015).

Persistent Organic Pollutants

Persistent organic pollutants (POPs) refer to an array of compounds that have the potential for long-range transport, persistence in the environment, and the ability to bio-magnify and bio-accumulate in ecosystems. The most encountered POPs are agrochemicals such as organochlorine pesticides (*e.g.* DDT), industrial chemicals and by-products (*e.g.* polychlorinated biphenyls (PCB), polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF)). POPs bio-magnify throughout the food chain and bio-accumulate in organisms. Therefore, the highest concentrations are often found in organisms at the top of the food web (UNEP *et al.*, 2021).

Ultimately, POPs pose risks to humans and manifest an increased risk of cancer, reproductive disorders, alteration of the immune system, neuro-behavioural impairment, endocrine disruption, genotoxicity, and increased birth defects (WHO, 2020). Herbicides and pesticides leaching into coastal ecosystems cause mangrove defoliation and mangrove dieback (Schaffelke *et al.*, 2005). PCBs and pesticides are also extremely toxic to corals which have been shown to display decreases in photosynthesis of the symbiotic algae, changes in coral metabolism and growth retardation when exposed to such contaminants (Pastorok and Bilyard, 1985).

The presence of POPs in the Kenyan coastal waters was found to be due to the use of pesticides in agricultural areas. DDT is supposedly used in upstream agricultural areas with significant concentrations of pesticides found in the Sabaki and Ramisi rivers. Fish samples from rivers and estuaries have exhibited residue concentrations of pesticides and sediments and have been found to contain POPs. Dioxins and furans produced when insulation is removed from scrap wire cables through burning, as well as from metals and old tyres, also contribute to the presence of POPs (ASCLME, 2012b).

Effects on mangrove forests in Mombasa and Lamu (Kenya) because of the pesticide loading have been observed (Mmochi and Francis, 2003). Elevated levels of DDT in sediments of the River Tana Estuary have been recorded posing potential ecotoxicological risks to the benthic fauna in the system (Okuku *et al.*, 2019). In Madagascar, DDT was used previously in controlling malaria but has been banned for more than a decade (ASCLME, 2012c). Sugarcane farming in Mauritius uses large amounts of pesticides (Mmochi and Francis, 2003) which have contributed to mangrove decline on the island. Studies on Spinner and Bottlenose dolphins along the Réunion coast showed contrasted contaminant profiles for PCBs and polybrominated diphenyl ethers (PBDEs), probably linked to different dietary and foraging habitat preferences (Dirtu *et al.*, 2016).

Common pesticide residues identified in Mozambique were 2, 4, 5-TCB, p, p'-DDT, p,p'-DDE, p,p'-DDD, Lindane and hexachlorobenzene (HCB). Although DDT is officially banned in Mozambique, it is still used in neighbouring countries (Massinga and Hatton, 1997). However, the analysis of pollutants adsorbed to plastic pellets indicates comparatively low concentrations of DDTs compared with elsewhere in the world but showed very high concentrations of hexachlorocyclohexane (Lindane) (Ogata *et al.*, 2009). Studies on DDTs and perfluorooctanesulfonic acids (PFAS) in swordfish and tunas suggested their similar feeding habitats resulted in the presence of the same type of POPs, while tuna from the Mozambique Channel showed unique DDT profiles (Munschy *et al.*, 2020a).

In the Seychelles, agricultural activities are the main sources of POPs. These activities are relatively small in scale, but low concentrations of chlorinated pesticides such as Aldrin, Lindane, Dieldrin, pp'- DDT and the breakdown products of DDT (pp'-DDD and pp'-DDE) have been detected in sediments. Even though the use of DDT and Aldrin has been banned, risk remains from leachate from landfills (ASCLME, 2012e). Investigation into the presence of POPs in swordfish along the Seychelles coast showed the major contaminants to be chlorinated (organochlorine pesticides (OCPs) and PCBs) and perfluorinated (PFASs) compounds, although at relatively low levels (Munschy *et al.*, 2020b).

Current data on POP levels in water, sediment, and biological tissue in the coastal and marine environment of South Africa is limited (ACSLME, 2012g). However, previous studies showed that POP levels in coastal waters further offshore were not significant using international standards (Griffiths *et al.*, 2004; CSIR, 2009a&b), possibly because of the high-energy nature of the coast preventing significant settling of fine-grained sediment and organic matter with which most POPs preferentially associate. However, since most monitoring is restricted to about 3-4 km offshore and in small areas, there remains poor understanding of whether contaminants are accumulating further offshore (*e.g.* the Tugela Bank) (ASCLME, 2012g).

POPs have also been detected in the sediments of estuaries and ports in coastal cities. These include pesticides and polychlorinated biphenyls whose production was banned decades ago (Newman *et al.*, 2015). These chemicals pose a toxic risk to aquatic fauna and flora (Vogt *et al.*, 2018) based on studies conducted on marine organisms, for example in fish (Grobler *et al.*, 1996), seals (Stewardson *et al.*, 1999) and dolphins (De Kock *et al.*, 1994). A study on the levels of Octacalcium Phosphates (OCPs) in reef organisms from marginal coral reefs in Sodwana Bay (South Africa) showed significantly elevated levels, which were attributed to groundwater seepage (Porter *et al.*, 2018).

In Tanzania, high levels of PCBs and OCP residues have been detected in Dar es Salaam habour (Machiwa, 1992; Mwevura *et al.*, 2002), while chlorinated compounds associated with pesticides have also been reported in sediment and polychaetes in Chwaka Bay and near Stone Town, Zanzibar (Mmochi, 2005, Mwevura *et al.*, 2020) and in the Rufiji Delta, in Tanzania (Mwevura *et al.*, 2021). Another study along the coast of Dar es Salaam found POPs accumulation in sediment and oysters mainly attributed to insufficient wastewater treatment (Machiwa, 2010).

1.6 Measures to Control Coastal and Marine Pollution

Several countries in the WIO region are signatories to international conventions or agreements linked to the combatting and prevention of marine pollution (Table 1.4).

Table 1.4: Key International and regional conventions/agreements applicable to coastal and marine pollution management, indicating signatory countries (UNEP et al. 2021a)

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
International Convention on Civil Liability for Oil Pollution Damage (CLC) (1969, enforced 1975), replaced by 1992 Protocol (1992, enforced 1996)	ensure that adequate compensation is available to persons who suffer oil pollution damage resulting from maritime casualties involving oil-carrying ship	•	•	•	•	•	•	•		•	•
International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (INTERVENTION) (1969, enforced 1975)	Affirms right of coastal states to measures on high seas to prevent, mitigate or eliminate danger to its coastline or related interests from pollution by oil or threat thereof, following upon a maritime casualty				•		•			•	•
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) and London Protocol (1996)	Prohibiting dumping of certain hazardous materials. In addition, a special permit is required prior to dumping of several other identified materials and a general permit for other wastes or matter	•				•	•		•	•	
	1996 Protocol to Convention prohibits all dumping, except for possibly acceptable wastes on the so-called 'reverse list'		•	•						•	
International Convention for Prevention of Pollution from Ships (MARPOL) (1973)											
	Annex I: Regulations for the Prevention of Pollution by Oil	•	•	•	•	•	•	•	•	•	•
	Annex II: Control of Pollution by Noxious Liquid Substances	•	•	•	•	•	•	•		•	•
	Annex III: Harmful Substances Carried by Sea in Packaged Form	•	•	•	•	•	•	•		•	•
	Annex IV: Sewage from Ships	•	•	•	•	•	•	•		•	•
	Annex V: Garbage from Ships	•	•	•	•	•	•	•		•	•
	Annex VI: Air Pollution from Ships		•	•	•		•	•		•	
United Nations Convention on the Law of the Sea (UNCLOS) (1982)	This convention is cornerstone of ocean governance at the national, regional, and global levels. Section 5 addresses prevention of pollution of the marine environment - www.iucn.org/theme/marine-and-polar/our-work/international-ocean-governance/unclos	•	•	•	•	•	•	•	•	•	•

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
Regional Seas Programme: Nairobi Convention (1985, enforced 1996)	Partnership between governments, civil society, and private sector, working towards a prosperous Western Indian Ocean Region. This Convention offers a regional legal framework and coordinates efforts of member states to plan and develop programmes that strengthen their capacity to protect, manage and develop their coastal and marine environment	●	●	●	●	●	●	●	●	●	●
International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) (1990, enforced 1995)	Require parties to establish measures for dealing with pollution incidents, either nationally or in co-operation with other countries	●	●	●	●	●	●	●	●	●	●
International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND) 1992 Protocol (1992, enforced 1996)	Under this Convention, victims of oil pollution damage may be compensated beyond level of ship owners' liability	●	●	●	●	●	●	●		●	●
International Convention on Civil Liability for Bunker Oil Pollution Damage (BUNKER) (2001, enforced 2008)	The Convention ensures adequate, prompt, and effective compensation availability to persons who suffer damage caused by spills of oil, when carried as fuel in ships' bunkers	●	●	●	●		●	●			
Stockholm Convention (2001, enforced 2004)	Convention on Persistent Organic Pollutants is a global treaty to protect human health and the environment from chemicals that remain intact in the environment for long periods	●	●	●	●	●	●	●	●	●	●
International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM) (2004, enforced 2017)	This Convention aims to prevent the spread of harmful aquatic organisms from one region to another, by establishing standards and procedures for management and control of ships' ballast water and sediments		●	●			●	●		●	
2030 Agenda for Sustainable Development (2015)	Adopted by UN member states as an agenda for people, planet, and prosperity. Seventeen Sustainable Development goals were identified of which some are relevant to marine pollution prevention (www.un.org.za/sdgs/2030-agenda/)	●	●	●	●	●	●	●	●	●	●

The key international convention aimed at combating land-based coastal and marine pollution in the WIO regions is the Regional Seas Programme: Nairobi Convention (1985) to which all countries in the region are signatories. At the national level, countries in the regions also have promulgated legislation aimed at combatting land-based coastal and marine pollution, albeit to varying degrees (UNEP *et al.*, 2021a).

Under the Nairobi Convention, strategic objectives and targets for coastal and marine pollution management in the WIO region have been defined in the *Strategic Action Programme Protection of the Coastal and Marine Environment of the Western Indian Ocean from Land-based Sources and Activities* (WIOSAP) (UNEP/Nairobi Convention Secretariat, 2009) which has been adopted by Contracting Parties into a formal *Protocol on Land-Based Sources and Activities in support of the Nairobi Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region* (UNEP, 2010).

The WIOSAP set the following s strategic objective: *Water quality in the WIO region meets international standards by year 2035* which will be achieved when (i) quality of coastal and marine waters in the WIO region meets regionally agreed standards, (ii) wastewater discharges adhere to agreed national and regional effluent standards, and (iii) there is increased government budget allocations for pollution prevention (UNEP/Nairobi Convention Secretariat, 2009).

The WIOSAP further identified the following specific targets towards achieving the strategic objective, mainly focused on mitigating, and preventing impacts from land-based sources and activities:

- Effluent discharge standards developed and regionally harmonized;
- Marine water standards (or guidelines) developed and regionally harmonized;
- Regional best practice framework models for municipal wastewater management developed and adopted;
- Collection, treatment, and disposal of effluents undertaken in accordance with regional standards;
- Environmental management systems and cleaner production technologies encouraged;
- Stakeholder's sensitized and political support harnessed in favour of pollution prevention.

In 2010, it was decided to initiate a joint Transboundary Diagnostic Assessment and Strategic Programme of Action process under ASCLME and SWIOFP pertaining to all issues pertinent to the coastal and offshore areas of the LMEs that have not fallen under the SAP of the WIO-LaB initiative. The *Strategic Action Programme for the Sustainable Management of the Western Indian Ocean Large Marine Ecosystems* (SAP WIOLME) was therefore published (ASCLME *et al.*, 2014). To ensure a comprehensive ecosystem-based approach (watershed to outer offshore boundaries) the two SAPs need to be implemented in collaboration through a cooperative understanding, whilst recognising and respecting the mandates of the various management bodies and institutions.

The SAP WIO-LME also identified water quality degradation as a key concern in the region, and posed the following ecosystem quality objectives (or targets) that are specifically related to the coastal and marine pollution management:

- Restore ground- and surface-water quality and prevent further degradation occurring in the future;
- Reduce microbiological contamination in coastal waters;
- Reduce solid waste (marine debris) from shipping and land-based sources in coastal water;
- Develop the capacity to prevent and mitigate the effects of oil spills at regional and national level. To achieve these targets, the SAP WIO-LME posed the following actions pertaining to the mitigation of water quality deterioration in coastal and offshore areas;
- Develop and adopt a general programme for long-term water quality monitoring (biochemical and physical) with the partners of the Western Indian Ocean Sustainable Ecosystem Alliance (WIO-SEA) and ensure that such water quality monitoring programmes target vulnerable areas as well as point-sources (*e.g.* coral reefs and other critical habitats as well as marine aquaculture facilities);
- Review current capacity and then design and implement improved monitoring and evaluation systems for microbial contamination and for solid and liquid waste discharges - both coastal and offshore (ship-based and platform based);
- Review existing vulnerability assessments to oil and hazardous chemical spills and develop an effective monitoring mechanism with specific indicators;
- Develop and adopt a monitoring system for exotic, non-native and nuisance species;
- Monitoring and reporting of microbial contamination; solid waste; oil and hazardous chemicals; run-off from agriculture and sewage, etc;
- Design, construction and operation of various forms of waste reception facilities including oil and hazardous chemicals handling, sewage systems, etc;
- Use of oil and hazardous chemical spill clean-up equipment, response measures and rapid response contingency plans;

- Development and adoption of effective and standardized Environmental Impact Assessment criteria, standards and regulations for watershed, coastal and offshore activities that could contaminate/pollute the marine ecosystem (including marine aquaculture and impacts from contamination, waste, and potential invasive species);
- Review existing national plans for waste management and develop new plans and programmes as necessary, including the development of appropriate port facilities for recycling and reuse of ship-borne wastes, and the implementation of incentive measures/mechanism for use of such facilities and implement an awareness and educational campaign;
- Ratify and adopt International Maritime Organization (IMO) protocols into all domestic legislation and regulations throughout participating countries;
- Review existing national and regional Oil and Hazardous Materials Spill Contingency Plans (OHMSCP) and Oil Spill Response measures;
- Prepare, adopt or modify/improve regional guidelines for OHMSCP and rapid response including the development and/or support any on-going process to adopt a regional response facility and emergency centre for oil and hazardous materials;
- Collaborate closely with the oil, gas, chemical and shipping industry, and IMO to develop appropriate responses, equipment stockpiles and response coordination centre(s).

In response to the above regional-level achievements in terms of coastal and marine pollution management include:

- WIO Action Plan on Marine Litter (UNEP, 2018);
- African Marine Litter Monitoring Manual (Barnardo and Ribbink, 2020);
- WIO Marine Highway development and Coastal and Marine Contamination Prevention Project (2020);
- Regional oil spill preparedness in eastern Africa and WIO (UNEP *et al*., 2020a and b).

Reflecting on the status of land-based coastal and marine pollution management, countries are signatories to the key international convention pertaining to the combating of land-based coastal and marine pollution, the Regional Seas (Nairobi Convention). Most of WIO region countries have some form of legislation in place to enable the control and management of land-based pollution, some more advanced than others. Good progress is being made to combat marine litter in the WIO region. For example, the Western Indian Ocean Marine Science Association (WIOMSA) partnered with Sustainable Seas Trust

(SST), through its African Marine Waste Network, and initiated an observation and monitoring programme involving Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa, and Tanzania which run from 2019-2021 and focused on land-based sources of litter (WIOMSA, 2020).

To develop uniform ways of measuring marine litter the Sustainable Seas Trust and WIOMSA published the *African Marine Litter Monitoring Manual* in 2020 (Barnardo and Ribbink, 2020).The WIO Regional Marine Litter Action Plan (UNEP, 2018), prepared in response to UNEA Resolutions 1/6, 2/11 and 3/20, aims to address marine litter in a coordinated and collaborative manner across the region towards implementation of the Protocol on Land Based Sources and Activities (LBSA Protocol) as well as supporting achievement of Sustainable Development Goal 14. A Regional Technical Working Group on Marine Litter and microplastics was also established by the Nairobi Convention and WIOMSA to promote shared learning across the region and to provide regional governments with appropriate technical support on interventions to combat this challenge.

In spite of the above efforts, the dedicated management focusing on coastal and marine pollution management is limited, and where policies and plans have been put in place, implementation remains a major challenge. Consequently, there is need to address numerous root causes, such as inappropriate governance, inadequate knowledge and awareness, and inadequate financial resources, in order to ultimately achieve effective marine water quality management. There are a few more direct measures that could be undertaken to advance improvements in the region. The lack of effective development or implementation of initiatives is often a result of a silo-based, fragmented approach, instead of a more holistic, ecosystem-based approach that is critical for successful management of the environment – in this case the coastal marine environment.

Such programmes are largely lacking in countries of the region, and consequently there is no coordinated and consistent monitoring and reporting of marine pollution matters. This gravely impairs policy decision-making, management, and interventions to improve the water quality and protect ocean flora and fauna. Within this context, the Nairobi Convention Secretariat has recently establish a *Strategic framework for coastal and marine water quality management* to fast-track implementation (UNEP *et al.*, 2021b), which builds on and refines their previous initiatives linked to coastal and marine pollution management (UNEP *et al.*, 2009a, 2009b), including guidance on monitoring the development of water and sediment water quality targets_ (UNEP *et al.*, 2022).

1.7 References

Abdallah, F. A., Bacari, A., Sinane, H.M., Ibrahim, Y. and Mouridi, A, A. (2006). Comores rapport national sommaire sur les activitesterrestes, les sources de pollution et les niveaux des polluants dans l'eau et les sediments: Comores. Draft report submitted to WIO-LaB PMU, Nairobi, Kenya.

Abuodha, J. O. Z., and Hayombe, P. O. (2006). Protracted environmental issues on a proposed titanium minerals development in Kenya's south coast. *Marine Georesources and Geotechnology*, 24(2), 63-75.

Abuodha, P. A. W., & Kairo, J. G. (2001). Human-induced stresses on mangrove swamps along the Kenyan coast. *Hydrobiologia*, 458, 255–265. https://doi.org/10.1023/A:1013130916811

Adams, J. B. (2020). Salt marsh at the tip of Africa: Patterns, processes and changes in response to climate change. *Estuarine, Coastal and Shelf Science*, 237, 106650.

Adams, J. B., Taljaard, S., Van Niekerk, L., and Lemley, D. A. (2020). Nutrient enrichment as a threat to the ecological resilience and health of South African microtidal estuaries. *African Journal of Aquatic Science*, 45(1-2), 23-40.

Adams, J. B., Veldkornet, D., & Tabot, P. (2016). Distribution of macrophyte species and habitats in South African estuaries. *South African Journal of Botany*, 107, 5–11. https://doi.org/10.1016/j.sajb.2016.08.001

Alongi D. M., (2002). Present sate and future of the world's mangrove forests. Environmental Conversation 29(3): 331 - 349.

Alusa, A. L., and Ogallo, L. J. (1992). Implications of expected climate change in the Eastern African coastal region. An overview. UNEP Regional Seas Reports and Studies No. 149. UNEP, Nairobi.

AMERICAN METEOROLOGICAL SOCIETY. 2000. *American Meteorological Society glossary of metereology*. http://amsglossary.allenpress.com/glossary/search?id=somali-current1: 20 January 2009.

Antoine, H., Carolus, I., Naya, N., Radegonde, V., and Sabury, E. (2008). Seychelles national summary report on land-based activities, sources of pollution and pollutant levels in water and sediment. Draft report submitted to WIO-LaB PMU, Nairobi, Kenya.

Arabi, S., and Nahman, A. (2020). Impacts of marine plastic on ecosystem services and economy: State of South African research. *South African Journal of Science*, 116(5-6), 1-7.

ASCLME 2012a.National Marine Ecosystem Diagnostic Analysis. Comoros. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012b.National Marine Ecosystem Diagnostic Analysis. Kenya. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012c.National Marine Ecosystem Diagnostic Analysis. Madagascar. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012d. National Marine Ecosystem Diagnostic Analysis. Mozambique. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012e.National Marine Ecosystem Diagnostic Analysis. Seychelles. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012g.National Marine Ecosystem Diagnostic Analysis. South Africa. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME 2012h.National Marine Ecosystem Diagnostic Analysis. Tanzania. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME, GEF and UNDP 2014.A strategic action programme for sustainable management of the Western Indian Ocean Large Marine Ecosystems (*https://asclme.org/SAP/*).

ATSDR (2007) Public Health Assessment Guidance Manual, US Department of Health and Human Services, Agency for Toxic Substances and Disease Registry. Public Health Service, Atlanta, GA

Bakun, A. (1998). Coastal upwelling and other processes regulating ecosystem productivity and fish production in the Western Indian Ocean. In: SHERMAN K, OKEMWA EN and NTIBA MJ (eds) Large marine ecosystems of the Indian Ocean: Assessment, sustainability and management. Blackwell Science, London: 103 - 142.

Barasa, M. W., Lalah, J. O., & Wandiga, S. O. (2008). Seasonal variability of persistent organochlorine pesticide residues in marine fish along the Indian Ocean coast of Kenya. *Toxicological and Environmental Chemistry*, 90(3), 535–547. *https://doi.org/10.1080/02772240701556312*

Barnardo, T., and Ribbink, A. J. (2020). African Marine Litter Monitoring Manual. African Marine Waste Network. Sustainable Seas Trust.

Beckley L. (1993). The Agulhas current ecosystem with particular reference to dispersal of fish larvae. In: SHERMAN K, OKEMWA EN and NTIBA MJ (2009) Large marine ecosystems of the Indian Ocean: Assessment, sustainability and management. Blackwell Science, London: 255 - 276.

Björk, M., Mohammed, S. M., Bjorklund, M., and Naaslund, I. (1996). Distribution of coral associated algae at four locations near Zanzibar Town, Tanzania. In: BJÖRK M, SEMESI AK, PEDERSEN M and BERGMAN B (eds) Current trends in marine botanical research in the East African region. Proceedings of the symposium on the biology of microalgae, macroalgae and seagrasses in the Western Indian Ocean. 3-10 December 1995. University of Mauritius, pp. 347 - 357.

Bjork, M., Mohammed, S. M., Bjorklund, M., and Semesi, A. (1995). Coralline algae, important coral-reef builders threatened by pollution. *Ambio*, 24(7-8), 502-505.

Bosch, A. C., O'Neill, B., Sigge, G. O., Kerwath, S. E., and Hoffman, L. C. (2016). Heavy metals in marine fish meat and consumer health: a review. *Journal of the Science of Food and Agriculture*, 96(1), 32-48.

Bosire, J. O., Kaino, J. J., Olagoke, A. O., Mwihaki, L. M., Ogendi, G. M., Kairo, J. G., ... Macharia, D. (2014). Mangroves in peril: Unprecedented degradation rates of peri-urban mangroves in Kenya. *Biogeosciences*, 11(10), 2623–2634. *https://doi.org/10.5194/bg-11-2623-2014*

Botte, M. D. M. (2001). Monitoring of coral bleaching at four sites around Mauritius (Doctoral dissertation, BSc thesis. University of Mauritius, Mauritius).

City of Cape Town., (2020). Know your coast 2020. Report produced by the City of Cape Town, South Africa (*https://resource.capetown.gov.za/documentcentre/Documents/City%20research%20reports%20and%20review/Know_Your_Coast_2020.pdf*)

Cliff, G., Dudley, S. F., Ryan, P. G., and Singleton, N. (2002). Large sharks and plastic debris in KwaZulu-Natal, South Africa. *Marine and Freshwater Research*, 53(2), 575-581.

CNN. 2020. Residents of a Kenyan village awarded $12 million in a lawsuit over lead poisoning. (*https://edition.cnn.com/2020/07/17/africa/kenya-pollution-ruling/index.html*)

CSIR. 2009a. Sea disposal of sewage: Environmental surveys in the Durban outfalls region. Report No 27: Surveys made in 2008. CSIR Report CSIR/NRE/CO/ER/2009/0059/A

CSIR.2009b. Assessment of sediment quality in the Port of Richards Bay – 2009. CSIR Report CSIR/NRE/ CO/ER/2009/0114/B

Danielsson, M. (2017). The plastic bag ban in Rwanda: local procedures and successful outcomes.

Daudi, L. N., Lugomela, C., Uku, J. N., and De Troch, M. (2012). Effect of nutrient enrichment on seagrass associated meiofauna in Tanzania. *Marine environmental research*, 82, 49-58.

De Kock, A. C., Best, P. B., Cockcroft, V., and Bosma, C. (1994). Persistent organochlorine residues in small cetaceans from the east and west coasts of southern Africa. *Science of the Total Environment*, 154(2-3), 153-162.

Den Hartog, C. (1979). Seagrasses and seagrass ecosystems, an appraisal of the research approach. *Aquatic Botany*, 7, 105-117.

Dirtu, A. C., Malarvannan, G., Das, K., Dulau-Drouot, V., Kiszka, J. J., Lepoint, G., ... and Covaci, A. (2016). Contrasted accumulation patterns of persistent organic pollutants and mercury in sympatric tropical dolphins from the south-western Indian Ocean. *Environmental research*, 146, 263-273.

Duarte, C. M. (2002). The future of seagrass meadows. *Environmental Conservation*, 29(2), 192–206. *https://doi.org/10.1017/S0376892902000127*

Dulymamode, R., Bhikajee, M. and Sanassee, V. (2002). Development and protection of the coastal and marine environment in sub-Saharan Africa: Mauritius National Report Phase 1: Integrated Problem Analysis. March 2002. GEF MSP Sub-Saharan Africa Project (GF/6010-0016) Sponsored by GEF, UNEP, IOC-UNESCO, GPA and ACOPS. (*http://archive.iwlearn.net/acops.org/African_Process/National_Reports.htm*)

Ellison, A. M., & Farnsworth, E. J. (1996). Anthropogenic Disturbance of Caribbean Mangrove Ecosystems: Past Impacts, Present Trends, and Future Predictions. *Biotropica*, 28(4), 549–565. *https://doi.org/10.2307/2389096*

Fabricius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine pollution bulletin*, 50(2), 125-146.

Fagoonee, I. (1990). Coastal marine ecosystems of Mauritius. *Hydrobiologia*, 208, 55-62.

Fernandes A., (1995). Pollution in Maputo Bay: Contamination levels from 1968 to 1996. *Revista Medica de Mozambique* 6 (34). Instituto Nacional de Saide.

Fernandes A., (1996). Poluição: Factos e figuras. Proceedings from the Workshop on the Role of Research in Coastal Zone Management, Maputo, 24-25 de Abril, 1996. Departamento de CiênciasBiológicas, Universidade Eduardo Mondlane.

Forbes, T., and Demetriades, N. (2008). Durban's Estuaries, KwaZulu-Natal, South Africa. Report prepared for eThekwini Municipality (*www.durban.gov.za/City_Services/development_planning_management/environmental_planning_climate_protection/Publications/Documents/Estuaries%20of%20Durban%20%28technical%20report%29.pdf*)

Griffiths, C. L., Van Sittert, L., Best, P. B., Brown, A. C., Clark, B. M., Cook, P. A., ... and Van der Lingen, C. D. (2004). Impacts of human activities on marine animal life in the Benguela: a historical overview. *Oceanography and marine biology*: an annual review, 42, 303-392.

Grobler, D. F., Badenhorst, J. E., and Kempster, P. L. (1996). PCBs, chlorinated hydrocarbon pesticides and chlorophenols in the Isipingo Estuary, Natal, Republic of South Africa. *Marine pollution bulletin*, 32(7), 572-575.

Hamilton, H. G. H., and Brakel, W. H. (1984). Structure and coral fauna of East African reefs. *Bulletin of Marine Science*, 34(2), 248–266.

Harris, L.R., Sink, K.J., Skowno, A.L. and Van Niekerk, L. (eds). 2019. South African National Biodiversity Assessment 2018: Technical Report. Volume 5: Coast. South African National Biodiversity Institute, Pretoria. *http://hdl.handle.net/20.500.12143/6374*

Horrill, J. C., Kamkuru, A. T., Mgaya, Y. D., and Risk M. (2000). Northern Tanzania and Zanzibar. In: McCLANAHAN TR, SHEPPARD CRC and OBURA DO (eds) Coral reefs of the Indian Ocean - their ecology and conservation. Oxford University Press, Oxford: 167 - 198.

Jeevanaraj, P., Hashim, Z., Elias, S. M., and Aris, A. Z. (2019). Risk of dietary mercury exposure via marine fish ingestion: assessment among potential mothers in Malaysia. *Exposure and Health*, 11, 227-236.

Jones, T., Payet, R., Beaver, K., and Nalletamby, M. (2002). Development and protection of the coastal and marine environment in sub-Saharan Africa: Seychelles National Report Phase 1: Integrated Problem Analysis. March 2002. GEF MSP Sub-Saharan Africa Project (GF/6010-0016) Sponsored by GEF, UNEP, IOC-UNESCO, GPA and ACOPS.

Kamau, J. N. (2001). Heavy metals distribution in sediments along the Killindini and Makupa creeks, Kenya. *Hydrobiologia*, 458, 235-240.

Kanayev, V. F., Morgan, J. R., and Verlaan, P. A. (eds) (2009) Indian Ocean. Encylopaedia Britannica. (*http://www.britannica.com/EBchecked/topic/285876/Indian-Ocean*)

Kazungu, J.M., Munga, D., Mwaguni, S. M., and Ochiewo, J. (2002). Development and protection of the coastal and marine environment in sub-Saharan Africa: Kenya National Report Phase 1: Integrated Problem Analysis. March 2002. GEF MSP Sub-Saharan Africa Project (GF/6010-0016) Sponsored by GEF, UNEP, IOC-UNESCO, GPA and ACOPS.(*http://archive.iwlearn.net/acops.org/African_Process/National_Reports.htm*)

Kitheka, J. U., Obiero, M., & Nthenge, P. (2005). River discharge, sediment transport and exchange in the Tana Estuary, Kenya. *Estuarine, Coastal and Shelf Science*, 63(3), 455-468.

Kitheka, J. U., Ochiewo, J., Nthenge, P., & Obiero, M. (2003a). Coastal impacts of damming and water abstraction in the Tana and Athi-Sabaki river basins. LOICZ-START AfriCAT project report.

Kitheka, J. U., Ongwenyi, G. S., & Mavuti, K. M. (2003b). Fluxes and exchange of suspended sediment in tidal inlets draining a degraded mangrove forest in Kenya. *Estuarine, Coastal and Shelf Science*, 56(3-4), 655-667.

Kwach, B. O., and Lalah, J. O. (2009). High concentrations of polycyclic aromatic hydrocarbons found in water and sediments of car wash and kisat areas of Winam Gulf, Lake Victoria-Kenya. *Bulletin of environmental contamination and toxicology*, 83, 727-733.

Lane S. (2007). Regional Overview and Assessment of Marine Litter Related Activities in the West Indian Ocean Region (Nairobi Convention and GEF WIO-LaB Project Countries). Prepared for WIOMSA on behalf of UNEP (GPA and the Regional Seas Programme).

Lapointe, B. E., and Clark, M. W. (1992). Nutrient Inputs from the watershed and coastal eutrophication in the Florida Keys. *Estuaries* 15(4): 465-476.

Lutjeharms, J. R. E., (2006). The Agulhas Current Springer-Verlag, Berlin, Germany; https://doi.org/10.1007/3-540-37212-1.

Lyimo, T. J. (2009). Microbial and nutrient pollution in the coastal bathing waters of Dar es Salaam. Aquatic Conservation: *Marine and Freshwater Ecosystems*, 19(S1), S27-S37.

Machiwa, J. F. (1992). Anthropogenic pollution in the Dar es Salaam harbour area, Tanzania. *Marine Pollution Bulletin*, 24(11), 562-567.

Machiwa, J. F. (2000). Heavy Metals and Organic Pollutants in Sediments of Dar es Salaam Harbour Prior to Dredging in 1999. *Tanzania Journal of Science*, 26, 29-46.

Machiwa, J. F. (2010). Coastal marine pollution in Dar es Salaam (Tanzania) relative to recommended environmental quality targets for the Western Indian Ocean. *Western Indian Ocean Journal of Marine Science*, 9(1), 17-30.

Mapunda, E. C., Othman, O. C., Akwilapo, L. D., Bouwman, H., and Mwevura, H. (2017). Concentrations of metallic elements in kidney, liver, and lung tissue of Indo-Pacific bottlenose dolphin Tursiops aduncus from coastal waters of Zanzibar, Tanzania. *Marine Pollution Bulletin*, 122(1-2), 483-487.

Mardon, D., and Stretch, D. (2004). Comparative assessment of water quality at Durban beaches according to local and international guidelines. Water SA, 30(3), 317-323.

Massinga, A., and Hatton, J. (1997). Status of the coastal zone of Mozambique. In: C.G. Lundin and O. Linden (eds) Integrated Coastal Zone Management in Mozambique. Proceedings of the National Workshop on Integrated Coastal Zone Management in Mozambique. Inhaca Island and Maputo, Mozambique, May 5-10, 1996. 7 - 68 pp.

McClanahan, T. (1988). Seasonality in East Africa's coastal waters. *Marine Ecology Progress Series*, 44, 191–199. https://doi.org/10.3354/meps044191

McClanahan, T. R. (2002). The near future of coral reefs. *Environmental Conversation* 29(4): 460 - 483.

McClanahan, T. R., and Obura, D. (1997). Sedimentation effects on shallow coral communities in Kenya. *Journal of Experimental Marine Biology and Ecology*, 209(1-2), 103-122.

Mengesha, S., Dehairs, F., Elskens, M., & Goeyens, L. (1999). Phytoplankton nitrogen nutrition in the western Indian Ocean: Ecophysiological adaptations of neritic and oceanic assemblages to ammonium supply. *Estuarine, Coastal and Shelf Science*, 48(5), 589–598. https://doi.org/10.1006/ecss.1999.0468

Mgana, S., and Mahongo, S. (1997). Land-based sources and activities affecting the quality and uses of the marine, coastal and associated freshwater environment: Tanzania Mainland. In Report presented at the UNEP Regional Workshop, Institute of Marine Sciences, Zanzibar (pp. 6-9).

Mgana, S., and Mahongo, S. (2002). Strategic Action Plan for Land-Based Sources and Activities Affecting the Marine, Coastal and Associated Fresh Water Environment in the Eastern African region. A Report prepared by Food and Agriculture Organisation of the United Nations project for the Protection and Management of the Marine and Coastal Areas of the Eastern African region (EAF/5).

Mmochi, A. J. (2005). Chemodynamics of pesticide residues and metabolites in Zanzibar coastal marine environment (Doctoral dissertation, Ph.D Thesis. Dar es Salaam, Tanzania: University of Dar es Salaam).

Mmochi, A., and Francis, J. (2003). Land Based Activities and Sources of Pollution to the Marine, Coastal and Associated Fresh Water Ecosystems in the Western Indian Ocean Region. 21. Retrieved from *http://www.oceandocs.org/handle/1834/209*

Mohammed, S. M. (2002). A review of water quality and pollution studies in Tanzania. AMBIO: *A Journal of the Human Environment*, 31(7), 617-620.

Mremi, S. D., and Machiwa, J. F. (2003). Heavy metal contamination of mangrove sediments and the associated biota in Dar es Salaam, *Tanzania. Tanzania Journal of Science*, 29(1), 61-76.

Munga, D. (1993). The impact of pollution on the mangrove ecosystem in Kenya. In National Workshop for Improved Management and Conservation of the Kenyan Mangroves. (pp. 255-272).

Munga, D., Mwangi, S., Kamau, J., Nguli, M., Gwada, P., Daudi, L., ... and Machua, S. (2006). Land-Based Activities, Pollution Sources and Levels in Water and Sediment in the Coastal and Marine Area of Kenya: draft report.

Munschy, C., Bely, N., Heas-Moisan, K., Olivier, N., Pollono, C., Hollanda, S., and Bodin, N. (2020b). Tissue-specific bioaccumulation of a wide range of legacy and emerging persistent organic contaminants in swordfish (Xiphias gladius) from Seychelles, Western Indian Ocean. *Marine Pollution Bulletin*, 158, 111436.

Munschy, C., Vigneau, E., Bely, N., Héas-Moisan, K., Olivier, N., Pollono, C., ... and Bodin, N. (2020b). Legacy and emerging organic contaminants: Levels and profiles in top predator fish from the western Indian Ocean in relation to their trophic ecology. *Environmental Research*, 188, 109761.

Mushi, D. (2020). Bacteriological quality of marine recreational water in a tropical environment reflects coastal residential patterns. *Scientific African*, 8, e00326.

Mwaguni, S. M. (2002). Public health problems in Mombasa District: A case study on sewage management (Doctoral dissertation).

Mwaguni, S., and Munga, D. (1997). Land based sources and activities affecting the quality and uses of the marine coastal and associated fresh water environments along the Kenyan coast. National Report prepared for the Protection and management of the marine and coastal areas of the Eastern African region (EAF/5) Project.

Mwakalobo, S. L., Namkinga, L., Lyimo, T. J., and Lugomela, C. (2013). Assessment of Faecal Bacteria Contamination in Selected Coastal Waters of Tanzania. *Journal of Biology and Life Science*, 4(2), 63–82. *https://doi.org/10.5296/jbls.v4i2.3414*

Mwaura, J., Umezawa, Y., Nakamura, T., and Kamau, J. (2017). Evidence of chronic anthropogenic nutrient within coastal lagoon reefs adjacent to urban and tourism centers, Kenya: A stable isotope approach. *Marine pollution bulletin*, 119(2), 74-86.

Mwevura, H., Bouwman, H., Kylin, H., Vogt, T., and Issa, M. A. (2020). Organochlorine pesticides and polycyclic aromatic hydrocarbons in marine sediments and polychaete worms from the west coast of Unguja island, Tanzania. *Regional studies in marine science*, 36, 101287.

Mwevura, H., Kylin, H., Vogt, T., and Bouwman, H. (2021). Dynamics of organochlorine and organophosphate pesticide residues in soil, water, and sediment from the Rufiji River Delta, Tanzania. *Regional Studies in Marine Science*, 41, 101607.

Mwevura, H., Othman, O. C., and Mhehe, G. L. (2002). Organochlorine pesticide residues in sediments and biota from the coastal area of Dar es Salaam city, Tanzania. *Marine Pollution Bulletin*, 45(1-12), 262-267.

Naidoo, T., and Rajkaran, A. (2020). Impacts of plastic debris on biota and implications for human health: A South African perspective. *South African Journal of Science*, 116(5-6), 1-8.

New, A. L., Stansfield, K., Smythe-Wright, D., Smeed, D. A., Evans, A. J., Alderson, S. G., … Lloyd, I. (2005). Physical and biochemical aspects of the flow across the Mascarene Plateau in the Indian Ocean. Philosophical Transactions of the Royal Society A: Mathematical, *Physical and Engineering Sciences*, 363(1826), 151–168. https://doi.org/10.1098/rsta.2004.1484

Newman, B., Arabi, S., Weerts, S., Pieters, R., and Vogt, N. (2015). Prevalence and significance of organic contaminants and metals in aquatic ecosystems in the eThekwini area of Kwazulu-Natal. WRC Report No. 1977/1/15. Pretoria, South Africa.

Ngusaru, A. (1997). Geological history. In: RICHMOND, M.D. ed. A guide to the seashore of eastern Africa and the western Indian Ocean islands. Sida, Stockholm: 7 - 8.

Niekerk, L.V., Adams, J., Stephen, L., Mackay, F., Taljaard, S., Jane, T., Weerts, S.P., and Raimondo, D.C. (2019). South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm.

Nyanda, F., Mtei, R. P., Mohammed, S. M., & Mmochi, A. J. (2016). Nutrient and Bacteria Concentrations in the Coastal Waters off Zanzibar Town. *WIO Journal of Marine Science*, 15(2), 9–17.

Obura, D. (2005). Coral reef degradation in the Indian Ocean, Status report 2005: East Africa summary. CORDIO east Africa, Mombasa, Kenya.(*https://www.iucn.org/resources/publication/coral-reef-degradation-indian-ocean-status-report-2005*)

Ochiewo J. (2006). National Overview and Assessment of Marine Litter Related Activities in Kenya. Kenya Marine and Fisheries Research Institute (KMFRI). Report submitted to West Indian Ocean Marine Science Association (WIOMSA), Zanzibar, Tanzania.

Ogata, Y., Takada, H., Mizukawa, K., Hirai, H., Iwasa, S., Endo, S., ... and Thompson, R. C. (2009). International Pellet Watch: Global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. *Marine pollution bulletin*, 58(10), 1437-1446.

Okemwa, E. N. (1998). Application of the large marine ecosystem concept to the Somali Current. In: SHERMAN K, OKEMWA EN and NTIBA MJ (2009) Large marine ecosystems of the Indian Ocean: Assessment, sustainability, and management. *Blackwell Science*, London: 73 - 100.

Okuku, E. O., Imbayi, K. L., Omondi, O. G., Wayayi, W. V. O., Sezi, M. C., Maureen, K. M., ... and Oduor, N. (2019). Decadal pollution assessment and monitoring along the Kenya Coast. In Monitoring of Marine Pollution. IntechOpen. (*https://www.intechopen.com/chapters/66333*)

Orth, R., Heck, K., and van Montfrans, J. (1984). Faunal Communities in Seagrass Beds : A Review of the Influence of Plant Structure and Prey Characteristics on Predator : *Prey Relationships*. http://www.jstor.or. 7(4), 339–350.

Pastorok, R., and Bilyard, G. (1985). Effects of sewage pollution on coral-reef communities. *Marine Ecology Progress Series*, 21(1), 175–189. *https://doi.org/10.3354/meps021175*

Peter, N., Semba, M., Lugomela, C., and Kyewalyanga, M. S. (2018). The influence of physical-chemical variables on the spatial and seasonal variation of Chlorophyll-a in coastal waters of Unguja, Zanzibar, Tanzania. *Western Indian Ocean Journal of Marine Science*, 17(2), 25-34.

Peters, E. C., Gassman, N. J., Firman, J. C., Richmond, R. H., and Power, E. A. (1997). Ecotoxicology of tropical marine ecosystems. *Environmental Toxicology and Chemistry*, 16(1), 12–40. *https://doi.org/10.1002/etc.5620160103*

Porter, S. N., Humphries, M. S., Buah-Kwofie, A., and Schleyer, M. H. (2018). Accumulation of organochlorine pesticides in reef organisms from marginal coral reefs in South Africa and links with coastal groundwater. *Marine pollution bulletin*, 137, 295-305.

Prayag, R., Jootun, L., and Bheeroo, R. A. (1995). Integrated coastal zone management. Protection and management of marine and coastal areas of the Eastern African region. Report prepared for UNEP/FAO/IOC/IUCN EAF5 project. Ministry of Environment and Quality of Life, Mauritius.92 pp.

Radegonde, V. (1997). Update Seychelles National Overview on land-based sources and activities affecting the marine, coastal and associated freshwater environment. Seychelles Bureau of Standards, Seychelles.31 pp.

Rainbow, P. S. (1995). Biomonitoring of heavy metal availability in the marine environment. *Marine Pollution Bulletin*, 31(4–12), 183–192. *https://doi.org/10.1016/0025-326X(95)00116-5*

Ramessur, R. T. (2002). Anthropogenic-driven changes with focus on the coastal zone of Mauritius, south-western Indian Ocean. *Journal of Material Cycles and Waste Management*, 3(1–3), 99–106. *https://doi.org/10.1007/s10113-002-0045-0*

Ramessur, R. T. (2004). Statistical comparison and correlation of zinc and lead in estuarine sediments along the western coast of Mauritius. *Environment international*, 30(8), 1039-1044.

Republic of South Africa, Department of Environmental Affairs (RSA DEA) 2016. Review of all coastal discharges authorised prior to the Integrated Coastal Management Act (No 24 of 2008). Draft Report. Cape Town, South Africa.

Richmond, M. (2002). A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean Islands. 2nd Edition. Sida/Department of Research Corporation, SAREC and University of Dar es Salaam.

Rumisha, C., Elskens, M., Leermakers, M., and Kochzius, M. (2012). Trace metal pollution and its influence on the community structure of soft bottom molluscs in intertidal areas of the Dar es Salaam coast, Tanzania. *Marine pollution bulletin*, 64(3), 521-531.

Rumisha, C., Leermakers, M., Elskens, M., Mdegela, R. H., Gwakisa, P., and Kochzius, M. (2017b). Genetic diversity of the giant tiger prawn Penaeus monodon in relation to trace metal pollution at the Tanzanian coast. *Marine Pollution Bulletin*, 114(2), 759-767.

Rumisha, C., Leermakers, M., Mdegela, R. H., Kochzius, M., and Elskens, M. (2017a). Bioaccumulation and public health implications of trace metals in edible tissues of the crustaceans *Scylla serrata* and *Penaeus monodon* from the Tanzanian coast. *Environmental monitoring and assessment*, 189, 1-13.

Rumisha, C., Mdegela, R. H., Kochzius, M., Leermakers, M., and Elskens, M. (2016). Trace metals in the giant tiger prawn Penaeus monodon and mangrove sediments of the Tanzania coast: is there a risk to marine fauna and public health?. *Ecotoxicology and Environmental Safety*, 132, 77-86.

Schaffelke, B., Mellors, J., & Duke, N. C. (2005). Water quality in the Great Barrier Reef region: Responses of mangrove, seagrass and macroalgal communities. *Marine Pollution Bulletin*, 51(1–4), 279–296. https://doi.org/10.1016/j.marpolbul.2004.10.025

Schouten, M. W., de Ruijter, W. P. M., and van Leeuwen, P. J. (2002). Upstream control of Agulhas Ring shedding. *Journal of Geophysical Research: Oceans*, 107(8). https://doi.org/10.1029/2001jc000804

Sheppard, C. R. C. (2000). Coral reefs of the western Indian Ocean: an overview. Coral reefs of the Indian Ocean: Their ecology and conservation, Oxford University Press, Oxford: 3-38.

Slingo, J., Spencer, H., Hoskins, B., Berrisford, P., and Black, E. (2005). The meteorology of the Western Indian Ocean, and the influence of the East African Highlands. Philosophical Transactions of the Royal Society A: *Mathematical, Physical and Engineering Sciences*, 363(1826), 25–42. https://doi.org/10.1098/rsta.2004.1473

Stewardson, C. L., De Kock, A., and Saunders, C. (1999). Concentrations of heavy metals (Cd, Cu, Pb, Ni & Zn) and organochlorine contaminants (PCBs, DDT, DDE & DDD) in the blubber of Cape fur seals Arctocephalus pusillus pusillus off the Eastern Cape coast of South Africa. *Transactions of the Royal Society of South Africa*, 54(2), 205-215.

Ubomba-Jaswa, E., & Kalebaila, N. (2020). Framing the plastic pollution problem within the water quality-health nexus: Current understandings and policy recommendations. *South African Journal of Science*, 116(5-6), 1-3.

UN Environment (2018). Western Indian Ocean Regional Action Plan on Marine Litter. UN Environment/Nairobi Convention, Nairobi, vi + 24 pp.

UNEP 2010. Final Act of the Conference of the Plenipotentiaries for the Adoption of the Protocol for the Protection of the Marine and Coastal Environment of the Western Indian Ocean from land-Based Sources and Activities.Adopted in Nairobi, Kenya on 31 March 2010. (https://wedocs.unep.org/handle/20.500.11822/25901)

UNEP and Nairobi Convention SECRETARIAT. (UNEP/Nairobi Convention Secretariat) 2009. Strategic Action Programme for the Protection of the Coastal and Marine Environment of the Western Indian Ocean from Land-based Sources and Activities, Nairobi, Kenya, 140 pp.

UNEP and WIOMSA. 2008. Marine Litter in the Eastern Africa Region: An Overview Assessment. United Nations Environment Programme.60 pp.

UNEP, GPA and WIOMSA. 2004. Regional overview of the physical alteration and destruction of habitat (PADH) in the Western Indian Ocean region. United Nations Environment Programme.73 pp.

UNEP, Nairobi Convention and International Maritime Organization (UNEP *et al.*)2020a. Regional oil spill preparedness in eastern African and the western Indian Ocean.Background Document. (*https://www.nairobiconvention.org/clearinghouse/sites/default/files/Regional%20Oil%20Spill%20Preparedness.pdf*)

UNEP, Nairobi Convention and International Maritime Organization.2020b. Regional oil spill preparedness in eastern African and the western Indian Ocean. Workshop Report – 3 to 5 March 2020. (*https://www.nairobiconvention.org/clearinghouse/node/476*)

UNEP, Nairobi Convention Secretariat, CSIR and WIOMSA (UNEP *et al.*, 2009c). Towards a Protocol for long-term monitoring of marine environmental quality in the Western Indian Ocean.UNEP, Nairobi, Kenya, 86 pp.

UNEP/Nairobi Convention Secretariat and CSIR (2009b). Guidelines for the Establishment of Environmental Quality Objectives and Targets in the Coastal Zone of the Western Indian Ocean (WIO) Region, UNEP, Nairobi, Kenya, 169p

UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009a. Regional Synthesis Report on the Status of Pollution in the Western Indian Ocean Region. UNEP, Nairobi, Kenya, 91 pp.

UNEP-Nairobi Convention and WIOMSA (2015). The Regional State of the Coast Report: Western Indian Ocean. UNEP and WIOMSA, Nairobi, Kenya, 546 pp.

UNITED NATIONS ENVIRONMENT PROGRAMME, NAIROBI CONVENTION SECRETARIAT AND COUNCIL FOR SCIENTIFIC & INDUSTRIAL RESEARCH. 2021a. Western Indian Ocean: Situation Assessment on Marine Pollution and Coastal & Marine Water Quality Management. UNEP, Nairobi, Kenya, 61 pp.

UNITED NATIONS ENVIRONMENT PROGRAMME, NAIROBI CONVENTION SECRETARIAT AND COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH. 2021b. Western Indian Ocean: Strategic Framework for Coastal & Marine Water Quality Management. UNEP, Nairobi, Kenya. 68 pp.

United Nations Environment Programme, Nairobi Convention Secretariat and Council for Scientific and Industrial Research. 2022. Western Indian Ocean: Guidelines for Setting Water and Sediment Quality Targets for Coastal and Marine areas. UNEP, Nairobi, Kenya. XXIV + 109 pp +

Van der Schyff, V., Yive, N. S. C. K., and Bouwman, H. (2020). Metal concentrations in corals from South Africa and the Mascarene Basin: a first assessment for the Western Indian Ocean. *Chemosphere*, 239, 124784.

Verster, C., and Bouwman, H. (2020). Land-based sources and pathways of marine plastics in a South African context. *South African Journal of Science*, 116(5-6), 1-9.

Vinayachandran, P. N., Murty, V. S. N., and Ramesh Babu, V. (2002). Observations of barrier layer formation in the Bay of Bengal during summer monsoon. *Journal of Geophysical Research: Oceans*, 107(C12), SRF-19.

Vogt, T., Pieters, R., and Newman, B. K. (2018). PAHs, OCPs and PCBs in sediments from three catchments in Durban, *South Africa. African Journal of Aquatic Science*, 43(1), 35-49.

Wakibya, J. G. (1995). The potential human-induced impacts on the Kenya seagrasses.

Weller, R. A., Baumgartner, M. F., Josey, S. A., Fischer, A. S., and Kindle, J. C. (1998). Atmospheric forcing in the Arabian Sea during 1994-1995: Observations and comparisons with climatology and models. Deep-Sea Research Part II: *Topical Studies in Oceanography*, 45(10–11), 1961–1999. https://doi.org/10.1016/S0967-0645(98)00060-5

WIOMSA. (2020). Sustainable Seas Trust. Marine Litter Monitoring Project (https://sst.org.za/projects/african-marine-waste-network/wiomsa-marine-litter-monitoring-project/).

Wong, Y. S., Tam, N. F. Y., & Lan, C. Y. (1997). Mangrove wetlands as wastewater treatment facility: A field trial. *Hydrobiologia*, 352(1–3), 49–59. https://doi.org/10.1007/978-94-011-5234-1_6

WORLD HEALTH ORGANIZATION (WHO). 2020. Persistent organic pollutants (POPs) (https://www.who.int/news-room/questions-and-answers/item/food-safety-persistent-organic-pollutants-(pops))

Yim, M. W., & Tam, N. F. Y. (1999). Effects of wastewater-borne heavy metals on mangrove plants and soil microbial activities. *Marine Pollution Bulletin*, 39(1–12), 179–186. https://doi.org/10.1016/S0025-326X(99)00067-3

This page is intentionally blank

Chapter 2: Municipal Wastewater Treatment in Western Indian Ocean Region

By Zaina Mseli, Asumin Kantanga and Richard Kimwaga
University of Dodoma and University of Dar es Salaam, Tanzania

HIGHLIGHTS

The world over, including the WIO region, various wastewater and faecal sludge treatment options exist whose application is contextually bound. Depending on the context, a particular wastewater treatment can either be appropriate or not. This chapter presents an overview of the existing wastewater and faecal sludge treatment technology options which have long, and most been applied in WIO region. Further, the chapter briefly describes the associated design and operational performances and challenges. It is on these challenges that the foundation and need has been derived for CW application as yet another option but nature-based solution to wastewater and faecal sludge treatment in the WIO region.

2.1 Overview of Municipal Wastewater Treatment in the Western Indian Ocean Region

As previously described in Chapter one, the WIO region is comprised of five coastal states (Kenya, Somalia, Tanzania, Mozambique, and South Africa), and four island states (Mauritius, Seyschelles, Madagascar, and Comoros) and the Reunion, a department of France and part of the Eurozone. An unprecedented rate of the rapid urbanization and population growth has given rise to the proliferation of cities that have substantially put more pressure on land requirements, social services, and an enormous waste generation in the WIO region (UNEP *et al*., 2021). As a result, wastewater and faecal sludge as sources of marine and coastal ecosystems pollution from land-based activities is a major environmental management challenge of growing concern in this region (UNEP *et al*., 2021).Effective and appropriate wastewater and faecal treatment systems are required to adequately manage wastewater from various sources including residential, industrial, commercial, and institutional establishments and operations. Often, good environmental management practices require wastewater to be adequately and properly treated before safe discharge into the environment to comply with physical, biological, and chemical standards. Several wastewater treatment systems including onsite and offsite technologies are usually implemented to address the wastewater treatment objectives. A brief description of various technologies used to treat wastewater and faecal sludge in the WIO region are presented in Table 2.1 (Kitheka, 2015).

Table 2.1: Wastewater and faecal sludge treatment systems in the WIO region (Kitheka, 2015; UNICEF, 2020)

WIO country	Central sewer system	Septic tank+soakaway pit	Pit latrine	Others (dry and chemical toilets)	None
South African	47%	4%	18%	14.5%	16.5%
Kenya	11%	17%	72%		
Tanzania	2.2%	9.8%	80.9%	0.1%	7%
Mozambique	5.4%	24.6%	70%		
Comoro	0.3%	5.3%	94.4%		
Madagascar		11%	70%		19%
Seychelles	7.5%	86.9%	3.9%		
Mauritius	25%	73%	2%		
Somalia					28%
Reunion					

According to the analysis, pit latrines form predominant onsitewastewater management systems accounting for 62% (Kitheka, 2015). Septic tanks which account for 10% are secondly placed while municipal sewers (13%) and sea outfalls make up 4%. Unbelievably, 12% of residents still practice open defecation and are seriously lacking the access to the proper, adequate, and safe sanitation facilities (Kitheka, 2015).

Pit latrines are the dominant sanitation means oftenly used in most of the WIO region countries of Comoros (94%), Tanzania (81%), Kenya (72%), Mozambique (70%), Madagascar (70%), Mauritius (2%), and Seychelles (4%) (Kitheka, 2015). Septic tanks are the most used sanitation system in Seychelles (87%) and Mauritius (73%), while their use is less than 20% in the remaining WIO countries (Kitheka, 2015). Obviously, effective and adequate wastewater and faecal sludge treatment is a serious environmental management problem of concern in most of the cities and urban centres of the WIO region countries (Kitheka, 2015). Several towns located along the Indian Ocean coastal lines including Tanga, Zanzibar, Mombasa, and parts of Dar es Salaam release either partially or untreated wastewater into the ocean, (Kitheka, 2007).

2.2 Types of Wastewater

An understanding of the type of wastewater is critical since largely it influences the choice of the type of wastewater treatment option. One of the criteria used to classify the type of municipal wastewater is its source. The following sub-sections describe the source-based types of wastewater in the WIO region.

The rapid and often uncontrolled coastal urbanisation and tourism development is a growing concern in countries of the WIO region (UNEP *et al*., 2021). Consequently, it has given rise to inappropriate management and control of waste (UNEP *et al*., 2021). Key activities that considerably contribute to marine pollution include municipal wastewater disposal, point and non-point (diffuse) urban runoff, discharge as well as solid waste disposal (UNEP, 2020). In many cases, basic infrastructure cannot cope with the increased volume of waste water (UNEP, 2020). Sewage from sanitary facilities (septic tanks, pit latrines, wastewater and faecal sludge treatment plants) is a major source of marine pollution, with the level of treatment, and the type of treatment (or lack thereof) differing from country to country (UNEP *et al.* 2009c). Microbial contaminants, nutrients, biodegradable organic matter, and suspended solids are the main pollutants in untreated municipal sanitary wastewater (UNEP, 2020). The highest concentrations of these pollutants are therefore found close to major cities in the region, although in many rural coastal areas, low-level sewage contamination from open defecation on beaches is common phenomenon (UNEP, 2020). Urban stormwater can also introduce toxicants, such as metals and petroleum hydrocarbons, associated with road runoff.

2.2.1 Municipal Wastewater

This is one of the types of municipal wastewater which is generated in WIO region (UNEP *et al*., 2021). Domestic wastewater is the effluent that results from human activities in a home, such as bathing, washing, cleaning, dishwashing, toilet flushing etc. (Tchobanoglous *et al*., 2003). This type of wastewater is divided into two primary categories; grey water, which comes from sources like kitchen sinks, wash basins, laundry, showers, and baths; and black water which comes from toilets and urinals (Tilley *et al*., 2018). Even if domestic wastewater often contains only a modest amount of toxins, it can, nonetheless, have a relatively serious and detrimental negative environment impact (Metcalf and Eddy, 2014). Normally, domestic wastewater's strength and composition varies hourly, daily, and seasonally, with the average strength depending on such factors as habitual water use, nutrition, level of living, and lifestyle (Metcalf and Eddy, 2014).

Because of limited credible wastewater characteristics data in WIO region, the physical, chemical, and biological composition is adapted from well researched literature according to Metcalf and Eddy, 2014 and Doglas *et al*., 2021. Wastewater is represented by its musty smell, grey colour and a solid level of 0.1% (Metcalf and Eddy, 2014). A mixture of faeces, food scraps, toilet paper, grease, oil, soap, salts, metals, detergents, sand, and grit constitute the solid proportion of wastewater Both suspended (approximately 30%) and dissolved (about 70%) materials are possible (Metcalf and Eddy, 2014). Dissolved solids can be precipitated by both chemical and biological mechanisms. When released into the receiving environment, suspended solids have the potential to cause anaerobic conditions and sludge deposits from a physical standpoint (Metcalf and Eddy, 2014)

Chemically, domestic wastewater is made up of a variety of gases, organic and inorganic chemicals. The main components of the organic fractions are reflected in the molecules found in the human diet like carbohydrates (25 %), proteins (65 %), and fats (10 %) (Metcalf and Eddy; 2014). Heavy metals, nitrogen, phosphorus, pH, sulfur, chlorides, alkalinity, hazardous substances, etc. are examples of inorganic components (Metcalf and Eddy, 2014). Wastewater contains more dissolved particles than suspended ones. Consequently, between 85 to 90 percent of the total inorganic component is dissolved, and between 55 to 60 percent of the total organic components are both dissolved. Gases such as hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_3), oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) are frequently dissolved in wastewater (Metcalf and Eddy, 2014). The first three gases are produced because of decomposing of organic compounds found in wastewater and faecal sludge (Metcalf and Eddy, 2014).

Biologically, wastewater comprises a variety of microorganisms, but water borne pathogenic organisms including bacteria, viruses, protozoa, fungi, and algae are of public health concern .Coliforms are indicator microorganisms of faecal contamination .Faecal coliforms fractions in raw wastewater typically range from a few hundred thousand to tens of millions per 100 mL sample (Metcalf and Eddy,2014).

Available information on the estimated volume of municipal wastewater that potentially enters coastal and marine environments in the WIO region is summarised in Table 2.1 (as updated from (UNEP *et al*., 2009c). Recent studies have shown that inadequately treated wastewater is a major route by which microplastics enter water bodies (Ubomba-Jaswa and Kalebaila, 2020).

Table 2.2: Estimated volumes of municipal wastewater generated in coastal areas of the WIO region (and potentially entering the coastal and marine environment) (Updated from UNEP et al., 2009 unless otherwise indicated)

COUNTRY	ESTIMATED VOLUME (m^3/day)
Comoros	168[a]
Kenya	145,500
Madagascar	176,000
Mauritius	100,000
Mozambique	29,149[c]
Seychelles	4,922 (10,372[b])
South Africa (including discharges to estuaries)*	898, 581
Tanzania (Tanzania mainland and Islands)	37,912
* DEA (2016) and Van Niekerk et al. (2019)	

2.2.2 Industrial Wastewater

Another type of wastewater generated in WIO region is industrial wastewater. Industrial wastewater is the wastewater generated form industrial activities whose composition and characteristics are much stronger than domestic wastewater *e.g.* domestic COD range between 100 to 500 mg/L while that of industrial wastewater ranges between 100 to 10,000 mg/L depending on the type of industry (UNEP, 2020). The generation of industrial wastewater is a result of the industrial water use (Metcalf and Eddy, 2014). Water is necessary in almost every industrial production stage, ranging from food, paper, and chemicals, among other production processes (Metcalf and Eddy, 2014). This water gets contaminated along the production process and generates the so-called industrial wastewater containing contaminants, which, if inadequately managed cause negatively impacts to the public and environmental health (Metcalf and Eddy, 2014). Industrial contaminants should be removed from the wastewater to an acceptable level before discharging it into the environment (Metcalf and Eddy, 2014). Industrial wastewater characteristics vary appreciably from one industry to the other since they have very distinct product requirements and thus different processes resulting into different chemical compositions (Metcalf and Eddy, 2014). Typical industrial wastewater contains Total Suspended (TSS), fats, oils, grease, pH, bacteria, selenium, heavy metals, BOD, COD(Metcalf and Eddy, 2014). Negative environmental impacts associated with inadequate release, and treatment of industrial wastewater is kills of fish and other faunal species (UNEP *et al.*, 2022).

Another problem in the WIO region is the contribution of industrial effluent to eutrophication and sedimentation in the nearshore environment (UNEP, 2015). The majority of industries in Comoros deal with the processing of agricultural and livestock products. However, it has been determined that their influence on coastal pollution is modest compared to household wastewater (UNEP, 2021).

On the Kenyan coast, most industries are located in the counties of Mombasa, Kilifi, and Lamu. Few of them treat their wastewater and majority release their untreated effluents into stormwater drains or municipal sewage systems (UNEP, 2021).

The majority of industries in Madagascar are concentrated in coastal urban areas, particularly close to the ports of Antsiranana, Ambilobe, Mahajanga, Tolagnaro, and Toamasina. These industries primarily focus on processing of seafood, extraction of sugar, production of oil and soap production, breweries, tanneries, and sisal production (UNEP, 2021). Previous studies identified that the wastewater generated and faecal sludge from many of these enterprises is not adequately treated (UNEP 2021).

In Mauritius, the three main industrial areas are Plaine Lauzun, Vacoas-Phoenix, and Coromandel. Breweries and food processing facilities, textile and sugar processing facilities are the most common sources of effluent discharge to the municipal wastewater treatment plants (UNEP, 2021). Some factories that produce sugar release waste materials directly into rivers and canals that empty into shallow coastal areas (UNEP, 2021).

The majority of Mozambique's industrial facilities, which include textile, paper, and manufacturers as well as a brewery, are situated in the coastal cities of Maputo, Matola, and Beira. In Maputo, most people release untreated sewage into the River Infulene, which empties into Maputo Bay (UNEP, 2021).

Industries most likely to be involved in Seychelle's marine pollution are those dealing with food and chemical industries. Additional industries that significantly pollute the island's estuary waterways include canning and brewing (UNEP, 2021).

Untreated waste from the slaughterhouse, fish markets, and tanneries is dumped into the sea in Somalia (UNEP, 2021). An estimated 722,151 m^3 of industrial wastewater is released into marine or estuary waters each day in South Africa, mostly in the bigger metropolitan coastal centres such as Durban and Richards Bay (UNEP, 2021).

In Tanzania, about 80% of its industries are found in Dar es Salaam (Machiwa, 2010). The beaches of the city are the hub of tourism, as well as hotel, and hospitality industry. Pollutants from industries enter the Dar es Salaam maritime environment through streams, sewers, and stormwater outfalls (Mremi and Machiwa, 2003). Pollution hotspots are noted along Dar es Salaam shoreline from Msimbazi Creek to Mzinga Creek (Machiwa, 2010). A sizable percentage of the city's industrial and residential areas are drained by the River Msimbazi. At the same time, industries located along Nyerere, Morogoro, and Mandela Roads discharge waste into the Mzinga and Msimbazi Rivers.

Several activities have been reported to significantly contribute to the effects of marine pollution on the mangrove and seagrass ecosystems (UNEP, 2020). An unintentional oil spill in Kenya's Port Reitz Creek in 2005 completely damaged almost 200 acres of mangroves (UNEP, 2015). In Mombasa (Kenya), the same problem was observed, resulting in mangrove death, and the effects are still valid ten years after the last oil spill accident (UNEP, 2021). In South Africa, oil pollution is dominant in estuaries in large cities such as Richards Bay (UNEP, 2015).

2.2.3 Hospital Wastewater

Hospital wastewater is characterized by a variety of new contaminants, such as pharmaceutically active compounds, several microorganisms such as bacteria with antibiotic resistance genes, persistent viruses etc. (Lien *et al.*, 2016). Compared to domestic wastewater, hospital wastewater frequently has greater quantities of biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia, and nitrogen (Verlicchi *et al.*, 2015; Tchobanoglous *et al.*, 2003).

Hospital wastewater is more difficult to treat using the conventional biological wastewater treatment technologies because it has a lower biodegradability index than municipal wastewater (Tchobanoglous *et al.*, 2003). There is a significant risk to the environment from many of the refractory organic compounds (humic substances and natural organic matter-(NOM) and, dissolved Carbon) found in hospital wastewater because they are highly hazardous-viruses, antibiotic-resistant bacteria antibiotic-resistant genes, as well as persistent viruses continue to exist after wastewater treatment, and their discharge into the aquatic ecosystem results in a serious threat to the environment (Majumder *et al*. 2019).

The removal of contaminants from hospital wastewater varies greatly depending upon the chemicals used, operating conditions, and the type of treatment technology (Benjamin *et al.*, 2013). The presence of pharmaceuticals and personal care products (PCPs) in the hospital wastewater (Daughton and Ternes, 1999) is of growing environmental concern. PCPs pose risks to aquatic life associated with their exposure to water and the risks to humans when they reach drinking water sources (AfDB, *et al.*, 2020).

In developing countries, particularly in Africa, the information on the occurrence of pharmaceuticals in the environment is very scarce (K'oreje *et al.*, 2016). Hospital wastewater in Africa has not been the subject of enough research, therefore anonymous information on its characteristics and treatment has been provided (AfDB *et al.*, 2020). According to the studies from South Africa, hospitals produce large amounts of wastewater, ranging from 362 to 745 litres per occupied bed per day (This wastewater contains high levels of organic matter, pathogens, and heavy metals like copper, chromium, lead, cadmium, mercury, nickel, and zinc (AfDB *et al*., 2020; UNEP *et al*., 2020) Selected medicines were found in wastewater, surface water, bio-solids, and sediments along the Umgeni River in KwaZulu-Natal, South Africa (Matongo *et al*., 2015).

2.2.4 Stormwater

Stormwater is a non-domestic source that carries pollutants from yards and agricultural areas as well as trash and other contaminants from streets. Nitrogen, chloride, copper, zinc, manganese, nickel, cadmium, pathogens, oil, and grease are the typical pollutants in stormwater (AfDB *et al*., 2020). If absorbed into the soil, these toxins can affect the quality of soil, groundwater and runoff generated from the metropolitan areas causing a detrimental effect on the water quality in aquatic habitats downstream.

Tanzania's coast including Zanzibar and some beaches in Dar es Salaam (*e.g.* Ocean Road and Banda beaches) have been shut down for swimming and other recreational activities due to the microbial contamination detected at these sites (UNEP *et al*., 2021). The extent of microbial contamination along urbanized coastal beaches is high during the rainy season, demonstrating the impact of sewage and urban runoff contamination (UNEP *et al*., 2021).

The nutrients from terrestrial agricultural areas including those entering the rivers through storm runoff play a significant role into the eutrophication. Nutrients input to the Rivers draining the Madagascan Highlands are a vital cause of nutrients intrusion to the coast. The application of fertilizers causes nutrient enrichment, leading to eutrophication (UNEP *et al*., 2021). In Mauritius, eutrophication is common, particularly in Port Louis, where coral mortality is dominant (UNEP *et al*., 2021).

2.3 Pollutants of Concern in Municipal Wastewater Treatment

In municipal wastewater treatment, pollutants of concern (PCs) include pharmaceuticals, illicit substances, and personal-care-products. Preservatives, sunscreen ingredients, plasticizers, stimulants, anti-bacterial compound, anticancer agents, analgesics, lipid regulators, metabolites, hypertension, and antidepressants (UNEP 2002). The PCs are widely distributed in the aquatic environment and mostly arise from the discharges of municipal wastewater (UNEP, 2002).

Due to their potential negative impacts of endocrine disruption on the environment's biota, their existence is of concern. The detection of PCs in wastewater is currently not adequately undertaken due to the limited analytical capacity The challenges associated with the limited analytical capacity cause various PCs to enter wastewater treatment works (WWTWs) without being quantified. . Additionally, sludge can serve as a medium for the determination of concentrations of compounds during wastewater treatment, but analytical capacity for sludge properties is also limited.

2.4 Wastewater Management Systems in the Western Indian Ocean Region

2.4.1 Sewerage System

A network of pipes and accessories known as a sewerage system, sometimes known as a wastewater collection system, is used to transport sewage from its place of origin to the point of treatment and disposal. The system has been divided into the combined system and separate system with centralized or decentralized locations. With the exception of Madagascar and the Comoros, both systems are used in WIO regions. Most of the countries using centralized sewerage systems are South Africa (47%), Mauritius (25%), Kenya (11%), Seychelles (8%), Mozambique (5%) and Tanzania (2%) (Kitheka, 2007).

Systems that carry a mixture of both domestic sewage and storm sewage are called combined sewers. Combined sewers typically consist of large-diameter pipes or tunnels because of the large volumes of stormwater that must be carried during wet-weather periods (Metcalf and Eddy, 2014). They are widespread in older cities but are no longer designed and built as part of new sewerage facilities. As such, combined sewers are not being implemented in the growing and urbanizing cities of the WIO region. During rainy weather, stormwater must be discharged directly into the receiving waterbodies. For instance, runoff in Mombasa enters the Indian Ocean without passing through the Kipevu wastewater treatment plant (Figure 2.1).

Combined sewer overflows containing untreated domestic sewage cause recurring water pollution problems and serves as troublesome sources of water pollution (Metcalf and Eddy, 2014). In some large cities globally, the combined sewer overflow problem has been reduced by diverting the first flush of combined sewage into a large basin or underground tunnels (Vyamazal, 2011). It can be temporarily stored and then treated by settling and disinfecting before being discharged into a receiving waterbody or treated in a nearby wastewater treatment plant at a rate that will not overload the facility (Vyamazal, 2011). However, no experience has reported with these systems in WIO region.

The design of modern wastewater collection facilities makes it possible to transport either domestic sewage or storm runoff, but not both (Metcalf and Eddy, 2014). Surface runoff is typically transported by drainage channels to a

Figure 2.1: Stormwater bypassing the Kipevu wastewater treatment plant in Mombasa draining directly into the Indian Ocean.

suitable point where it is disposed-off in a stream or river. Small detention basins may be constructed as a part of the system to temporarily store stormwater and reduce the peak flow rate. Sanitary sewers, on the other hand, transport domestic wastewater to a sewage treatment facility. Stormwater excludes industrial wastewater and is sometimes permitted to enter the municipal sewerage systems. Interceptors are usually built with precast sections of reinforced concrete pipe, up to 5 meters (15 feet) in diameter (Metcalf and Eddy, 2014).

Sanitary sewers can be constructed by vitrified clay, asbestos cement, plastic, steel, or ductile iron (Metcalf and Eddy, 2014). Because it is lightweight and simple to install, plastic is increasingly used for lateral sewers. Pipes made of iron and steel are utilized in pumping stations or as force mains. When sewage needs to be pushed, force mains are pipelines that transport it under pressure.

In Mauritius, general wastewater collection methods consist of centralized public sewer networks in the more urbanized parts of the country and onsite disposal systems consisting of either individual cesspit or septic tanks followed by absorption systems (UNEP, 2002). Communal onsite disposal systems consist of sewer network draining to communal septic tanks followed by absorption systems (UNEP, 2002). Most houses are equipped with flush-cistern toilets (UNEP, 2002). All sewer systems in Mauritius operate as separate systems, *i.e.*, they are designed to carry only wastewater and not stormwater.

2.4.2 Faecal Sludge Management (FSM)

Faecal sludge is the slurry that contains solid and liquid waste and accumulates in onsite containment systems, *e.g*, septic tanks and pit latrines (Strande *et al.*, 2014). It also contains substantial amounts of grease, grit, hair, debris, and harmful germs, as well as scum, effluent, and sludge with an unpleasant odor (Strande *et al.*, 2014). All these facilities—septic tanks, dry latrines, bucket latrines, public restrooms, and others accumulate faecal sludge that must be regularly removed upon filling (Strande *et al.*, 2014). When the origin of the faecal sludge is a septic tank, often it is referred to as septage. If faecal sludge is inadequately managed, it may negatively impact the environment and public health (Strauss, 2002).

Proper management of faecal sludge includes adequate desludging of sanitation facilities, safe handling, collection, transport, treatment, and safe disposal or reuse of treated septage (Strande *et al.*, 2014). Faecal sludge differs from wastewater as it contains a higher concentration of contaminants having a direct impact on the efficiency of the system (Strande *et al.*, 2014). Compared to wastewater, FS typically contains more solids and is more pathogen- and inorganic-substance-rich material (Strande *et al.*, 2014). Additionally, the FS characteristics of various worksite sanitation technologies and system management types vary greatly. The type of toilet, its design and construction, its application, method of FS collection and frequency of FS collection, all have an impact on the quantity of FS treated and collected (Strauss, 2002).

Collection: It is the safe removal of faecal sludge from onsite containment systems. In urban areas, different situations prevail that facilitate or restrict septage collection from septic tanks. There is a variety of onsite sanitation systems in urban/ small towns and cities where the rate of faecal sludge generation will vary and thus influence the collection.

Transportation: It is taking the faecal sludge from the source to the treatment facility. Most commonly desludging trucks, mounted tractors, and vacuum trucks are used to collect the faecal sludge. Most WIO region except Mauritius and Morocco uses desludging truck of $10m^3$.

Treatment: Faecal sludge can be treated in various ways that are best suitable for the region. There are numerous solutions that can be appropriately selected considering factors like cost and reusability. The quality and quantity of faecal sludge desludged from onsite containment affects the treatment option selection. Land application, involving deep row entrenchment, natural treatment options, dewatering and composting with solid waste are some standards and easily adaptable treatment options. In Mauritius, Picket Fence and Belt Thickener, Anaerobic Sludge Digestion and Centrifugal Sludge Dewatering are used to treat primary and secondary sludge (UNEP, 2007).

Disposal/reuse: The humus produced after composting can be used as a soil conditioner, and faecal sludge can also be used as an energy resource. However, the use of sludge as a soil conditioner should be done with caution after treatment to sanitize it, and reduce the disease causing micrororganisms to safe levels. In Mauritius, all the sludge produced in wastewater treatment plants is disposed of in a landfill at Mare Chicose (UNEP, 2007).

2.4.3 Storm Water Management System

Stormwater comprises rainfall and snowmelt that seeps into the ground or runs off the land into storm drains, streams, and lakes. Additionally, runoff from washing automobiles, draining pools and watering lawns, may be included (UNEP, 2007). In a natural area, such as forest and agricultural land, stormwater infiltrates into the soil and is absorbed by the plants/ crops. In urban environments with buildings and roadways, most stormwater ends up as runoff and needs to be managed. The goals of managing stormwater include protecting the environment, reducing the floods, protecting people and their properties, reducing demand on the public stormwater drainage system, supporting healthy streams and rivers, and creating healthier and more sustainable communities.

Globally, important infrastructure, such as stormwater drainage networks, have come under pressure from urbanization and rising development, frequently because of flash floods and blocked drainage systems. Runoff is accelerated by the giant structures, roadways, parking lots, and other impervious surfaces and becomes problematic. In most of the coastal cities around the world, stormwater is gathered, transported, and released into nearby streams before being released into the sea using gutters, drains, pipelines, and other structures (Armitage *et al.*, 2013).

Stormwater management in the urban areas of South Africa has and continues to predominantly focus on collecting runoff and channelling it to the nearest watercourse. They currently prioritize quantity (flow) management with little emphasis on preserving the water. In Mauritius, most town centres, their immediate suburbs, and some localities have been provided with the road drains that discharge surface water into 25 major and 21 minor rivers in the Central Plateau and flow radially to the sea (UNEP, 2007).

Except for the central business district of Nairobi, where there is a partial combined sewer system. Stormwater management in Kenya involves stormwater drainage systems that emptying into nearby streams (RoK, 2008). In Seychelles, the stormwater is directed through lateral drainage systems located adjacent to the roads towards the main drainage into the ocean. The area is closer to the ocean, which experiences periodic coastal floods (Government of Seychelles, 2016).

2.5 Wastewater Treatment Technologies in WIO Region

There is no one-size-fits-all approach to wastewater treatment due to the large local variation in metropolitan settings. A combination of centralized and decentralized, small- and large-scale, on- and off-site wastewater treatment facilities may be necessary to meet the sanitation needs of urban people in WIO regions (URT, 2018). To safeguard the environment and public health, it is recommended that wastewater generated from a variety of sources must be treated either onsite or offsite before being disposed-of in the designated places (MoHCDGEC, 2015).

2.5.1 Onsite Technology

Systems that treat wastewater onsite, including those that temporarily store wastes onsite, are referred to as "onsite systems". In these systems, the waste material normally decomposes to some extent (Yates, 2011). Before being returned to the receiving environment, onsite (or decentralized) wastewater treatment systems treat the wastewater from a home or company. They are situated close to the area where the wastewater is produced. Examples of onsite sanitation methods include traditional pit latrines, ventilated improved pit (VIP) latrines, composting latrines, septic tanks with or without soak away pits, and sea outfall pipes (Sangeu and Enock, 2007). Onsite wastewater treatment solution includes decentralized septic tank systems or anaerobic reactor systems (MoHCDGEC, 2015).

Onsite wastewater treatment is frequently employed when housing density is so low that centralized wastewater treatment is not economically feasible. Additionally, because of the resource and technological constraints, it is used in locations where centralized wastewater treatment facilities are not in place (Yates, 2011). Due to increasing urbanization, these systems are rapidly approaching their physical and environmental impact limits. This highlights the need for and efficient Faecal Sludge Management (FSM) and increased efforts to develop wastewater treatment technologies that reduce faecal sludge formation (URT, 2018). Onsite wastewater treatment systems strive to reduce the levels of contaminants to acceptable levels before the treated waste reaches water supplies or encounters people (Yates, 2011).

In Mauritius, individual onsite disposal systems are used by 75% of the population in rural areas; cesspits are used by 70%, septic tanks by 23%, and pit latrines by 2% (UNEP, 2007). This is because water supply pipes are present in more than 99% of the residential buildings in Mauritius (UNEP, 2007).

2.5.2 Offsite Technology

Offsite treatment is the processing of wastewater that has been transported through a sewage system (Metcalf and Eddy, 2014). Large volumes of wastewater are often treated in offsite of centralized systems, which use either standard gravity or pumping sewers (Metcalf and Eddy, 2014). Waste stabilization ponds, lagoons, land-based treatment (sewage farming) and constructed wetlands are some examples of the mostly used offsite wastewater treatment technologies in WIO region (URT, 2018).The offsite system is intended to serve the vast majority of the entire neighbourhood (URT, 2018). These are publicly owned and maintained wastewater treatment infrastructure because they are normally built for the general public; and as a result, the sewer network is a part of the system (Tilley *et al.*, 2008).

In WIO region, most large-scale offsite treatment is accomplished in centralized wastewater treatment plants (Kayombo *et al.*, 1998). For instance, in Tanzania seven out of 19 coastal districts have sewer system with centralized sewage treatment plants (Sangeu and Enock, 2007). Except for Tanga, Zanzibar and a small area of Dar es Salaam, all municipal wastewater is generally treated in waste stabilization ponds (Sangeu and Enock, 2007). Sewer networks are usually not connected to industrial areas to collect industrial wastewater. Finding the areas with the highest demand for connections and building more lateral sewers appears to be the immediate need for the existing systems to increase the numbers of new customers. As wastewater treatment systems normally finally discharge into receiving environments such as land or water bodies, it is necessary to regularly monitor the quality of the effluents exiting these system (Sangeu and Enock, 2007).

Based on the National Reports only few urban areas in WIO Region have been served by sewerage system (UNEP, 2007). In the region, cities and towns along the coast are typically only partially sewered. The proportion of the population served ranges from a small percentage to 18% in a very few cases. The regional synthesis on the usage of the sewerage systems for wastewater collection indicates that, in South Africa, the majority of the towns and cities are installed with sewerage system for wastewater collection (UNEP, 2007). A large percentage of the population in Seychelles and Mauritius lives in sewered areas. In Tanzania and Kenya, the percentage of the population served by sewers is very low and hence large population still relies on the use of onsite sanitation (Mwaguni, 2007; Sangeu, 2007). With the exception of Seychelles, Mauritius and South Africa, the sewerage systems in Tanzania, Kenya and Mozambique either discharge their wastewater to the poorly working treatment plants or discharge untreated sewage directly into the ocean (UNEP, 2007).

The use of networked sewers in the WIO region countries is very low compared to on site sanitation facilities (UNEP, 2007). For example, In Mozambique, Maputo is the only city with a central sewage system for collection and treatment of domestic sewage. However, it is estimated that only 50% of Maputo's sewage is treated (Buuren and Heide, 1995). For the WIO region, the annual average estimated volume of wastewater generated from the population using the sewerage system in the region is 64,788,772 m^3/year. The value is estimated based on the assumption that each person per year discharges 55m^3 as wastewater through the sewer (UNEP, 2007). If the whole population in the WIO region were connected to the sewerage system, then the total amount of wastewater generated would be 2,686,488,794 m^3/year from a population of 48,845,251 people for the year 2007.

Domestic wastewater treatment infrastructure used for wastewater treatment in the region includes conventional (Activated sludge systems etc.) and non-conventional (Waste stabilization ponds) systems. In Dar es Salaam, Tanzania nine sets of WSPs were installed and have a total area of 23.2 hectares and overall volume of 304,376 m^3 for wastewater collected from a part of Dar es Salaam City (Mgana, 2003). In Mombasa, Kenya, Aerated/biological oxidation sewage treatment plants were installed for domestic wastewater treatment. However, the treatment plant is not properly working due to management and operational problems. Hence raw sewage from Mombasa town is discharged directly into the ocean (UNEP, 2007). Some of the hotels in Mombasa have installed their wastewater treatment plants to avoid disposal of raw wastewater into the ocean (UNEP, 2007).

There are about 19 wastewater treatment plants in Mauritius for domestic and industrial wastewater. The type of treatment is usually biological with either activated sludge process or Rotating Biological Contractor (RBC) followed by re-use through irrigation. The total number of the sanitation and treatment plants includes septic tanks, conventional plants, and leaching fields. There are about 45 large hotels located along the coastal zone of Mauritius that possess their own wastewater treatment plants and treat their wastewater for irrigation of their golf courses and lawns. The volume of domestic wastewater treated in private treatment facilities, such as hotels, is about 5,000 m^3 per day.

There are 26 treatment plants in Seychelles used for treatment of domestic sewage from residential houses and hotels. Twenty-one treatment plants including, activated sludge systems (8 treatment plants), Bio-Disc (9 treatment plants), waste stabilization ponds (only one), Sequencing Batch Reactor (SBR) (one treatment plant), Upflow Anaerobic Sludge Blanket (UASB) (one treatment plant) and fixed film (one treatment plant) are installed in the hotels for wastewater treatment. There are five treatment plants used to treat wastewater generated from the community. The treatment plant installed for domestic wastewater treatment includes three activated sludge systems and two bio-discs.

In South Africa there are over 60 licensed pipelines discharging effluent along the South African coast (UNEP, 2007): one third discharge domestic sewage - about 66 million liters per day (66 ML/d), half discharge industrial wastes (230 ML/d), and the remainder discharge mixed effluent (360 ML/d). The types of technologies used are as follows; activated sludge systems, Biological rotating discs, waste stabilization ponds, upflow anaerobic sludge blanket, and biological fixed films (UNEP, 2007). The source of information for this aspect would indicate that treatment plants had been recently built and there are no data on their performance.

In Mozambique, the treatment plants consist of a series of anaerobic and facultative tanks, which are designed to treat organic matter (Buuren and Heide, 1995). The treatment plant was designed to treat sewage from 50% of the population of Maputo. The treatment plant is no longer functioning due to operational and maintenance problems (UNEP, 2007).

2.5.3 Reuse Technology

Due to limits to non-renewable resources availability, the world is pushing towards a circular society, a paradigm shift where waste is turned into something useful. Municipal or industrial wastewater can be converted into some useful products (Strande *et al*., 2014). The reuse of products takes various forms; for example, involve refilling surface and groundwater supplies or irrigation of gardens and agricultural areas (Andersson *et al*., 2016). Reusing the treated wastewater in irrigation is practiced in Mauritius and is limited to urban and industrial sewage (Radhay, 2007). Although the treated sewage is now being injected into boreholes for disposal, the quality of the treated effluent achieved is far superior to what is needed for irrigation. Additionally, 20 plants in South Africa use wastewater reuse as wastewater treatment technology (AfDB *et al*., 2020). In Tanzania and Kenya, the modern-day design of wastewater and faecal sludge treatment facilities mandatorily factor in the reuse aspect. The newly published design manual for water supply and sanitation projects famously dubbed as DCOM has consistently provided guidance for the design of sanitation resources recovery and re-use (MOW, 2020).

Reuse of treated wastewater in agriculture in Mauritius is presently limited to urban and industrial wastewater from the Plaines Wilhems District being treated to the tertiary level at the

St. Martin wastewater treatment plant (WWTP) and sold to the Irrigation Authority for irrigation of sugarcane fields in the western part of the island (UNEP, 2007). Nature based solution including CW technology presents a significant

2.6 Wastewater Treatment Challenges and Impacts in WIO Region

Various challenges exist which preclude the attainment of safe and adequate wastewater and faecal sludge treatment. The below are the factors usually cited to be the major challenges to a proper and effective wastewater management in the WIO region (UNEP *et al*., 2021).

2.6.1 Poor Urban Planning

Most of the WIO region countries are unplanned. For example, in Dar es Salaam, Tanzania, about 70% of its population lives in unplanned areas (Msuya, Moshi, and Levira, 2021). This presents a significant challenge in terms of services provision including wastewater and faecal sludge treatment (NBS, 2022). Due to the uncontrolled and rapidly urbanized expansion, the supply of utility services in most of the coastal zones is insufficiently and unsatisfactorily low (UNEP, 2022). It has reached a tipping point where the service demands have surpassed the supply, particularly in the residential sectors. The urban expansion has steadily continued to increase despite the due considerations for adequate services provision. Due to poor urban planning and inadequate land space availability, most wastewater and sanitation agencies are unable to provide wastewater and faecal sludge treatment facilities at a scale. The capability of the local authority has not kept up with the rate of population expansion and urbanization. Many of the previously available social services don't appear to be improved or increased to suit the urbanization and population expansion along the coast. CW technology as nature-based solution is a promising solution in resource constrained and poorly planned areas reminiscent of the WIO region urban and city areas.

2.6.2 Capital Investment Requirements

Given their low-income levels, the selection of technologies to serve urban residents' is heavily influenced by the capital expenditure in the various wastewater technology alternatives. The cost of conventional wastewater infrastructure is prohibitive when other socioeconomic and development considerations by the Local Authorities are considered. Price is therefore one of the key considerations when choosing these technologies. This may help to explain why pit latrines which are less expensive to construct even though the majority are used by more than 80% of the coastal communities. Given the investment intensive nature of wastewater treatment plants, most of urban utilities are unable to invest in wastewater treatment facilities meaningfully and wisely. CW technology is probably suited to address this particular wastewater challenge in the WIO region.

2.6.3 Attitude and Socio-cultural Barrier

Social factors are crucial when choosing a wastewater treatment option. A particular wastewater technological option may be appropriate in one particular context but inappropriately unacceptable in another due to the cultural attitudes partly arising from the perceived nature of high investment cost. This factor can be regarded to have considerably contributed to Dar es Salaam's situation of limited adoption of ecosan toilets. CW technology with multiple benefits including low cost can be a good fit and a choice of wastewater treatment in the WIO region.

2.6.4 Low Public Awareness

The success of a technology is heavily reliant on its feasibility in the short, medium and long time use. This also depends on how quickly new customers can be added to the base. A rise in public awareness could lead to a project that is profitable and has a stable customer base. The size of operations on sewage projects has a cumulative effect on the cost reduction if proper campaigns are launched from the start of the project. The uptake of CW technology has been unbearably low due to low public awareness because of its limited performance experience in WIO region. This book is an attempt to raise the CW technology profile.

2.6.5 Insufficient Attention in Selecting the Appropriate Technology

Over years, the appropriateness, affordability, and sustainability of the water supply and sanitation technology selection have not always been the primary considerations in any given context. Lack of care in choosing the best water supply and sanitation technology has resulted in high capital and operating expenses, unaffordable consumer charges, limited sustainability, and lack of consumer or community acceptance. Various performance and economic viability research have indicated that, CW technology has an economic edge and superiority over most of the conventional wastewater treatment technologies.

2.7 Concluding Remarks

The wastewater and faecal sludge management sector is still an issue of concern given inadequate investment. The wastewater and faecal sludge services are generally low. The existing conventional wastewater and faecal sludge treatment technologies have literally failed and this situation is likely to remain so in the near future. Consequently, there is a need for innovative and new approaches to sustainably and adequately address the wastewater and faecal sludge treatment in the WIO region. The CW technology as nature-based solution offers a promising solution to this effect. The adaptation and thus the application of this CW technology at scale, can significantly contribute to the attainment and achievement of SDGs 2030 and AU Agenda 2063.

2.8 References

AfDB, UNEP and GRID-Arendal. (2020). Sanitation and Wastewater Atlas of Africa. AfDB, UNEP and GRID-Arendal. Abidjan, Nairobi and Arenda

Armitage, N., Vice, M., Fisher-Jeffes, L., Winter, K., Spiegel, A., and Dunstan, J. (2013). Alternative technology for stormwater management: The South African guidelines for sustainable drainage systems. Report TT, 558, 13.

Blair, B. D., Crago, J. P., Hedman, C. J., and Klaper, R. D. (2013). Pharmaceuticals and personal care products found in the Great Lakes above concentrations of environmental concern. Chemosphere, 93(9), 2116-2123.

Daughton, C. G., and Ternes, T. A. (1999). Pharmaceuticals and personal care products in the environment: agents of subtle change?. Environmental health perspectives, 107(suppl 6), 907-938.

Doglas, B., Kimwaga, R., and Mayo, A. (2021). Variability of faecal sludge characteristics and its implication for dewaterability across different on-site sanitation containments in unplanned settlements in Dar es Salaam, Tanzania. *Water Practice & Technology*, 16(4), 1182-1193.

Government of Seychelles. (2016). Flood management control. Striving for resilience in the face of climate change.

Harris, L.R., Sink, K.J., Skowno, A.L. and Van Niekerk, L. (eds). 2019. South African National Biodiversity Assessment 2018: Technical Report. Volume 5: Coast. South African National Biodiversity Institute, Pretoria. *http://hdl.handle.net/20.500.12143/6374*

Kayombo, S., Mbwette, T., Mayo, A., Katima, J., and Jorgensen, S. (1998). Waste stabilization ponds in Tanzania. Operation and Maintenance. The proceedings of the international sysmposiym on engineering research partnership for sustainable development, University of Dar es Salaam, Tanzania.

Kitheka, J. U. (2007). WIO International Waters projects Workshop Governance, Institutions and Partnerships for IW Management in the Western Indian Ocean.

Kitheka, J. U. (2015). Municipal wastewater management in the western Indian ocean region.

Klingel, F., Montangero, A., Koné, D., and Strauss, M. (2002). Faecal sludge management in developing countries. A planning manual. EAWAG: Swiss Federal Institute for Environmental Science and Technology SANDEC: Department for Water and Sanitation in Developing Countries.

K'oreje, K. O., Vergeynst, L., Ombaka, D., De Wispelaere, P., Okoth, M., Van Langenhove, H., and Demeestere, K. (2016). Occurrence patterns of pharmaceutical residues in wastewater, surface water and groundwater of Nairobi and Kisumu city, Kenya. Chemosphere, 149, 238-244.

Lien, L. T. Q., Hoa, N. Q., Chuc, N. T. K., Thoa, N. T. M., Phuc, H. D., Diwan, V., ... and Lundborg, C. S. (2016). Antibiotics in wastewater of a rural and an urban hospital before and after wastewater treatment, and the relationship with antibiotic use—a one year study from Vietnam. *International Journal of Environmental Research and Public Health*, 13(6), 588.

Machiwa, J. F. (2010). Coastal marine pollution in Dar es Salaam (Tanzania) relative to recommended environmental quality targets for the Western Indian Ocean. *Western Indian Ocean Journal of Marine Science*, 9(1), 17-30.

Majumder, A., Gupta, B., and Gupta, A. K. (2019). Pharmaceutically active compounds in aqueous environment: a status, toxicity and insights of remediation. *Environmental research*, 176, 108542.

Matongo, S., Birungi, G., Moodley, B., and Ndungu, P. (2015). Occurrence of selected pharmaceuticals in water and sediment of Umgeni River, KwaZulu-Natal, South Africa. *Environmental Science and Pollution Research*, 22, 10298-10308.

Metcalf & Eddy, Abu-Orf, M., Bowden, G., Burton, F. L., Pfrang, W., Stensel, H. D., ... and AECOM (Firm). (2014). Wastewater engineering: treatment and resource recovery. McGraw Hill Education.

Mgana, S. M. (2003). Towards sustainable and robust on-site domestic wastewater treatment for all citizens. Wageningen University and Research.

MoHCDGEC. (2015). the National Guidelines for Water, Sanitation and Hygiene in Health Care Facilities. The United Republic of Tanzania Ministry. Ministry of Health, Community Development, Gender, Elderly and Children, (October), 1–121.

MoW. (2020). Design, Conctruction Supervision, Operation & Maintenance (DCOM) Manual. Design of Sanitation Projects. In Mkuki na Nyota. The United Republic of Tanzania. Ministry of Water (MoW).

Mremi, S. D., and Machiwa, J. F. (2003). Heavy metal contamination of mangrove sediments and the associated biota in Dar es Salaam, Tanzania. *Tanzania Journal of Science*, 29(1), 61-76.

Msuya, I., Moshi, I., and Levira, F. (2021). Dar es Salaam : the unplanned urban sprawl threatening neighbourhood sustainability. (March).

Mwaguni, Saeed. (2007). Report on the status of Municipal wastewater management in Kenya, Coast Development Authority, Kenya

Republic of South Africa, Department of Environmental Affairs (RSA DEA) 2016. Review of all coastal discharges authorised prior to the Integrated Coastal Management Act (No 24 of 2008). Draft Report. Cape Town, South Africa.

Ridhay, Jacques A. (2007). Report on the status of Municipal wastewater management in Mauritius, Wastewater Management Authority,

RoK (Republic of Kenya). (2008). Ministry of Water and Irrigation Draft Practice Manual for Sewerage and Sanitation Services in Kenya

Rosemarin, A., Andersson, K., Trimmer, C., & Dickin, S. (2016). Sanitation, wastewater management and sustainability: From waste disposal to resource recovery.

Sangeu, M., and Enock, J. (2007). THE UNITED REPUBLIC OF TANZANIA MUNICIPAL WASTEWATER MANAGEMENT IN by. (October), 136.

Strande, L., Ronteltap, M., & Brdjanovic, D. (2014). Faecal Sludge Management: Systems Approach for Implementation and Operation. 403.

Tchobanoglus, G., Burton, F., and Stensel, H. D. (2003). Wastewater engineering: treatment and reuse. *American Water Works Association. Journal*, 95(5), 201.

Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., & Schertenleib, R. (2008). Compendium of Sanitation Systems and Technologies. Development, 158.

Ubomba-Jaswa, E., and Kalebaila, N. (2020). Framing the plastic pollution problem within the water quality-health nexus: Current understandings and policy recommendations. *South African Journal of Science*, 116(5-6), 1-3.

UNEP, (2002). Draft Regional 'State-of-the-Art' Report on Municipal Wastewater Management in the WIO –Lab Region contributed by Sixtus Kayombo, UNEP-GEF WIO-LaB Project addressing Land Based activities in The Western Indian Ocean

UNEP, Nairobi Convention and International Maritime Organization. (2020). Regional oil spill preparedness in eastern African and the western Indian Ocean. Workshop Report – 3 to 5 March 2020. (*https://www.nairobiconvention.org/clearinghouse/node/476*)

UNEP, Nairobi Convention Secretariat, CSIR and WIOMSA (2009). Towards a Protocol for long-term monitoring of marine environmental quality in the Western Indian Ocean.UNEP, Nairobi, Kenya, 86 pp.

UNEP-GEF WIO-LaB PROJECT. (2007). National Report on Status of Municipal Wastewater Management in Mauritius

UNEP-Nairobi Convention and WIOMSA (2015). The Regional State of the Coast Report: Western Indian Ocean. UNEP and WIOMSA, Nairobi, Kenya, 546 pp.

UNITED NATIONS ENVIRONMENT PROGRAMME, NAIROBI CONVENTION SECRETARIAT AND COUNCIL FOR SCIENTIFIC & INDUSTRIAL RESEARCH. 2021. Western Indian Ocean: Situation Assessment on Marine Pollution and Coastal & Marine Water Quality Management. UNEP, Nairobi, Kenya, 61 pp.

United Nations Environment Programme, Nairobi Convention Secretariat and Council for Scientific and Industrial Research. 2022. Western Indian Ocean: Guidelines for Setting Water and Sediment Quality Targets for Coastal and Marine areas. UNEP, Nairobi, Kenya. XXIV + 109 pp +

United Republic of Tanzania. (2018). Guidelines for the Application of Small-Scale, Decentralised Wastewater Treatment Systems - A Code of Practice for Decision Makers. (December), 16.

Van Buuren, J. C. L., and van der Heide, J. (1995). Abatement of the Water Pollution in the Infulene Basin. Final Report of the Infulene Water Quality Management Project, 1991-1994.

Verlicchi, P., Al Aukidy, M., and Zambello, E. (2015). What have we learned from worldwide experiences on the management and treatment of hospital effluent?—An overview and a discussion on perspectives. *Science of the Total Environment*, 514, 467-491.

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: five decades of experience. *Environmental science & technology*, 45(1), 61-69.

Yates, M. V. (2011). On-site wastewater treatment. *Encyclopedia of Environmental Health*, 256.

This page is intentionally blank

Chapter 3: Introduction to Constructed Wetlands

By Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

As previously described, constructed wetlands technology has been widely acknowledged and applied as an alternative to the conventional wastewater and faecal sludge treatment method. The interest and application of CW for wastewater and FS treatment have gained considerable global and regional attention and popularity largely due to its multiple benefits including circularity. This chapter presents the concepts, types, design, and operational principles as well the pollutants removal mechanisms of constructed wetlands. Grossly, the chapter sets out the stepping stone for other proceedings chapters in terms of application of the CW technology in wastewater and FS treatment.

3.1 Understanding the Paradigm Shift towards Constructed Wetland as a Nature-Based Solution.

Almost all the world's major cities and urban centres including those of the WIO regions' have gone in to the 21st Century facing the coastal and marine pollution crisis (UN-HABITAT, 2008). The WIOs cities not only face the challenge of supplying sustainable, safe and adequate sanitation facilities to its residents (Figure 3.1) but must also ensuring that their coastal and marine ecosystems are protected from anthropogenic pollution (UN-HABITAT, 2008). The discharge of untreated and partially treated wastewater and faecal sludge is a growing concern that contributes to the deterioration of both public health and the environment comprising air, land and water systems (UNEP *et al*., 2021a). The problem is projected to maintain an upward trajectory largely due to the rapid rate of urbanization in WIO region (UNEP *et al*., 2021a).

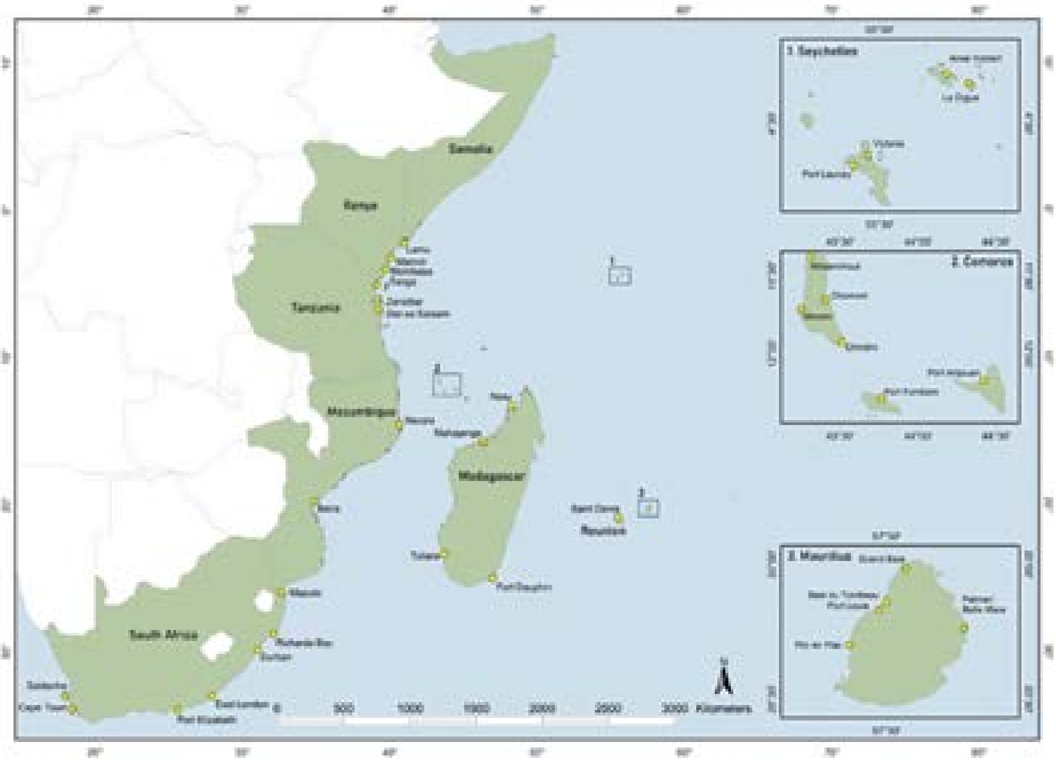


Figure 3.1: Hotspots' of marine pollution (major coastal urban cities) in the WIO region (Source: UNEP et al. 2009c)

Over years, the conventional wastewater and faecal sludge treatment methods including centralized, water-based sewer systems have been widely and intensively applied to comprehensively realize the public and environmental health benefits in urban areas of industrialized countries (Metacalf and Eddy, 2004). However, barriers to their global widespread application and adaptation includes high investment and operational and maintenance costs, which make them unaffordable to many developing countries (UN-HABITAT, 2008). Centralized wastewater treatment systems are repeatedly documented to be energy intensive, which are technologically complex and financially expensive, particularly for many communities of the developing countries (UN-HABITAT, 2008). Besides, these systems are generally described to have been pushed to the linear model of waste management systems (Nika *et al.*, 2020), which involves a one way flow of resources, discarding them as waste at the end of the pipe. In this regard, a paradigm shift to green approaches and solutions including constructed wetlands technology which promote the circularity in water systems has gained and increased much global attention (Nika *et al.*, 2020). Wetland systems are increasingly recognized as the green solution to the wastewater and faecal sludge management-related problems (UNEP, 2021a).

Wetland treatment systems use either the natural wetlands (NW) or constructed wetlands (CW) for wastewater and faecal sludge treatment. For more than 100 years, wetlands have been used as convenient wastewater discharge sites in some regions around the world (Vymazal and Lenka, 2008; Kadlec and Wallace, 2009). The application of CW technology is relatively recent in WIO region since it dates back to just about two decades (Nyakang'o and van Bruggen 1999, Mbwette *et al*., 2002 and Abira *et al*., 2005). Globally, an awareness of the wastewater purification potential of wetlands began to emerge nearly five decades ago (Seidel, 1976). Since then, significant scientific advances have been made in the engineering knowledge of CW that can closely imitate the specialized treatment functions which occur in the natural wetland ecosystems (Vymazal and Lenka, 2008). Many advantages such as simplicity of design and lower installation, operation, and maintenance costs offered by CW make them an appropriate alternative for both developed and developing countries (Nyakang'o and van Bruggen 1999, Mbwette *et al*., 2002, Kimwaga *et al*., 2003, Abira *et al*., 2005 and Vymazal and Lenka, 2008,).

CWs for wastewater treatment are engineered systems that are designed, constructed, and operated in order to use all applicable natural processes involved in the removal of pollutants from wastewaters (Vymazal, 1998; Kadlec *et al*., 2000). CWs are designed to take advantage of many of the same processes that occur in natural wetlands but do so within a more controlled environment. As the term suggests, CW are man-made wetlands artificially developed in the areas where they do not occur naturally (Vymazal, 1998; Kadlec *et al*., 2000). The development of CW may be necessitated by one or more of the following reasons (Sundaravadivel. and Vigneswaran, 2001):

- Constructed habitat wetlands. The reason is to create wetland habitats to compensate and offset the rate of conversion of natural wetlands resulting from agricultural and urban development, and hence to conserve native flora and fauna including aquatic plants, fish, waterbirds, reptiles, amphibians and invertebrates.
- Constructed flood control wetlands. The purpose of construction is to act as flood control facilities.
- Constructed aquaculture wetlands. The main objective is to be used for production of food and fibre; and
- Constructed treatment wetland (which is the focus of this book). The purpose is to be used for the treatment of a wastewater and faecal sludge thereby improving the water quality. In this book, constructed treatment wetlands will be used interchangeably with constructed wetlands to mean the same thing.

Despite CWs being developed in many parts of the world for various functions, their wastewater treatment capabilities potentials have attracted the attention of researchers for a wide range of treatment applications including domestic wastewater, urban stormwater, industrial/agricultural flows, landfill leachates, acid mine drainage, etc. (Vymazal and Lenka, 2008).

Structurally, a CW is a shallow basin filled with a substrate acting as plant growing media as well as filtering material for the wastewater. The most used substrates include sand or gravel, although there are other substrate materials *e.g.* pebbles, clays etc. which are planted with the vegetation tolerant of saturated conditions (Sundaravadivel and Vigneswaran, 2001, Mwegoha *et al.*, 2002). Wastewater is introduced into the basin and flows either over or under the substrate surface through the substrate and is discharged out of the basin through a structure which controls the depth of the wastewater in the wetland (Sundaravadivel and Vigneswaran, 2001).

3.2 Concept of Nature-Based Solution

As the modern society is transitioning and embarking into an era of sustainable development, new concepts, tools, and approaches are being explored for the efficient and minimal utilization of the world's precious and valuable resources (Nika *et al.*, 2020). Overall, the world is heading towards ensuring sustainable growth and development. Water is one of the most precious and essential resources for ensuring the sustainable development since it is critical for human well-being, social economic development, and vital ecosystem services (UNEP *et al.*, 2009c; IWA, 2016; Arup *et al.*, 2018). Over the years, water development and utilization have been pushed into a linear model, which is increasingly acknowledged of causing cumulative emissions of pollutants, waste stocks, and impacting on the irreversible deterioration of water and other resources (Nika *et al.*, 2020). Moving towards a circular model in the water sector, the configuration of future water infrastructure changes through the integration of grey infrastructure together with blue and green infrastructure, forming Nature-based Solutions (NBS) as an integral component that connects human-managed to nature-managed water systems (Nika *et al.*, 2020).

The transition to circular water systems requires the redesign of water infrastructure, utilization of recent technological developments and integration of nature-based ecosystems offering blue and green infrastructure as alternatives to the grey infrastructure (*i.e.* hybrid infrastructure) (O'Hogain and McCarton, 2018). Existing concepts and approaches using and enhancing nature protection, such as ecosystem-based adaptation (EbA), Blue-Green infrastructure (BGI), ecosystem services (ESS) and nature-based solutions ((Nika *et al.*, 2020), have gained momentum as they tackle challenges (*e.g.* climate mitigation and adaptation, water management, degradation and loss of natural capital, disaster risk reduction, etc.) in a more sustainable way, compared to the conventional hard engineering.

While all four concepts share the common principle of multi-functionality, NBS can be considered as an umbrella to the other concepts with a strong solution-oriented focus and biodiversity lying at its core (Pauleit *et al.,* 2017). Up to date, several definitions have been applied to describe NBS, *e.g.* the definitions provided by EC, 2015; Cohen-Shacham *et al.*, (2016); Raymond ***et al***. (2017); O'Hogain and McCarton (2018); and Langergraber *et al.*, (2020). According to them, NBS should be cost-effective, resource efficient and locally adapted. NBSs are systemic interventions that bring more, and more diverse, nature and natural features and processes (Nika *et al.*, 2020).

They address either a specific problem (*i.e.* societal challenge) or multiple challenges and simultaneously provide environmental, social and economic benefits, such as biodiversity, climate change mitigation and adaptation, resilience, human well-being etc. (Nika *et al.*, 2020). While circular economy (CE) seeks to reduce environmental stress of socio-economic activities, NBSs have the potential to enhance environmental and ecological status and to address human demand for natural resources (Nika *et al.*, 2020). NBSs can restore the crucial natural processes – by changing the fluxes of water, sediment, nutrients, and pollutants – that drive the water cycle and thus, return the circularity to the water systems (Nika *et al.*, 2020). NBS are also capable of resources' recovery from water, like nutrients, which fits in the natural water and nutrients cycles facilitating the transition from open to closed loops (Nika *et al.*, 2020). Therefore, the synergies fostered between the two concepts bring NBSs to the forefront of enabling the realization of circular water systems (Nika *et al.*, 2020).

Nature-based solutions such as green roofs, rain gardens, or constructed wetlands can minimize damaging runoff by absorbing stormwater, reducing flood risks, and safeguarding freshwater ecosystems (Zuñiga, 2020). More generally, 'nature-based solutions' is a term that can be used to describe alternative and non-traditional approaches to environmental issues, like flooding, water scarcity, or soil erosion, by harnessing natural capital (Zuñiga, 2020). Whilst the traditional method in infrastructural development is 'grey' – involving constructed and artificial structures – nature-based solutions encompass natural, green, and integrated infrastructure, which combines elements of all three (Zuñiga, 2020).

Nature-based solutions disengage with the construction of seawalls, reservoirs, dams, and drainage systems that grey infrastructures approach would take for certain climate risks (O'Hogain and McCarton, 2018). Instead, nature-based solutions could include, restoring and conserving coral reefs and mangrove belts to enhance the resilience to coastal flooding and sea level rise, acting as a first line of defence to help dissipate wave energy; upsloping vegetation to reduce the risks of landslides; and creating permeable green areas to help replenish groundwater in regions facing water scarcity (O'Hogain and McCarton, 2018).

Nature-based solutions directly address a potentially unsustainable over-reliance on grey infrastructure (O'Hogain and McCarton, 2018). The issue with grey infrastructure is two-fold – it is reliant on the use of often unrecyclable and finite resources *e.g.* ***cement, iron bars etc***, and it is often temporary. As climate risks increase and intensify, grey solutions will need to be improved or replaced. Nature-based solutions also need to be maintained and sometimes restored, but not to the same extent, so can be more versatile than their grey counterparts (O'Hogain and McCarton, 2018). By maintaining and replenishing natural elements, projects that integrate nature-based solutions help to conserve the environment, create habitats for endangered species, lower carbon emissions, and restore an aesthetic natural beauty to communities (O'Hogain and McCarton, 2018). Nature-based Solutions (NBSs) are gaining popularity and importance as solutions that integrate societal challenges and nature conservation across scales and landscapes. Arguably, constructed and natural wetlands are at the epicenter of NBSs (O'Hogain and McCarton, 2018)

3.3 Advantages of Constructed Wetland Systems

Overview

In the WIO region, CW technology enjoys much of the comparative advantages compared to other wastewater and faecal sludge treatment technologies in terms of treatment performance as well as energy efficiency (Nyakang'o and Bruggen 1999, Mbwette *et al.*, 2002, Abira *et al.*, 2005, Senzia *et al.*, 2003, Batchelor, 2003, Kimwaga *et al.*, 2004). Since its initial 'discovery', efforts to harness and develop the natural treatment ability of wetland systems have been undertaken by both government and private researchers around the world (Vymazal *et al.*, 1998, Kadlec *et al.*, 2000, Vymazal and Lenka, 2008, Kadlec and Wallace, 2008, Mburu *et al.*, 2019). Constructed treatment wetlands offer effective and reliable treatment to wastewater in a simple and inexpensive manner. Constructed wetlands are a cost-effective and technically feasible approach for treating wastewater and runoff for several reasons:

Major advantages of CTWs include (Vymazal *et al.*, 1998; Sundaravadivel and Vigneswaran (2001)):

- They operate on ambient solar energy and require low external energy input;

- They achieve high levels of treatment with little or no maintenance, making them especially appropriate in locations where no infrastructure support exists;
- They are relatively tolerant to shock hydraulic and pollutant loads that ensures the reliability of treated wastewater quality;
- No specific design life period is generally prescribed for CWs and as such they tend to have increased treatment capacity over time, by setting up feedback loops that result in self repairing systems;
- Wetland vegetation generate oxygen and consume carbon dioxide, thereby help improving air quality and fight global warming;
- Wetland vegetation provides indirect benefits such as green space, wildlife habitats, and recreational and educational areas;
- Wetalnds have considerable considerable buffering capacity and so are able to tolerate fluctuations in flow;
- CWs aesthetically enhance spaces, and gain favour from the public that is sympathetic to eco- and sustainable developments;
- CWs reduce the impacts posed by humans on environment

3.4 Limitations of Constructed Wetland Systems

Compared to energy intensive wastewater and faecal sludge treatment systems, CW almost without exception, will require a larger land area for implementation (Sundaravadivel and Vigneswaran (2001)). CWs are economical relative to other options, only where land is available and affordable. CW performance varies seasonally in response to changing environmental conditions, including rainfall and drought (Vymazal *et al.*, 1998; Kadlec *et al.*, 2000; Vymazal and Lenka, 2008; Kadlec and Wallace, 2008).

For the WIO region countries most of which are located within the tropical climate belt, the tropical conditions play a major role in mitigating some of the short comings related to climate-influenced performance (Mbwette *et al.*, 2002). While the average performance over the year may be acceptable, CW treatment cannot be entirely relied upon, if their effluent quality can't comply with the standards for effluent discharge (Sundaravadivel. and Vigneswaran (2001). The biological transformations brought about by CW vegetation and microbial communities, are sensitive to toxic chemicals, such as ammonia and pesticides (Sundaravadivel. and Vigneswaran (2001). Flushes of pollutants or shock loadings may temporarily reduce the effectiveness of the wetland treatment system (Table 3.1).

Table 3.1 : Effect of Pollutant Loading on Wetland Processes (Source: DLWC 1998b)

Pollutant	Primary Effect	Secondary Effect
Organic Matter	Decomposition consumes oxygen in the water column, leading to anaerobic conditions	Reversal of many pollutant removal processes
Nutrients	Eutrophication leading to algal blooms	Reversal of many pollutant removal processes, potential toxin accumulation in water and sediments, dead algae increase BOD through decomposition.
Sediments	Blanketing of plants and biofilms	Reduced biological processes
Toxins	Kills or harms biota	Reduced biological processes, bioaccumulation and biomagnification.

Mosquito breeding can be a problem for surface flow wetlands and for clogged subsurface CW particularly when it is overloaded organically (Kimwaga *et al.*, 2004). In overloaded CW systems, anaerobic conditions develop and thus malodours become an issue (Sundaravadivel and Vigneswaran (2001). To better address the incidence of such occurrences, actions such as pretreatment to reduce total organic loading, step feeding of the influent wastewater stream with effective influent distribution and effluent recycle, and vegetation management have been the common practice (Sundaravadivel and Vigneswaran 2001; Senzia *et al.*, 2002; Kimwaga *et al*, 2004). In general, natural controls are preferred because human-made control agents may result in developing resistance in disease vectors such as the mosquito (Wieder, 1989).

As with any other biological wastewater treatment system, the process rates and thus the treatment performances are dependent upon various factors such as temperature, pH, oxygen availability, hydraulic and pollutant loads (nitrogen and nutrients concentration) (Cooper 2003; Vymazal and Lenka, 2008). The chemical and biological processes are specifically prone to changes in environmental factors. Under some environmental conditions, process rates may slow down cease altogether, or even reverse, releasing pollutants. Biological activities in the rhizosphere and in the biofilms are particularly sensitive (Mwegoha *et al.*, 2002; Vymazal and Lenka, 2008).

Generally, low temperatures have been observed to reduce biological activities because of decrease in metabolic activities (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). Consequently, the effectiveness of pollutant removal processes is reduced (Vymazal and Lenka, 2008 and Kadlec and Wallace, 2008). Many metabolic and chemical activities are also pH dependent and are less effective if pH is too high or too low (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008).

The treatment capacity of CW is limited also by the hydraulic and pollutant loading rates (Mwegoha *et al*., 2002; Kimwaga *et al*., 2002; Kimwaga *et al*., 2004). Hydraulic overloading occurs when the flow exceeds the design capacity, thus reducing the actual hydraulic retention time. Pollutant overload or simply organic loading occurs when the influent pollutant loads exceed the process removal rates of the system (Vymazal *et al*., 1998). Other environmental factors, including excessive organic matter, nutrient or toxins, or lack of oxygen, also have effects on wetland processes (Table 3.1).

Depending on the size and design of CW, the salinity of water within wetlands can increase as the water levels drop, and the pollutants may become concentrated (Sundaravadivel and Vigneswaran (2001)). Subsequent high flows may flush pollutants from the CW systems and transport them to the discharging waterbodies further downstream.

As such, some of the limitations of CWs technology include (Sundaravadivel and Vigneswaran (2001)):

- They require large land area for the same level of treatment by conventional systems making them unsuitable for centralized treatment for sources that generate large quantities of wastewater, such as large cities;
- They relatively require a longer period of time to establish, typically two or three growing seasons, for the vegetation before optimal treatment efficiencies are achieved;
- The process dynamics of the CW systems are highly variables, and are yet to be clearly understood leading to imprecise design and operating criteria;
- Fluctuations in the environmental factors may affect the efficiency of the CW treatment system;
- CWs cannot be operated on actual wastewater from the start. Rather they require first operation on diluted wastewater followed by operating on stronger wastewater;
- These systems typically lie outdoor and spread over large area, their performance is susceptible to storm, wind, and floods;
- There are possibilities of problems due to mosquitoes and other pests and insects that may use these systems as their breeding grounds; and
- Steep topography and high-water table may also limit the adoption of these systems for wastewater treatment.

3.5 Types of Constructed Wetlands

Understanding of different types of CWs is a critical design factor. Different types of CWs behave differently and thus their design approaches are different (Vymazal, 2001). Numerous literatures have reported various types of CW (Vymazal *et al.*, 1998; Vymazal, 2001; Sundaravadivel and Vigneswaran, 2001; Kimwaga *et al.*, 2003; Kadlec and Wallace, 2008). Based on our long-term design and operational experience of CWs, there are, generally, two main criteria which are used to distinguish different types of CWs. The first criterion considers the wastewater flow level in CW, either above or below the macrophyte growing media and the direction of water and wastewater flow in CW. The second criterion considers the type of macrophytes. This sub-chapter discusses the various types of CW including their applications and limitations. The type of CW which is much more widely studied and applied than any other in the WIO region is the subsurface flow due to its performance versatility and effectiveness. These two different aspects are separately discussed in this book. The subsurface CW is more preferred than other types of CW because of its treatment effectiveness requiring less land and avoiding the mosquito breeding sites (Senzia *et al.*, 2002, Kimwaga *et al.*, 2003). Furthermore, the subsurface flow CW doesn't provide breeding grounds for mosquito (Senzia *et al.*, 2002; Kimwaga *et al.*, 2003).

3.5.1 Types of CW Based on Wastewater Level and Flow Direction.

Depending on the level of water column with respect to the substrate bed, CWs are generally classified into two broad categories as (Vymazal *et al.*, 1998; Kadlec and Wallace, 2008):

1. Free water surface flow (FWS) wetlands, and

2. Sub-surface flow (SSF) wetlands

3.5.1.1 Horizontal Surface Flow (HSF) Wetlands

In HSF wetlands (Figure 3.2), the substrate bed is densely vegetated, and the water column is above the surface of the bed (Vymazal *et al.*, 1998; Kadlec and Wallace, 2008).

Figure 3.2: Horizontal free water surface (Source: Vymazal et al., 1998, Kadlec and Wallace, 2008)

The surface flow systems are flooded and expose water surface in the system to the atmosphere. Plants predominantly grow on soil bed in these systems and the depth of water column is typically less than 0.4 m (Vymazal *et al.*, 1998; Kadlec and Wallace, 2008). Surface flow wetlands have much higher nutrients removal capacity through plant uptakes and volatilization process (Vymazal *et al.*, 1998; Senzia *et al.*, 2003; Kadlec and Wallace, 2008). This type of CW is highly unfavourable for the WIO region due to their potential mosquito breeding grounds.

3.5.1.2 Free Water Surface (FWS) Wetlands

These wetlands contain areas of open water, floating vegetation, and emergent plants, either by design or as an unavoidable consequence of the design configuration (Vymazal *et al.*, 1998; Kadlec and Wallace, 2008). Depending upon local regulations and soil conditions, berms, dikes, and liners can be used to control flow and infiltration. As the wastewater flows through the wetland, it is treated by the processes of sedimentation, filtration, oxidation, reduction, adsorption, and chemical precipitation through CW media (Vymazal *et al.*, 1998; Kadlec and Wallace, 2008). The components in a typical FWS wetland are shown in Figure 3.3.

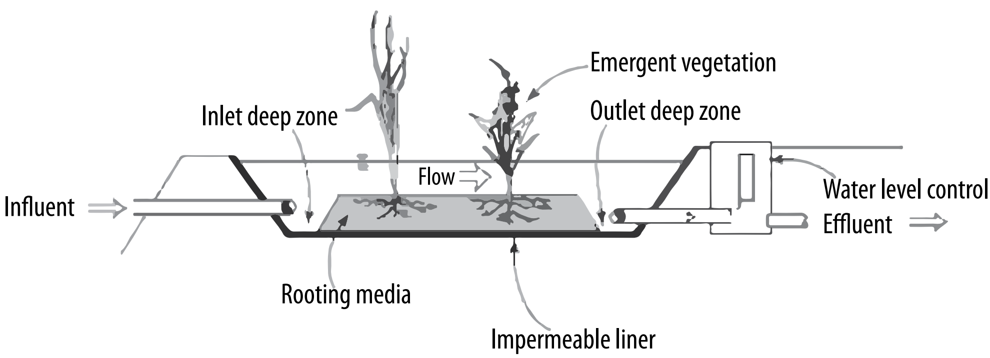


Figure 3.3: Basic elements of FWS wetland (Source: Kadlec and Wallace, 2008)

Because FWS CWs closely mimic natural wetlands, it should be no surprise that they attract a wide variety of wildlife, namely insects, mollusks, fish, amphibians, reptiles, birds, and mammals (NADB database, 1993; Kadlec and Knight, 1996). Because of the potential for human exposure to pathogens, FWS wetlands are rarely used for secondary treatment (U.S. EPA, 2000). The most common application for FWS wetlands is for advanced/tertiary treatment of effluent from secondary or tertiary treatment processes (*e.g.* lagoons, trickling filters, activated sludge systems, etc.). A typical application of a treatment process incorporating a FWS wetland is shown in Figure 3.4.

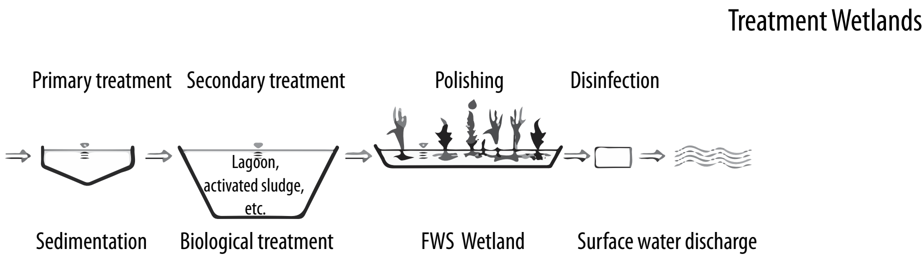


Figure 3.4: Typical application of FWS wetland for municipal wastewater treatment (Source: Wallace and Knight, 2006)

Operational and performance experience suggests that FWS wetlands are suitable for application in all climates, including the far north (Kadlec and Wallace, 2008; Vymazal and Lenka, 2008). While the functionality and thus the performance of CW can be slowed down in cold climate regions, this may not be the case for WIO region where most of the countries are in the tropical climates (Mbwette *et al.*, 2002; Senzia *et al.*, 2003; Kaseva, 2004; Kimwaga *et al.*, 2004) However, surface flow CW have not found their wide application in WIO region due to their potential to cause of mosquito breeding (Mbwette *et al.*, 2002; Senzia *et al.*, 2003; Kaseva 2004; Kimwaga *et al.*, 2004). The WIO CW case studies presented in Chapter 10 of this book confirm that the type of the CW which has been in use in the WIO region is the sub-surface flow.

FWS systems can provide significant ancillary benefits, primarily in the form of human uses and wildlife habitat. Treatment marshes are not expensive but are usually capital cost-competitive with alternative technologies. Operating costs are typically quite low compared with the alternatives.

3.5.1.3 Subsurface Flow Constructed Wetlands

In SSF constructed wetlands, the water level is maintained below the surface of the substrate bed. The substrate medium in SSF wetlands is usually made of gravel to provide high void space to enable wastewater loaded on the bed to quickly seep through the bed. Soil-based SSF wetlands are also found in northern Europe (Kadlec, 1995). Depending on the direction of flow of applied wastewater, SSF wetlands can be either horizontal flow type or vertical flow type (Vymazal *et al.*, 1998).

3.5.1.3.1 Horizontal Subsurface Flow

In horizontal SSF systems (Figure 3.5), the substrate is maintained water-saturated through continuous application of wastewater. The bed depth of horizontal flow SSF wetlands which is the function of the root penetration depth, which in turn depends on the type of macrophyte, typically ranged from 0.6 m to 1 m (Vyamazal *et al.*, 1998; Kimwaga *et al.*, 2003). The bottom of the bed is sloped to minimize flow above the surface. The experience has shown the recommended slope range is from 0.5 to 1% (Vyamazal *et al.*, 1998).

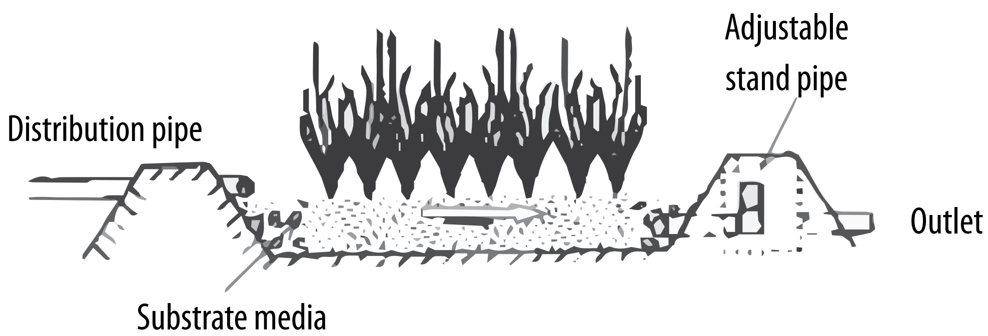


Figure 3.5: Horizontal flow subsurface CW (Source: Wallace and Knight, 2006)

HSSF constructed wetlands consist of gravel or soil beds planted with wetland vegetation. They are typically designed to treat primary effluent prior to either soil dispersal or surface water discharge (Vymazal., 1998; Kadlec and Wallace, 2008). The wastewater is intended to stay beneath the surface of the media and flows in and around the roots and rhizomes of the plants. Because the water is not exposed during the treatment process, the risk associated with human or wildlife exposure to pathogenic organisms is minimized (Knight *et al.*, 2001).

Properly operated HSSF constructed wetlands do not provide suitable habitat for mosquitoes (Mbwette *et al*., 2002). HSSF constructed wetland systems are generally more expensive than FWS wetlands, although maintenance costs remain low compared to the alternatives (Kadlec and Wallace, 2008). They are commonly used to treat wastewater for a variety of systems ranging from a single-family homes or small cluster systems (Wallace and Knight, 2006) to small and medium communities (Cooper *et al*., 1997). However, there are many other applications to special wastewaters from industry. In general, HSSF wetlands have been extensively utilized for smaller flow rates than FWS wetlands, probably due to low cost and space considerations (Crites and Tchobanoglous 1998; Wallace and Knight, 2006). HSSF constructed wetlands typically comprise the inlet piping network, clay or synthetic liner, filter media, emergent vegetation, berms, and outlet piping with water level control (Wallace and Knight, 2006).

A schematic of a conventional HSSF constructed wetland for warm climates is depicted in Figure 3.6. A typical application of a HSSF wetland for the treatment of domestic wastewater is shown in Figure 3.7.

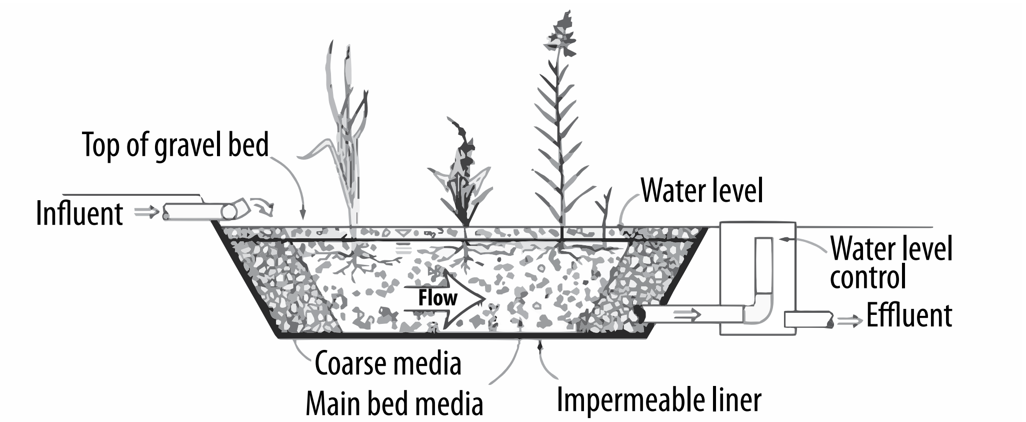


Figure 3.6: HSSF wetland schematic (Source: Wallace and Knight, 2006)

Figure 3.7: Application of a HSSF wetland to domestic wastewater treatment (Source: Wallace and Knight, 2006)

These systems can operate under colder conditions than FWS systems, because of their insulation ability on the top. A key operational consideration is the propensity for clogging of the media (Cooper, 1999; Vymazal and Lenka, 2008). HSSF constructed wetlands do not provide the same opportunities for ancillary benefits that FWS systems do. To address the clogging propensity, HSSF are normally preceded with pretreatment units such as WSP, dynamic roughing filters etc. The WIO regional experience of pretreatment units includes WSPs, Septic tanks, dynamic roughing filters (Senzia *et al.*, 2002; Kimwaga, *et al.*, 2004). HSSF CWs have found a widespread application of CW technology in the WIO region, mainly due to their well treatment performance records, reuse of treated products, handy and less land requirement, and avoidance of mosquito breeding sites (Mbwette *et al.*, 2002; Senzia *et al.*, 2002; Kimwaga *et al.*, 2004).

3.5.1.3.2 Vertical Subsurface Flow

In vertical SSF wetlands, wastewater is applied through different arrangement of wastewater feeding and collection mechanisms to maintain a vertical direction of flow. This is achieved either by intermittent wastewater application or by burying inlet pipes into the bed at a depth of 60 to 100 cm (Langergraber *et al.*, 2007) (Figure 3.8).

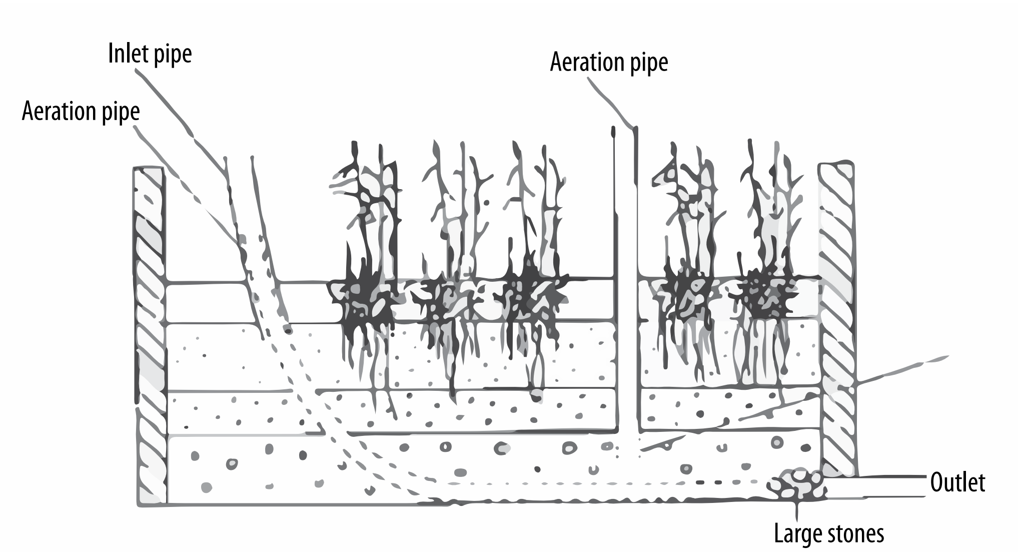


Figure 3.8:Vertical flow sub-surface CW (Source: Wallace and Knight, 2006)

The total bed depth is typically in the range of 2 to 3 m (*https://sswm.info/sites/default/files/reference_attachments/UN%20HABITAT%202008%20Constructed%20Wetlands%20Manual.pdf*). Since the wastewater infiltrates through the substrate bed, this type of wetlands are also called 'infiltration wetlands' (Langergraber *et al.*, 2007).

Several versions of VF constructed wetland exist. The most common type, used most often in Europe, employs surface flooding (pulse loading) of the bed in a single-pass configuration (Figure 3.9) (Langergraber *et al.*, 2007; Mburu *et al.*, 2019).

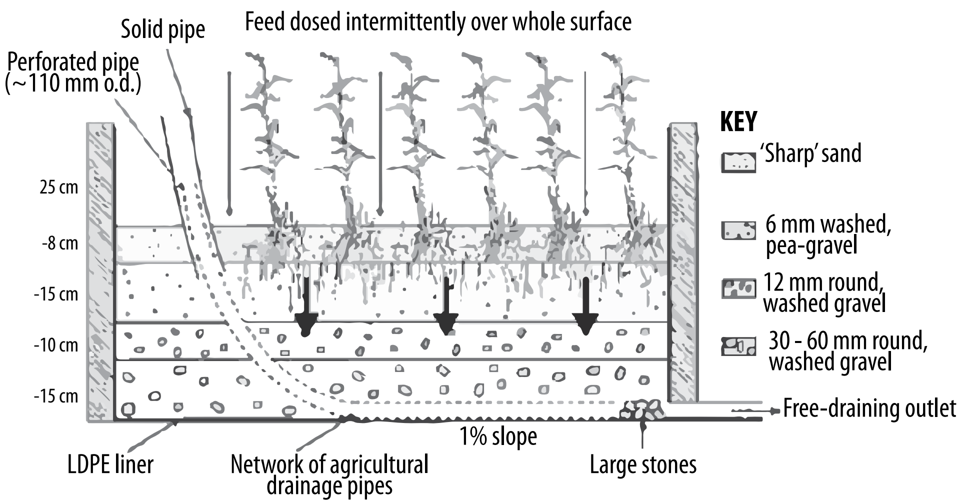


Figure 3.9: Typical arrangemet of a VF constructed wetland (Source: Cooper et al., 1997)

CV CWs systems are roughly analogous to the dosing scheme used in intermittent and filters. VF wetlands in North America have been designed as vegetated recirculating gravel filters (Lemon *et al.*, 1996). Up flow systems are known to minimize oxygen transfer and promote reductive dehalogenation (Kassenga *et al.*, 2004). The fill-and-drain (tidal flow) systems have been implemented, mainly in North America, to treat high-strength wastes and to oxidize ammonia (Behrends *et al.*, 1996; Austin and Lohan, 2005). In WIO region, VFWs were researched for the treatment of abbartoir wastewater in Nakuru, Kenya in order to understand the impacts of media depth and type on the treatment efficiency (Mburu *et al.*, 2019). The application experience of VFW in Nakuru is the first of its kind in the WIO region (Mburu *et al.*, 2019).

HSSF wetlands have a limited capacity to oxidize ammonia, because of limited oxygen transfer (Langergraber *et al.*, 2007). VF wetlands were developed in Europe to provide higher levels of oxygen transfer, thus producing a nitrified effluent (Langergraber *et al.*, 2007). The technology, initiated by Dr. Kathe Seidel in the early 1960s, became part of the Max Planck Institute Process (MPIP) (Brix, 1994). As described previously, the application experience of VFW is limited in WIO region. The body of literature has suggested that VFW are good at the removal of nitrogen laden wastewater (Langergraber *et al.*, 2007). This type of VF CW has neither been tested nor implemented in WIO region largely due to low chemical fertilizers application as compared to Europe and its stringent requirements in terms of operation and maintenance.

VF CW systems may be combined with HSSF or FWS CW to create nitrification-denitrification hybrid treatment systems (Figure 3.10; Cooper *et al.*, 1997).

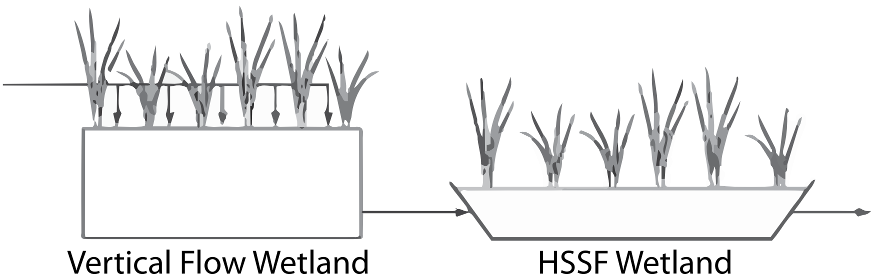


Figure 3.10: A hybrid wetland system (VF + HSSF) (Source: Wallace and Knight, 2006)

The ability of the VF to oxidize ammonia has resulted in their use in applications with higher ammonia than municipal or domestic wastewater. Landfill leachates and food processing wastewaters can have ammonia levels in the hundreds of milligrams per liter, and the key to reduction is the ability to nitrify. Successful VF wetlands therefore have formed part of the treatment process for those wastes (Burgoon *et al.*, 1999; Kadlec, 2003). Another variation of VF wetland relies upon exactly the opposite process: the use of overlying water to block oxygen transport, to create anaerobic conditions in the bottom bed sediments. A surface water pool on top of organics and limestone creates downflow into a zone with reducing conditions that fosters appropriate sulphur chemistry to immobilize metals (Younger *et al.*, 2002).

Highly concentrated wastewaters can be treated in VF systems. Unsettled raw sewage is added to VF wetlands in a French version of the technology (Molle *et al.*, 2005), and sludge from activated sludge plants may be dewatered in VF systems (Nielsen, 2005).

Biosolids dewatering wetlands consist of an enclosed basin with alternating filter layers, which trap organic biosolids on the surface of the wetland bed. Biosolids are applied to the surface of the wetland bed, and water percolates vertically down through the wetland bed primarily through mechanisms of unsaturated flow. Sludge dewatering systems target water removal and consolidation, rather than the elimination of dissolved constituents. Sludge dewatering beds consist of an enclosed basin with a sand layer underlain by drainage pipes.

The sand bed is planted with emergent wetland plants (typically *Phragmites*) and fed throughout the year in intervals with up to 20 cm of stabilized sewage sludge per loading (Barjenbruch *et al.*, 2002). Solids content is typically 35–40% after dewatering (De - Maeseneer, 1997). Higher solid contents may be effectively achieved, but this usually requires sacrificing the plants to drought stress (Nielsen, 1990).

In the WIO region, the application of VF-CW is limited and, in most cases, it has not been experienced majorly because of lack of performance data to warrant its adaptation or the need for its use. The vast majority of VFC is suited for wastewater with high ammonia level. VF-CW should find its application in WIO region. Other application limitations include difficult and costly maintenance of VF-CW systems because it involves excavation and other maintenance aspects.

3.5.2 Types of CW Based on Macrophytes (plants) Growth.

CW can also be classified based on type and nature of growth of the macrophytes (plants) in the system (Brix, 1993). Thus, CW can be:

- Free floating macrophyte systems;
- Submerged macrophyte systems; or
- Rooted emergent macrophyte systems.

3.5.2.1 Free Floating Macrophytes

These are the plant species that float on the surface of the water and do not require a substrate root media for their growth. Brix, (1993) reported that Algae, duckweed (*Lemna* sp.), water hyacinth (*Eichornia crassipes*), *M. aquaticum* and *Salvania* sp. are some of the floating macrophytes adapted for wastewater treatment as seen in Figure 3.11.

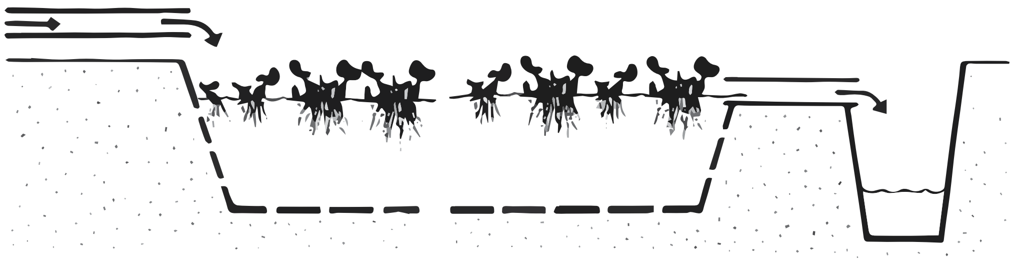


Figure 3.11: Schematic representation of a free-floating macrophyte-based wastewater treatment system (Brix, 1993)

3.5.2.2 Submerged Macrophyte Systems

These have plant species that are submerged in the water column and do protrude beyond the water surface. Further, Brix, (1993) noted that *Isoetes lacustris*, *Lobeliadortmanna*, *Egeria densa*, and *Elodea canadensis* are among the submerged aquatic plant species as seen in Figure 3.12.

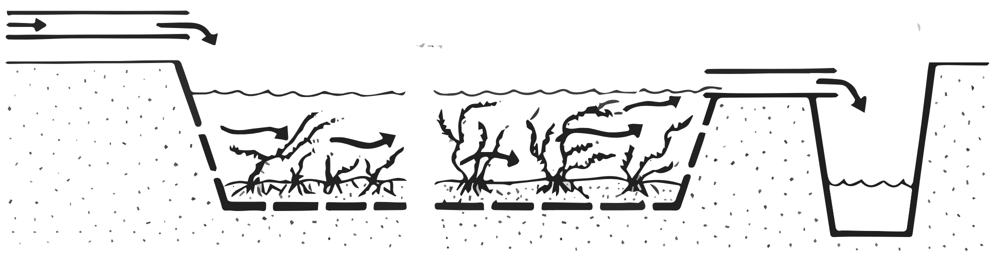


Figure 3.12: Schematic representation of a submerged macrophyte-based wastewater treatment system (Brix, 1993)

3.5.2.3 Rooted Emergent Macrophytes

These types of macrophytes also known as emergent macrophytes are plants that are generally attached to the substrate in the wetland with leaves extending above the water surface. Brix, (1993) documented that Reeds (*Phragmites* sp.), cattails (*Typha* sp.), bulrushes (*Scirpus* sp.) and sedges (*Carex* sp.) are common among the emergent aquatic plant species used in treatment wetlands (Figure 3.13). Unless specifically mentioned otherwise, wetland treatment systems mean constructed wetlands planted with rooted emergent macrophyte species.

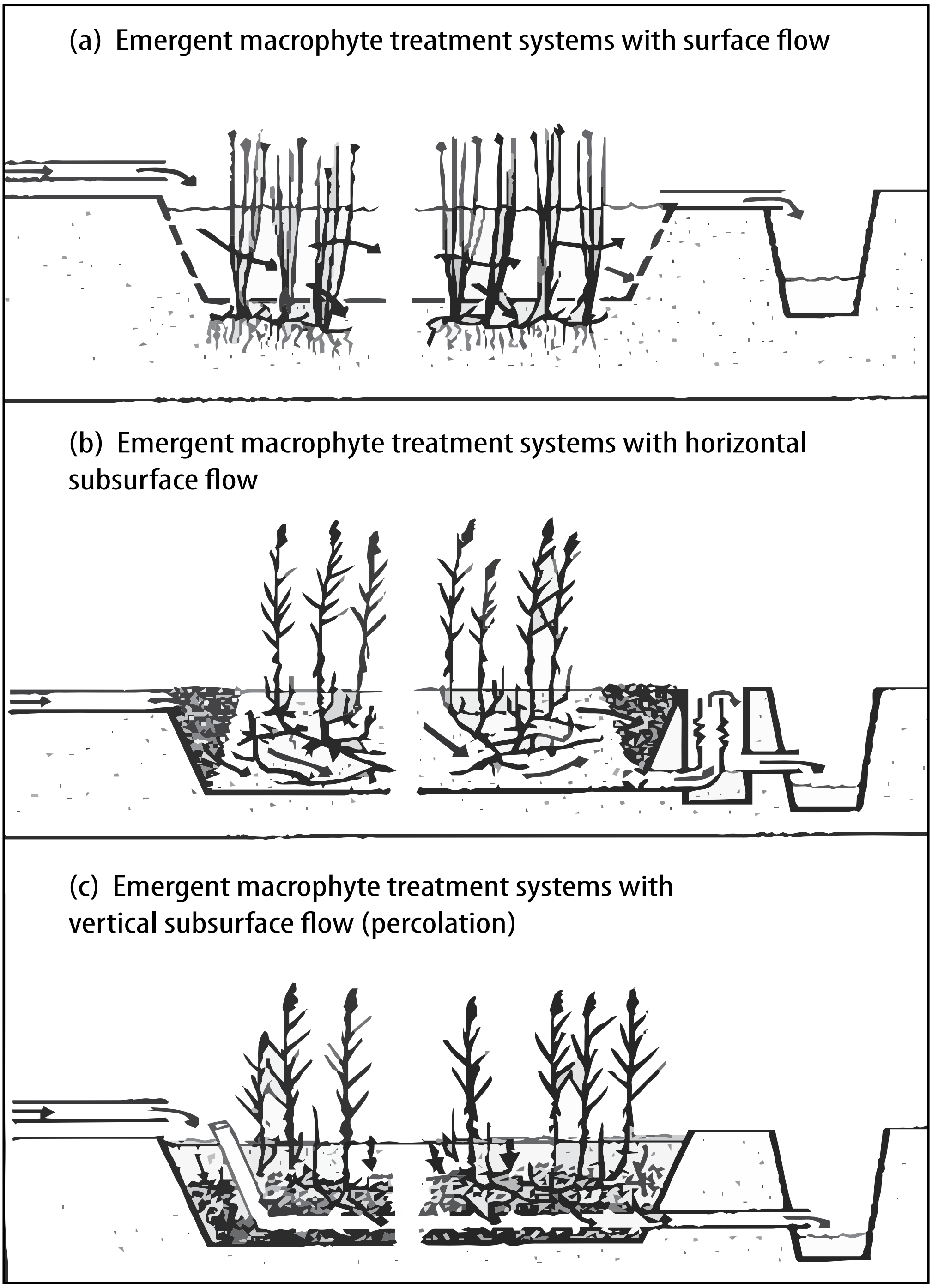


Figure 3.13: Schematic representation of emergent macrophyte-based wastewater treatment systems: a) system with surface flow, b) system with horizontal subsurface water flow, c) system with vertical subsurface water flow (Brix, 1993)

The emergent macrophytes have been mostly applied and adapted in the WIO region largely due to their easy local availability, high nutrient turns over, tolerance to a high loading rate and a high assemblage of microbial communities that enhance the conversion rate (Senzia *et al.*, 2002; Mwegoha *et al.*, 2002; Kimwaga *et al.*, 2004).

3.6 Pollutants Removal Mechanisms in Constructed Wetlands

- To be able to design, operate and maintain CW, an understanding of the pollutant removal mechanisms is imperative. These mechanisms provide the knowledge of CW behaviour which informs the design and hence the optimization of the treatment removal processes. Wastewater pollutants removal mechanisms have been comprehensively studied and are widely reported in a various studies (Vyamazal, 2001; Mwegoha *et al.*, 2002; Senzia *et al.*, 2003; Kimwaga *et al.*, 2004; Kadlec and Wallace 2008; Vymazal and Lenka, 2008; Mburu *et al.*, 2019). The pollutants removal mechanisms in CW have been studied and found to be accomplished through the following ways:direct uptake of pollutants by the plants;
- direct uptake of pollutants by the plants;
- degradation of pollutants by microorganisms attached to the plants and substrate media;
- sedimentation of solids due to the decreasing velocity of flow through CWs;
- filtering of large particles through root and reed masses;
- adsorption of nutrients (such as nitrates and phosphates) by soil and substrate media;
- wetland detention time allowing for natural die-off of pathogens;
- UV radiation and excretion of antibiotics by plants to destroy pathogens.

Pollutant removal mechanisms occur via a complex interaction involving CW vegetation, the water column, and the wetland substrate. Table 3.2 gives out the details of process types and the associated pollutants removed. The respective pollutants may be removed separately or by a combination of physical, chemical, or biological processes.

Table 3.2: Pollutant Removal Processes (Mitchell, 1996)

Pollutants removed	Processes
Organic material (measured as BOD)	Biological degradation, sedimentation, microbial uptake
Organic contaminants such as pesticides	Adsorption, volatilisation, photolysis and biotic/abiotic degradation
Suspended solids	Sedimentation, filtration
Nitrogen	Sedimentation, nitrification/denitrification, microbial uptake, plant uptake, volatilisation
Phosphorus	Sedimentation, filtration, adsorption, plant & microbial uptake
Pathogens	Natural die-off, sedimentation, filtration, predation, UV degradation, adsorption
Heavy metals	Sedimentation, adsorption, plant uptake

Physical Processes

The physical pollutant removal processes in CW systems occur through the combination of the plant biomass and substrate media factors (Vymazal *et al.*, 1998). Plants physically slow down the wastewater flow velocity enhancing sedimentation of suspended solids and particulate matter of organic and nutrient origin (Vyamazal, 2001; Mwegoha *et al.*, 2002; Senzia *et al.*, 2003; Kimwaga *et al.*, 2004; Kadlec and Wallace 2008; Vymazal and Lenka, 2008). The media (soil or gravel) acts as filter beds in filtration processes, thereby aiding the physical removal of suspended solids through straining (Vyamazal, 2001; Mwegoha *et al.*, 2002; Senzia *et al.*, 2003; Kimwaga *et al.*, 2004; Kadlec and Wallace 2008; Vymazal and Lenka, 2008).

3.6.1 Chemical Processes

Chemical reactions of various pollutants, particularly the metals, can lead to their precipitation from the water column as insoluble compounds (Vymazal *et al.*, 1998). Exposure to atmospheric gases and sunlight can lead to the breakdown of organic pesticides and destruction of pathogens. Antibiotic chemicals excreted by plants can also play a role in removal of pathogens present in wastewater (Vyamazal, 2001; Mwegoha *et al.*, 2002; Senzia *et al.*, 2003; Kimwaga *et al.*, 2004; Kadlec and Wallace 2008; Vymazal and Lenka, 2008).

3.6.2 Biological Processes

CW systems are biological systems in which biological processes play a major and critical role in the removal of pollutants (Vymazal, 2001; Mwegoha *et al*., 2002; Senzia *et al*., 2003; Kimwaga *et al*., 2004; Kadlec and Wallace 2008; Vymazal and Lenka, 2008). Six major biological reactions have been reported to facilitate the pollutant removal performance of CW systems (Mitchell, 1996). These are: photosynthesis, respiration, fermentation, nitrification, denitrification, and phosphorus removal (Vymazal, 2001, Mwegoha *et al*., 2002, Senzia *et al*., 2003, Kimwaga *et al*., 2004, Kadlec and Wallace 2008, Vymazal and Lenka 2008).

Photosynthesis is performed by wetland plants, which results in removal of organic carbon from the water column and addition of oxygen. Oxygen exhaled by plant leaves during photosynthesis may increase the partial pressure of oxygen in the atmosphere close to water surface, and hence enhance diffusion into water (Bedford *et al*., 1991). If floating or submerged plants are present, they will directly exhale oxygen into water.

During ***respiration***, micro-organisms utilize the leaked oxygen from pants hair for their metabolic activities (Vymazal *et al*., 1998). The oxygen leaking out through the root hairs of the plants into the surrounding water environment may create an oxygen-rich area around the rootzone (rhizosphere) of plants which could be easily and extensively utilized by the microbial communities. Hiley, (1995) reported that oxygen leaks help to maintain partial aerobic conditions in the water column.

Fermentation refers to the decomposition of organic carbon in the absence of oxygen with end products being energy-rich compounds like methane, alcohol, and volatile fatty acids. Fermentation is activated by the metabolic activities of microbial organisms present in the water column and the substrate media (Bedford *et al*., 1991).

Nitrification/denitrification are also microbial mediated processes which result into complete removal of the nitrogen from wastewater (Vyamazal, 2001; Senzia *et al*., 2003; Kadlec and Wallace 2008; Vymazal and Lenka 2008). While aiding biological degradation of organic pollutants, oxygen in combination with carbon, drives the nitrification process (Vyamazal, 2001; Mwegoha *et al*., 2002; Senzia *et al*., 2003; Kadlec and Wallace 2008; Vymazal and Lenka 2008). The chemical process of volatilization also contributes to nitrogen removal in the CW. Interplay of the aerobic and anaerobic environments that develop in the CW help to achieve nitrification and at the same time denitrification (Armstrong and Armstrong, 1988; (Vyamazal, 2001; Senzia *et al*., 2003, Kadlec and Wallace, 2008, Vymazal and Lenka, 2008).

Biological ***phosphorus removal*** occurs within biofilms that develop on the substrate and microorganisms present in sediments (Mwegoha *et al.*, 2002, Senzia *et al.*, 2003, Kadlec and Wallace, 2008, Vymazal and Lenka, 2008). Plants take up dissolved nutrients and other pollutants from water and convert them into additional plant biomass (Babaloki and Kimwaga, 2021). The nutrients and pollutants then move through the plant body to storage organs. When the plants age and die, these are deposited into the sediments as litter and peat.

Microorganisms present in the CW system, including bacteria, fungi, coagulate colloid material, stabilize, and remove dissolved and colloidal organic matter by converting them into various gases and new cell tissues (Bedford *et al.*, 1991). Many of the microorganisms in wetlands are the same as those occurring in conventional biological treatment systems (Bedford *et al.*, 1991).

3.7 Components of Constructed Treatment Wetlands

Wastewater treatment CW is composed of four functional elements and units including vegetation (macrophytes), soil or substrate (media) supporting vegetation growth, water column (in and above the substrate) and living organisms which all together make up the CW (Vymazal *et al.*, 1998). The detailed description of these components is presented in the next sections.

3.7.1 CW Vegetation/ Macrophytes

Principally, the basis for employing CW for wastewater treatment is the ability of the plants to translocate oxygen from air to their roots, and the surrounding water (wastewater, in case of treatment wetlands) environment (Brix, 1996; Brix, 1997; Haule *et al.*, 2002; Brix, 2003; Senzia *et al.*, 2003). Although several other pollutant removal processes have been well documented, the CW plants play a major role in the occurrence of most of these processes (Brix, 1996; Brix, 1997; Brix, 2003; Senzia *et al.*, 2003; Kimwaga *et al.*, 2004). Within the water column, the stems and leaves of the wetland plants significantly increase surface area for biofilm development (Brix, 1996; Brix, 1997; Brix, 2003; Senzia *et al.*, 2003). Plant tissues, moreover, are densely colonised by photosynthetic algae as well as by bacteria and protozoa. Likewise, the roots and rhizomes that are buried in the CW substrate provide for attached growth microorganisms (Brix, 1997). Major roles of vegetation in constructed treatment wetlands are summarized in Table 3.3.

Table 3.3: Major roles of macrophytes in constructed wetlands (Brix, 1997)

Wetland plant part	Role
Aerial plant tissues	• Light attenuation → reduced growth of phytoplanktons • Influence on microclimate →insulation during winter • Reduced wind velocity → reduced risk of resuspension of solids • Aesthetic appearance • Nutrient storage
Plant tissue in water	• Filtering effect → filter out large debris • Reduced current velocity → increased rate of sedimentation, reduced risk of resuspension • Surface area for attached microoorganisms • Excretion of photosynthetic oxygen →increased acrobic degradation • Nutrient uptake
Roots and rhizomes	• Stabilizing the sediment surface → less soil erosion • Prevents the medium form clogging in vertical flow systems • Release of oxygen increase organic degradation and nitrification • Nutrient uptake • Secretion of antibiotics for detoxification of root zone → pathogen removal

The contribution of CW vegetation for pollutant removal processes is brought about by five main factors, namely the type of wetland plant species which in turn influences the oxygen supply, plant physical effects, hydraulic conductivity, nutrient uptake and organic and antibiotic excretion (Brix, 1996; Vymazal *et al.*, 1998).

a. Wetland Plant Species

A wide variety of aquatic plants can be used in the CW systems designed for wastewater treatment (Tanner, 1996; Brix, 1996; 1997; Haule *et al.*, 2003). However, CW are planned as marsh-type wetlands and are planted with emergent macrophytes (rooted plants that anchor to the substrate media) and are adapted to water-dominated environment. Frequently used macrophytes species are cattails (*Typha* sp.), reeds (*Phragmites* sp.), bulrushes (*Scirpus* sp.), and sedges (*Carex* sp.) (Sundaravadivel and Vigneswaran, 2001). The general requirements and considerations for plants to suitably use in CW wastewater treatment systems include (Tanner, 1996, Brix, 1996; 1997, 2003):

- Ecological acceptability, that is, no significant weed or disease risks or danger to the ecological or genetic integrity of surrounding natural ecosystems;
- Tolerance to local climatic conditions, pests and diseases;
- Tolerance to pollutants and hypertrophic water-logged conditions;
- Ready propagation, and rapid establishment, spread and growth; and
- High pollutant removal capacity, either through direct assimilation, storage, or indirectly by enhancement of microbial transformations.

Specific requirements will vary depending on the functional role of CW plants in the treatment systems. This will be related to the type of wetland design and its mode of operation (continuous or batch), loading rate, and wastewater characteristics. Other ancillary objectives (such as ecological, aesthetic, recreational, and economic) of wetland developments may also affect the choice of the plants (Brix; 1996; Vymazal *et al*., 1998).

The physical presence of the CW vegetation distributes and reduces the wastewater flow velocities, which creates quiescent conditions for sedimentation of suspended solids (Kadlec and Wallace, 2008). Light attenuation by the wetland plants hinders the production of algae in water below the vegetation cover. The vegetation cover in a wetland can be regarded as a thick biofilm located between the atmosphere and the wetland soil or water surface in which significant gradients in different environmental parameters occur (Kadlec and Wallace, 2008). Wind velocities are reduced near the soil or water surface compared to the velocities above the vegetation, which reduces re-suspension of settled material and thereby improves the removal of suspended solids by sedimentation. In temperate areas, the plant cover provides insulation during winter and helps keep the substrate free of frost (Smith *et al*., 1997).

b. Oxygen Supply

Oxygen can be considered to cycle within wetlands (Armstrong, 1964, 1978). Oxygen enters via inflows or by diffusion at the water surface when the surface is turbulent (for example, due to wind mixing) (Armstrong, 1964, 1978; Armstrong *et al*., 1990). Oxygen is also produced within the water column during photosynthesis. It is well documented that aquatic macrophytes release oxygen from roots, which influences the biogeochemical cycles in the sediments due to the effects on the redox status of the sediments (Armstrong *et al*., 1990; Barko *et al*., 1991; Sorrel and Boon, 1992). Qualitatively, this is visualized by the reddish color associated with oxidized forms of iron on the surface of the roots (Vyamazal, 2001).

CW plants have not evolved new and novel structures for dealing with the environment where there is reduced oxygen availability for respiration, and lower light penetration and scarcity of carbon dioxide for photosynthesis. Rather they survive the harsh environment through many structural and physiological adaptations (Guntenspergen *et al.*, 1990). Formation of lacunae and/or are nchyma tissue is a characteristic feature of non-woody wetland plants that are commonly adopted in treatment wetlands. The lacunae or gas filled permeable aernenchyma allows oxygen from the atmosphere to be provided for root metabolism.

In anaerobic soils, oxygen is transferred to the roots primarily for plant respiration (Kadlec, 1995) and only excess oxygen is leaked to the micro-zone around the root (rhizosphere). Oxygen released is primarily at the root tip to detoxify and oxidize potentially harmful substances in the rhizosphere (Armstrong and Armstrong, 1990). In this zone, oxidation reactions can take place, while anaerobic reactions occurs only microns away (Figure 3.14).

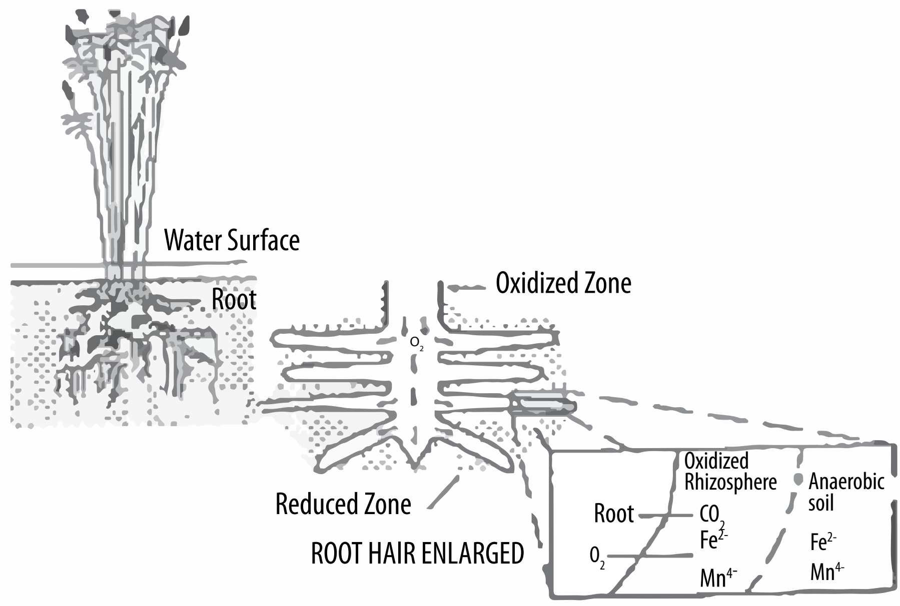


Figure 3.14: Oxygen transfer through root zone (Brix, 1993)

However, there are also some controversial claims about the magnitude of oxygen supply by plants to the wastewater in CW systems. Armstrong, (1988) found little oxygen is actually escaping from root-zone, and the small amount of this surplus oxygen varies with the plant species.

Lawson, (1985) estimated that up to 4.3 $g.m^{-2}.day^{-1}$ of oxygen flux is possible from the roots of *Phragmites* sp. Brix and Schierup, (1990) found that of a total oxygen influx of 5.86 $g.m^{-2}.day^{-1}$ to a CW planted with Phragmites, 3.76 $g.m^{-2}.day^{-1}$ comes from the atmosphere directly to the water column. The remaining 2.1g $m^{-2}.day^{-1}$ oxygen influx was through the plant tissues, of which 2.08 $g.m^{-2}day^{-1}$ gets transferred to the rhizome system for root respiration. Only 0.02 g $m^{-2}.day^{-1}$ of oxygen that was more than plant requirement was leaked by the roots into the water environment. Gries *et al.*, (1990) measured root oxygen release to be in the range of 1 to 2 $g.m^{-2}.day^{-1}$. Buchanan, (1987) found that in the short term, there were no difference between the treatment performance of filter beds planted with reeds and plastic substitutes in surface flow wetlands, and the beds with plants performed badly under high organic loading rates. The difference could be attributed to different types and age of plant species and the strength of wastewater (Haule *et al.*, 2002).

d. Hydraulic Conductivity

In treatment CW, wastewater flow is largely intended to be below the surface through channels created by living and dead roots as well as through the pore space of the substrate medium (Sundaravadivel and Vigneswaran, 2001; Mwegoha *et al.*, 2002). As roots and rhizomes grow, they disturb and loosen the soil (Mwegoha *et al.*, 2002). Furthermore, when the roots and rhizomes die and decay, they leave behind tubular pores and channel, which can improve the hydraulic conductivity of the substrate (Sundaravadivel and Vigneswaran, 2001). This may be largely true with gravel medium based substrate (Sundaravadivel and Vigneswaran, 2001).

On the contrary, the hydraulic conductivity of soil-based systems often decreases (Marsteiner *et al.*, 1996). Data on hydraulic conductivity in soil-based reed beds in Austria, Denmark, and in the UK also do not support the increase in hydraulic conductivity due to wetland plants in soil-based systems (Haberl and Perfler, 1990; Conely, Dick, and Lion, 1991). However, the study in the WIO region confirmed the increase in hydraulic conductivity with plants in soil substrate (Mwegoha *et al.*, 2002). The hydraulic conductivities increased in the order of soil, sand and gravel (Mwegoha *et al.*, 2002).

e. Nutrient Uptake

Nutrient for the growth of wetland macrophytes, mainly the nitrogen and phosphorus, are taken up primarily through their root systems (Sundaravadivel and Vigneswaran, 2001; Senzia *et al.*, 2003). Marginal uptake occurs also through immersed stems and leaves from the surrounding water (Gumbricht, 1993). Thus, the vegetation may be helpful in removal of nutrients from wastewater. Shaver and Mellio (1984) and Senzia *et al.*, 2003 have shown that nutrient uptake is maximum during the initial period of establishment of the plants in the CW, and the efficiency tends to decrease as available nutrient input rises. Consequently, when the nutrient loading rates increases, the uptake of nutrient by plants decreases. Tanner (1996) found that during the first 2-year period of operation, plant uptake of nutrients could only account for 6 to 10% for nitrogen and 6 to 13% of phosphorus removal from wetlands. However, a study conducted observed that the nitrogen removal through plant uptake is negligible in comparison to the nitrification/denitrification process in tropical climate like Tanzania (Senzia *et al*., 2003).

f. Organic and Antibiotic Excretion

Root systems of wetland plants release substances other than oxygen (Armstrong *et al*., 1990; Sundaravadivel and Vigneswaran (2001). Early experiments of the Max Planck Institute in Germany showed that the bulrush Schoenoplectus released antibiotics from its roots (Seidel, 1953). It is also known that a range of submerged macrophytes release compounds that affect the growth of other species (Vymazal *et al*., 1998). However, the role of these compounds in wetland treatment processes has not yet been experimentally verified (Sundaravadivel and Vigneswaran, 2001). Plants also release a wide range of organic compounds through their roots (Rovira, 1969; Barber and Martin, 1976). Reported values of these organic compounds are in the range of 5 to 25% of the photosynthetically fixed carbon (Brix, 1997). The organic carbon releases may act as a carbon source for denitrification process, and hence enhance the nutrient removal process in constructed wetlands (Platzer, 1996).

3.7.2 Soil or Substrate (Media) Supporting Vegetation

The media that physically supports vegetation in a constructed wetland is vital as it forms an integral link in treatment processes that occur in the wetland (Mwegoha, 2003). While soil generally supports the media in natural wetlands, CWs more often rely on coarse and fine gravel (Mwegoha, 2003). Apart from supporting vegetation, the substrates also act as the principal storage of all biotic and abiotic components that exist in a wetland (Mwegoha 2003). In addition, coarse sand and gravel substrates provide surface area for attached growth microorganisms and promote filtration and settling of suspended solids (Mwegoha, *et al*., 2002; Kimwaga *et al*., 2004). Hydraulic conductivity of the substrate is a major factor for the functionality and performance of CW. Maintenance of hydraulic conductivity is required to stabilize the hydraulic retention time of the CW system. Generally, CW systems with fine sand soil-based substrates have low hydraulic conductivity; while coarse sand and gravel based medium display higher hydraulic conductivity values (Mwegoha *et al*., 2002). Soils have a hydraulic conductivity of 10^{-5} ms^{-1} or less, whereas a uniform gravel in the range of 3 to 6 mm or 5 to 10 mm have an initial value in the order of 10^{-2} ms^{-1} or higher (Chen *et al*. 1993). Characteristics of various types of media and their hydraulic conductivity are presented in Table 3.4.

Table 3.4: Media characteristics (Chen et al., 1993)

Media type	Effective size (D_{10}) (mm)	Porosity (η)	Hydraulic conductivity (k_s, ms^{-1})
Coarse sand	2	0.32	1.2×10^{-2}
Gravelly sand	8	0.35	5.8×10^{-2}
Fine gravel	16	0.38	8.7×10^{-2}
Medium gravel	32	0.40	11.6×10^{-2}
Coarse rock	128	0.45	115.7×10^{-2}

Microbial and chemical degradation and their subsequent accumulation under the CW environment normally determine the solids accumulation and hence the clogging rate (Kimwaga *et al.*, 2002). Beauchamp *et al.* (1988) calculated the theoretical service life of a hypothetical gravel-bed CW in relation to clogging by organic and inorganic wastewater solids and microbial detritus (but ignoring plant litter contributions) to be in the order of 100 years. Reed and Brown (1992) estimated solids accumulation during the first 18 months operation of a coarse gravel wetland to be less than 1% of the available pore space of the media. Measurements of hydraulic gradients in gravel-bed wetlands treating domestic wastewater at Richmond, Australia (Fisher, 1990) showed major reductions in substrate hydraulic conductivity at the head of the wetlands during the first year of operation. The downstream permeability remained relatively stable over the 2.5 years monitoring period, with no indication of advancement in the solids accumulation along the length of the bed (Kadlec and Wallace, 2008).

3.7.3 Water Column (In and Above the Substrate)

Maintaining the water column is an important requirement of CW functionality since the wastewater level governs the major ecological functions taking place in the system (Sundaravadivel and Vigneswaran, 2001). Water provides the environment for biochemical reactions to occur and acts as a transport medium to carry the end-products such as gases, organic acids etc., from one reaction site to another reaction site (Sundaravadivel and Vigneswaran, 2001).

3.7.4 Living Organisms

A biodiversity of beneficial micro- and macro-organisms is an integral part of CW ecosystem functions (Sundaravadivel and Vigneswaran, 2001). While the presence of vertebrates and invertebrates (higher level animals, *e.g. Sitatunga*) may not be essential for the functioning of CWs, microbial forms of organisms play a critical role

(Kadlec and Wallace, 2008; Vymazal and Lenka, 2008). Microorganisms that are naturally found in water and wastewater, such as bacteria, fungi, protozoa, etc., thrive and become adaptive in CW, thereby providing suitable environmental conditions for their survival and proliferation (Kadlec and Wallace, 2008; Vymazal and Lenka, 2008).

3.8 Types and Selection of Wetland Configuration

The configuration of a CW affects the hydrologic factors controlling pollutant removal process (Sundaravadivel and Vigneswaran 2001; Njau *et al.*, 2011). It is important, therefore, that the configuration seeks to minimize short-circuiting to maximize wastewater contact with the entire surface area of wetland systems, and the cross-sectional area of an SSF system so as to utilize the effective volume of the CW (Kimwaga *et al.*, 2002; Kimwaga *et al.*, 2004). The ratio of length to the width (L/W) is a key design factor to achieve this condition (Vymazal *et al.*, 1998; Senzia *et al.*, 2003; Mwegoha, 2003; Haule, 2003; Kimwaga *et al.*, 2004).

For a SF system, the length/width (L/W) ratio of at least 10 is required (Vymazal *et al.*, 1998). Performance studies indicate that SF systems with high L/W ratios (as high as 75) consistently outperformed systems with lower L/W ratio (Steiner and Freeman Jr., 1990; Vymazal *et al.*, 1998). For SSF systems, on the other hand, L/W ratio of as low as one will be adequate, where solids must be distributed over a greater portion of the bed. L/W ratio of 3 has been adapted in many designs of CW in Tanzania (Senzia *et al.*, 2003; Mwegoha, 2003; Haule, 2003; Kimwaga *et al.*, 2004). Configuration of CW also depends on the degree of pre-treatment given to the wastewater, required treatment area, shape and grading of the available land, etc. (Kimwaga *et al.*, 2002).

General requirements for the CW cell configuration are (DLWC, 1998; Vymazal *et al.*, 1998; Mashauri *et al.*, 2000; Sundaravadivel and Vigneswaran, 2001) are;

- Graded bed slopes and associated structures to assist water movement and to enable self-draining when required (typically 0.1 to 1.0%). Lower slopes are more appropriate for SF systems, and higher slopes for SSF systems because of their higher hydraulic resistance;
- Capability to vary operational water depth, particularly during planting and commissioning periods, and also during operation. This is essential because it is likely to be the sole degree of operational control in constructed wetland systems;
- Minimization of stagnation zones, short-circuiting and causing mixing by designing for plug-flow;
- Appropriate length to width (L/W) ratio; and
- Adequate arrangement of flow distribution devices at the inlet section, and multiple collection devices at the outlet section of each cell.

Alternative configurations of CWs (Figure 3.18) include a single cell, parallel cells, series cells, and a combination of series and parallel cells (Sundaravadivel and Vigneswaran, 2001). The single rectangular cell is the simplest design and least expensive to build. However, its operational flexibility is limited. Hence, the single cell is recommended for small flows, where wastewater disposal after only primary treatment during short maintenance periods of the system is not objectionable (Sundaravadivel and Vigneswaran, 2001). The design of CW in WIO region has adapted a single cell approach (Senzia *et al*., 2003; Mwegoha, 2003; Haule, 2003; Kimwaga *et al*., 2004).

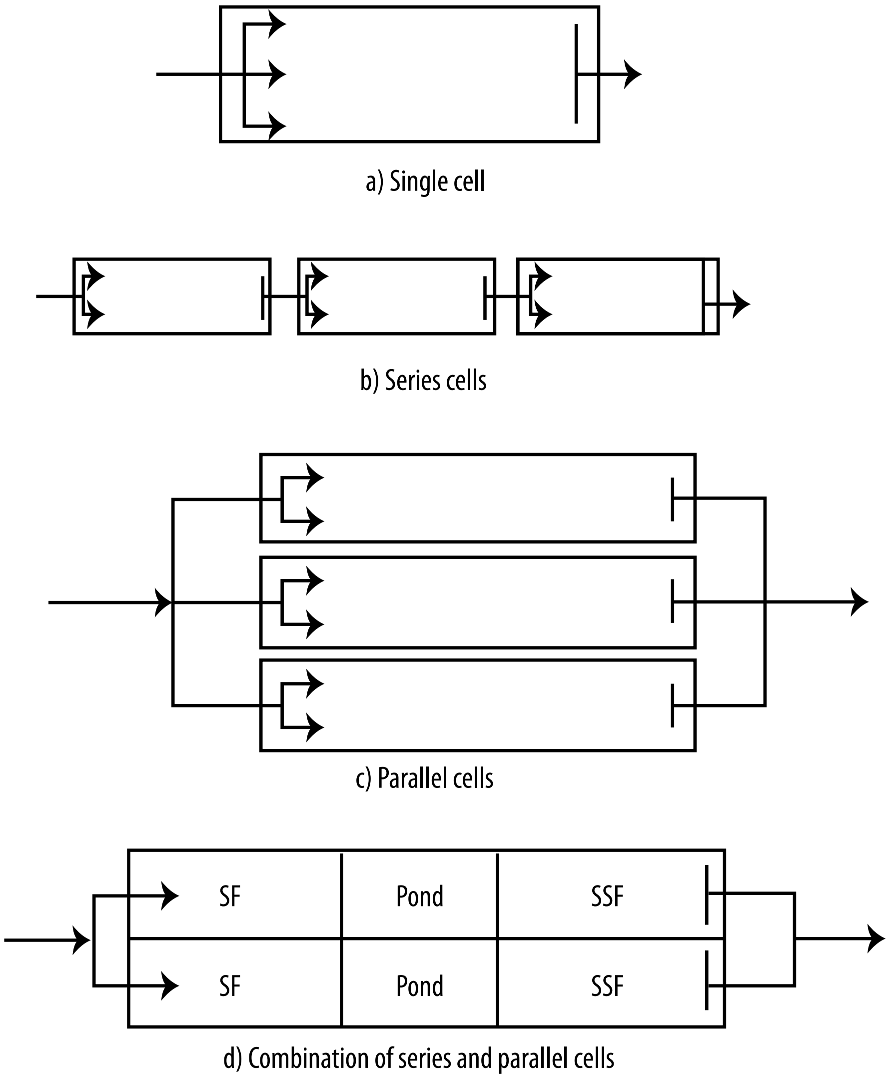


Figure 3.15: Introduction to Constructed Wetlands-18: Configurations for CTW (Sundaravadivel and Vigneswaran, 2001)

Through the use of CWs in Tanzania, single cell has been adopted and has not created any operational problems (Kaseva *et al*., 2000; Kaseva *et al*., 2002; Mwegoha *et al*., 2002; Kimwaga *et al*., 2002; Senzia *et al*., 2002; Senzia *et al*., 2003; Kimwaga, *et al*., 2004; Mbuligwe, 2004; Kaseva, 2004). This kind of configuration has demonstrated to be cost effective compared to other configurations. With limited operational capacity, single cell CW can be a problematic (Sundaravadivel and Vigneswaran, 2001). The likely problems of single cell CW system can be avoided by adopting configurations containing at least two parallel cells (Sundaravadivel and Vigneswaran, 2001). The flow is split and simultaneously fed to cells in operation. This will increase the operational and maintenance flexibility. One cell can be operated when the other is drained for maintenance. The possibility for mosquito control is enhanced by draining and each cell at regular intervals. Depending on site conditions, care may be taken during construction to ensure appropriate flow splitting in parallel systems. Simple weir structures like splitter boxes would normally suffice for flow splitting in small systems. Splitter boxes, internal flow divider dikes, and flow distribution boxes, etc. increase the cost of the treatment system (Sundaravadivel and Vigneswaran, 2001). When the CW system contains more than one cell, wetland cells can be operated also in series where in the flow moves sequentially from one cell to another. The main operational advantage of cells in series is minimization of short circuiting, leading to overall better performance (Sundaravadivel and Vigneswaran, 2001). Another advantage is the operational flexibility. Cells in series provide opportunity to recirculate wastewater between cells, and physically separate treatment zones for various pollutants. For example, while the removal of organic can take place in first (or first and second) cell, nitrogen removal can be enhanced in the subsequent cell(s) by maintaining special operating conditions in these cell(s) (Sundaravadivel and Vigneswaran, 2001). During construction, it is important to include the ability to bypass each cell individually. If one cell from a set of cells in series requires repair or maintenance, the design of the system should allow for bypassing only this cell, so that the performance of the system is affected to a minimum.

Combining parallel and series flow options gives both operational flexibility of cells in parallel, and the improved treatment capacity for different pollutants. However, these advantages may have to be offset against the additional costs of earth works, inlet and outlet structures, and flow distribution structures (Sundaravadivel and Vigneswaran 2001).

An open water pond system between consecutive wetland cells could provide pollutant removal and operational benefits (Sundaravadivel and Vigneswaran, 2001). The pond will enhance ammonia reduction and nutrient removal through algal uptake, increased pH, and nitrification. A common configuration of CTW system with ponds is a SF cell and a SSF cell preceding and succeeding the pond, respectively (Senzia *et al*., 2002, 2003). The pond can interrupt short-circuiting in the upstream cell and re-establish uniform flow distribution in the downstream cell. Also, for mosquito control, *Gambusia* fish can be stocked, which will migrate between pond and SF cells. The pond can facilitate aeration (natural or using mechanical aerators) to wastewater entering the downstream SSF cell to enhance nitrification. In some instances, it may be desirable to recirculate the flow back through the wetland in order to:

- Improve the treatment efficiency of the wetland, notably for nitrogen removal through denitrification;
- Effectively dilute the influent and therefore decrease peak loading and avoid localized overloading; and
- Return poorly treated effluent to the system.

While recycling within the system may not change the overall system HRT, it may change local velocities and HRTs. Therefore, if recirculation is planned, hydraulics and control systems may need to be designed and installed accordingly.

3.9 Where Can Wetland Find their Applications?

Various research and practical applications of CW have been comprehensively documented in the WIO region. CW may be used to provide some or all of the functions of secondary treatment and higher (Mbwette *et al*., 2002; Senzia *et al*., 2002; Kimwaga *et al*., 2003). Effluents that have undergone primary treatment may be further treated in CW. Experience of CW application in the WIO region has demonstrated that most of the CWs are restrictedly applied to the relatively small sized communities of schools, colleges, prisons, and household level with simple pretreatment systems of septic tanks. Common applications are:

Secondary treatment for small communities. For example, the WSP and CW research group of the University of Dar es Salaam implemented the CW technology for St Antony Secondary School in Dar es Salaam and Ruaha Secondary School in Iringa and concluded that they were the technology of choice for villages of up to 2,000 populations (Mbwette *et al*., 2002).

- Add-ons to aging or overloaded conventional secondary plants. The wetland acts as a buffer to complete the treatment when there are upsets or extreme flow events that create bypass and concentration excursions in the conventional plant outflow. In Kleruu in Iringa, CW technology was used to replace the conventional activated sludge systems
- Add-ons to lagoons. The solids trapping properties of wetlands can compensate for the export of algal debris from facultative ponds and provide further nutrient removal.
- Tertiary and higher treatment of non - compliant secondary discharges. Changing regulatory requirements can create the need for advanced treatment, which may be provided by constructed wetlands.

3.10 References

tential of a tropical subsurface constructed wetland to remove phenol from pre-treated pulp and papermill wastewater. *Water Science and Technology*, 51(9), 173-176.

Armstrong, J., and Armstrong, W. (1988). Phragmites australis–A preliminary study of soil-oxidizing sites and internal gas transport pathways. *New phytologist*, 108(4), 373-382.

Armstrong, W. (1964). Oxygen diffusion from the roots of some British bog plants. *Nature*, 204(4960), 801-802.

Armstrong, W. (1978). Root aeration in the wetland condition.

Armstrong, W., Armstrong, J., and Beckett, P. M. (1990). Measurement and modelling of oxygen release from roots of Phragmites australis. In Constructed wetlands in water pollution control (pp. 41-51). Pergamon.

Arup, A. G., and Ellen MacArthur, F. (2018). Water and Circular Economy: White Paper, Arup Group. Antea Group & Ellen MacArthur Foundation.

Austin, D. C., and Lohan, E. (2005). Patent: Tidal vertical flow wastewater treatment system and method. United States US, 6, B2.

Baboloki, A. and Kimwaga, R. (2021). Effects of Constructed Wetlands Plants on Phosphorus Removal from Domestic Wastewater In Gaborone, Botswana, Tanzania Journal of Engineering And Technology, Vol. 40(2), pp. 82-96, Dec. 2021, ISSN 1821-536X (print), ISSN 2619-8789 (electronic)

Barber, D. A., and Martin, J. K. (1976). The release of organic substances by cereal roots into soil. *New Phytologist*, 76(1), 69-80.

Barjenbruch, M., Kopplow, O., and Muller, R. (2002, September). Sludge mineralisation as a sustainable and simple method of sewage sludge treatment. In Proceedings of the 8th International Conference on Wetland Systems for Water Pollution Control (pp. 1109-1116). Dar Es Salaam, Tanzania: Comprint International Limited.

Barko, J. W., Gunnison, D., and Carpenter, S. R. (1991). Sediment interactions with submersed macrophyte growth and community dynamics. *Aquatic botany*, 41(1-3), 41-65.

Batchelor, A. (2003). The application of subsurface flow wetlands in South Africa: From pilot to full-scale. *Advances in Ecological Sciences*, 11, 161-180.

Beauchamp, D., Conley, L., Hufton, D., and Stone, C. (1988). The root-zone method of wastewater treatment: a technology assessment. Unpublished project report, School of Civil and Environmental Engineering, Cornell Univesrity, Ithaca, New York. 227p.

Bedford, B. L., Bouldin, D. R., and Beliveau, B. D. (1991). Net oxygen and carbon-dioxide balances in solutions bathing roots of wetland plants. *The Journal of Ecology*, 943-959.

Behrends, L. L., Bailey, E., Bulls, M. J., Coonrod, H. S., & Sikora, F. J. (1996). Seasonal trends in growth and biomass accumulation of selected nutrients and metals in six species of emergent aquatic macrophytes (No. Z-359). Tennessee Valley Authority, Muscle Shoals, AL (United States).

Brix, H. (1994). Functions of macrophytes in constructed wetlands. *Water Science and Technology*, 29(4), 71-78.

Brix, H. (1997). Do macrophytes play a role in constructed treatment wetlands?. *Water science and technology*, 35(5), 11-17.

Brix, H. (2003, May). Plants used in constructed wetlands and their functions. In 1st International Seminar on the use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands, edit. Dias V., Vymazal J. Lisboa, Portugal (pp. 81-109).

Brix, H. 1993. Wastewater treatment in constructed wetlands: system design and treatment performance. In: Constructed wetlands for water quality improvement (ed Moshiri, G.A.). CRC Press Inc., Boca Raton. pp. 9-22

Brix, H., 1996. Role of macrophytes in constructed treatments wetlands, in: Proc. 5th Internat. Conf. Wetland Systems for Water Pollution Control, Universität für Bodenkultur, Vienna,Austria, keynote address 2-1

Brix, H., and Schierup, H. H. (1990). Soil oxygenation in constructed reed beds: the role of macrophyte and soil-atmosphere interface oxygen transport. In Constructed wetlands in water pollution control (pp. 53-66). Pergamon.

Buchanan, R. M. (1987). The use of constructed wetlands for tertiary sewage treatment (Doctoral dissertation).

Burgoon, P. S., Kadlec, R. H., & Henderson, M. (1999). Treatment of potato processing wastewater with engineered natural systems. *Water science and technology*, 40(3), 211-215.

Chen, S., Malone, R. F., and Fall, L. J. (1993). A theoretical approach for minimization of excavation and media costs of constructed wetlands for BOD5 removal. *Transactions of the ASAE*, 36(6), 1625-1632.

Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). Nature-based solutions to address global societal challenges. IUCN: Gland, Switzerland, 97, 2016-2036.

Conley, L. M., Dick, R. I., and Lion, L. W. (1991). An assessment of the root zone method of wastewater treatment. *Research Journal of the Water Pollution Control Federation*, 239-247.

Cooper, P. (1999). A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. *Water Science and Technology*, 40(3), 1-9.

Cooper, P. F. (2003, May). UK experience with reed bed and constructed wetland systems 1985 to 2003. In Proceedings of the International Seminar The Use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands, Lisbon, Portugal (pp. 8-10).

Cooper, P. F., Job, G. D., Green, M. B., and Shutes, R. B. E. (1997). Reed beds and constructed wetlands for wastewater treatment. *European water pollution control*, 6(7), 49.

Crites, R., and Tchobanoglous, G. (1998). Small and decentralized wastewater management systems. Boston: WCB/McGraw-Hill.

De Maeseneer, J. L. (1997). Constructed wetlands for sludge dewatering. *Water Science and Technology*, 35(5), 279-285.

DLWC (Department of Land and Water Conservation) (1998) The constructed wetland manual vol.2 DLWC, New South Wales.

DLWC (Department of Land and Water Conservation) (1998) The constructed wetland manualvol.1 DLWC, *New South Wales Earth* 27: 773-781.

EC (European Commission). (2015b). Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-naturing Cities. Final Report of the Horizon 2020 Expert Group on "Nature-Based Solutions and Re-naturing Cities. https://doi.org/10.2777/765301. *Ecological Engineering* 2: 1–30.

Fisher, P.J., (1990). Hydraulic characteristics of constructed wetlands at Richmond, NSW, Australia, in: Constructed Wetlands in Water Pollution Control, P.F. Cooper and B.C. Findlater, eds., Pergamon Press, Oxford, U.K., pp. 21-31

Gries, C., Kappen, L., and Lösch, R. (1990). Mcchanism of flood tolerance in reed, Phragmites australis (Cav.) Trin. ex Steudel. *New Phytologist*, 114(4), 589-593.

Gumbricht, T. (1993). Nutrient removal processes in freshwater submersed macrophyte systems. *Ecological Engineering*, 2(1), 1-30.

Guntenspergen, G. R, Stearns. F, and Kadlec, J. A. (1990) Wetland vegetation in Constructed wetlands for wastewater treatment, 2nd printing ed Hammer D A, Lewis Publishers, Chelsea, Michigan, pp 73–88.

Haberl, R., and Perfler, R. (1990). Seven years of research work and experience with wastewater treatment by a reed bed system. In Constructed wetlands in water pollution control (pp. 205-214). Pergamon.

Haule, A (2003) Investigation of the potential of macrophytes during the treatment of domestic wastewater using Constructed Wetlands: Unpublished Master of Science in Botany, University of Dar es Salaam

Haule, K. S., Johnsen, F. H., & Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. *Journal of environmental management*, 66(1), 31-42.

Hiley, P. D. (1995). The reality of sewage treatment using wetlands. *Water Science and Technology*, 32(3), 329-338.

IWA (International Water Association), 2016. Water utility pathways in a circular economy: charting a Course for Sustainability. *https://iwa-network.org/waterutility- pathways-circular-economy-charting-course-sustainability/*.

Kadlec, R. H. (1995). Overview: surface flow constructed wetlands. *Water Science and Technology*, 32(3), 1-12.

Kadlec, R. H. (2003). Integrated natural systems for landfill leachate treatment. Wetlands–nutrients, metals and mass cycling, 1-33.

Kadlec, R. H., and Wallace, S. (2008). Treatment wetlands. CRC press.

Kadlec, R. H., and Wallace, S. D. (2009). Treatment Wetlands, Second Edition TOC and References. In Treatment Wetlands, Second Edition

Kadlec, R., Knight, R., Vymazal, J., Brix, H., Cooper, P., and Haberl, R. (2000). Constructed wetlands for pollution control: processes, performance, design and operation. IWA publishing.

Kadlec, R.H., Axler, R., McCarthy, B., and Henneck, J. (2003). Subsurface treatment wetlands in the cold climate in Minnestota, in: Constructed Wetlands for Wastewater treatment in Cold Climates, Ü. Mander and P. Jenssen, eds., WIT Press, Southampton, UK, pp. 19-52.

Kaseva, M. E. (2004). Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater—a tropical case study. *Water research*, 38(3), 681-687.

Kaseva, M. E., Mbwette, T. S., and Katima, J. H. (2002). Domestic Sewage Treatment in a Pilot Plant Composed of Septic Tank and Constructed Wetlands-A Case Study in Dar es Salaam, Tanzania. In IWA Conference on Wetland Systems for Water Pollution Control, Arusha, Tanzania.

Kaseva, M. E., Mbwette, T. S., Katima, J. H., and Mashauri, D. A. (2000, November). Performance of a subsurface horizontal flow constructed wetland in polishing upward flow anaerobic sludge blanket pre-treated domestic wastewater under tropical conditions—A case study in Dar es Salaam, Tanzania. In Wetland Systems for Water Pollution Control (eds. K. Reddy & R. Kadlec). Lake Buena Vista, Florida. International Water Association, London, UK, 7th International Conference on Wetlands for Water Pollution Control (pp. 11-16).

Kassenga, G., Pardue, J. H., Moe, W. M., and Bowman, K. S. (2004). Hydrogen thresholds as indicators of dehalorespiration in constructed treatment wetlands. *Environmental science & technology*, 38(4), 1024-1030.

Kimwaga, R. J., Mashauri, D. A., Mbwette, T. S. A., Katima, J. H., and Jørgensen, S. E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. *Physics and Chemistry of the Eart*h, Parts A/B/C, 29(15-18), 1243-1251.

Kimwaga, R., Mashauri, D., and Mbwette, T. (2003). Meeting health improvement indicators in waste stabilization ponds effluents by a coupled dynamic roughing filters and subsurface horizontal flow constructed wetland in Tanzania. Prospective College of Engineering and Technology, University of Dar es Salaam, Dar es Salaam, Tanzania.

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E., 2002. Mathematical modelling of the TSS removal in a coupled dynamic roughing filter and subsurface horizontal flow constructed wetland system treating WSP effluent, in: Proc s. 8th Internat. Conf. Wetland Systems for Water Pollution Control, University of Dares- Salaam, Tanzania and IWA, pp. 843-857.

Knight, R. L., Clarke Jr, R. A., and Bastian, R. K. (2001). Surface flow (SF) treatment wetlands as a habitat for wildlife and humans. *Water Science and Technology*, 44(11-12), 27-37.

Langergraber, G., Prandtstetten, C., Pressl, A., Rohrhofer, R., and Haberl, R. (2007). Removal efficiency of subsurface vertical flow constructed wetlands for different organic loads. *Water science and technology*, 56(3), 75-84.

Langergraber, G., Pucher, B., Simperler, L., Kisser, J., Katsou, E., Buehler, D., ... and Atanasova, N. (2020). Implementing nature-based solutions for creating a resourceful circular city. *Blue-Green Systems*, 2(1), 173-185.

Lawson, G. J. (1985). Cultivating reeds (Phragmites australis) for root zone treatment of sewage. Contract Report ITE. Water research centre, Gumbria, UK.

Lemon, E., Bis, G., Rozema, L., and Smith, I. (1996, June). SWAMP Pilot Scale Wetlands–Design and Performance, Niagara-On-The-Lake, Ontario. In Constructed Wetlands in Cold Climates: Design, Operation, Performance Symposium, The Friends of St. George, Niagara-on-the-Lake, Ontario.

Mashauri, D. A., Mulungu, D. M., & Abdulhussein, B. S. (2000). Constructed wetland at the University of Dar es Salaam. *Water research*, 34(4), 1135-1144.

Masteiner, E. L., Collins, A. G., Theis, T. L., and Young, T. C. (1996). The influence of macrophytes on subsurface flow wetland hydraulics. 5th Internat. In Conf. Wetland Systems Water Pollution Control. Viena, Àustria.

Mbuligwe, S. E. (2004). Comparative effectiveness of engineered wetland systems in the treatment of anaerobically pre-treated domestic wastewater. *Ecological engineering*, 23(4-5), 269-284.

Mburu, C., Kipkemboi, J., and Kimwaga, R. (2019). Impact of substrate type, depth and retention time on organic matter removal in vertical subsurface flow constructed wetland mesocosms for treating slaughterhouse wastewater. *Physics and Chemistry of the Earth*, Parts A/B/C, 114, 102792.

Mbwette, T. S. A., Katima, J. H. Y., Pratap, H. B., and Kayombo, S. (2002, September). Wetland systems for water pollution control. In Proc. 8th Int. Conf. on Wetland Systems for Water Pollution Control (pp. 16-19).

Metcalf L, and Eddy HP (2004). Wastewater engineering, treatment and reuse. McGraw-Hill, New York

Mitchell C (1996) Pollutant removal mechanisms in artificial wetlands unpublished course notes for the International Winter Environmental School (IWES), July, Gold Coast. Mitsch W J and Gosselink J G (1993) Wetlands, 2nd edition. New York: Van Nostrand Reinhold.

Molle, P., Liénard, A., Boutin, C., Merlin, G., and Iwema, A. (2005). How to treat raw sewage with constructed wetlands: an overview of the French systems. *Water Science and Technology*, 51(9), 11-21.

Mwegoha, W., Katima, J. H. Y., Mbwette, T. S. A., Njau, K. N., Jorgensen, S. E., and Nielsen, S. N. (2002). Modeling the effects of suspended solids accumulation on the hydraulic conductivity of gravel packed horizontal subsurface flow constructed wetlands. University of Dar es Salaam, PO Box, 35131.

Mwegoha, W.S. (2003). Effects of substrate on Constructed Wetlands performance: Unpublished Master of Science in Chemical and Processing Engineering, University of Dar es Salaam

NADB database (1998) North American Treatment Wetland Database (NADB). Version 2.0. Compiled by CH2MHill. Gainesville, Florida.

Nielsen, S. (2005). Sludge reed bed facilities: operation and problems. *Water Science and Technology*, 51(9), 99-107.

Nielsen, S. M. (1990). Sludge dewatering and mineralisation in reed bed systems. In Constructed Wetlands in Water Pollution Control (pp. 245-255). Pergamon.

Nika, C. E., Gusmaroli, L., Ghafourian, M., Atanasova, N., Buttiglieri, G., and Katsou, E. (2020). Nature-based solutions as enablers of circularity in water systems: A review on assessment methodologies, tools and indicators. *Water Research*, 183, 115988.

Njau, K. N., Gastory, L., Eshton, B., Katima, J. H., Minja, R. J., Kimwaga, R., and Shaaban, M. (2011). Effect of diffusional mass transfer on the performance of horizontal subsurface flow constructed wetlands in tropical climate conditions. *Water Science and Technology*, 63(12), 3039-3045.

Nyakang'o, J. B., and Van Bruggen, J. J. A. (1999). Combination of a well - functioning constructed wetland with a pleasing landscape design in Nairobi, Kenya. *Water Science and Technology*, 40(3), 249-256.

O'Hogain, S., and McCarton, L. (2018). A technology portfolio of nature based solutions. Innovations in Water Management; Springer: Cham, Switzerland.

Pauleit, S., Zölch, T., Hansen, R., Randrup, T. B., and Konijnendijk van den Bosch, C. (2017). Nature-based solutions and climate change–four shades of green. Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice, 29-49.

Platzer, C. (1996). Enhanced nitrogen elimination in subsurface flow artificial wetlands-a multi stage concept. In Proceedings of the Fifth International Conference on Wetland Systems for Water Pollution Control, Vienna, Austria, September (pp. 15-19).

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., ... and Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, 77, 15-24.

Reed, S. C., and Brown, D. S. (1992). Constructed wetland design—the first generation. *Water Environment Research*, 64(6), 776-781.

Rovira, A. D. (1969). Plant root exudates. *The botanical review*, 35, 35-57.

Seidel, K. (1953). Pflanzungen zwischen gewassern und land. *Mitteilungen Max-Planck Gesselschaft*, 8, 17-20.

Seidel, K. (1976). Macrophytes and water purification. Biological control of water pollution, 109.

Senzia, M. A., Mashauri, D. A., and Mayo, A. W. (2003). Suitability of constructed wetlands and waste stabilisation ponds in wastewater treatment: nitrogen transformation and removal. *Physics and Chemistry of the Earth*, Parts A/B/C, 28(20-27), 1117-1124.

Senzia, M. A., Mashauri, D. A., Mayo, A. W., Mbwette, T. S., Katima, J. H., Pratap, H. B., and Nielsen, S. N. (2002, September). Performance of horizontal subsurface flow constructed wetlands located downstream of primary facultative and maturation ponds in Tanzania. In Int. Conf. on Wetlands Systems for water Pollution Control, Arusha, Tanzania.

Shaver, G. R., and Melillo, J. M. (1984). Nutrient budgets of marsh plants: efficiency concepts and relation to availability. *Ecology*, 65(5), 1491-1510.

Smith, I. D., Bis, G. N., Lemon, E. R., and Rozema, L. R. (1997). A thermal analysis of a sub-surface, vertical flow constructed wetland. *Water Science and Technology*, 35(5), 55-62.

Sorrell, B. K., and Boon, P. I. (1992). Biogeochemistry of billabong sediments. II. Seasonal variations in methane production. *Freshwater Biology*, 27(3), 435-445.

Steiner G R and Freeman R J, Jr. (1990). Configuration and substrate design considerations for constructed wetlands wastewater treatment, in Constructed wetlands for wastewater treat- ment, 2nd ed. D A Hammer, Lewis Publishers, Chelsea, Michigan, pp. 363–377.

Sundaravadivel, M., and Vigneswaran, S. (2001). Constructed wetlands for wastewater treatment. *Critical reviews in environmental science and technology*, 31(4), 351-409.

Tanner, C. C. (1996). Plants for constructed wetland treatment systems—a comparison of the growth and nutrient uptake of eight emergent species. *Ecological engineering*, 7(1), 59-83.

U.S. EPA (2000) Guiding principles for constructed treatment wetlands: Providing water quality and wildlife habitat, EPA 843/B-00/003, U.S. EPA Office of Wetlands, Oceans,

UNEP, Nairobi Convention Secretariat, CSIR and WIOMSA (2009c). Towards a Protocol for long-term monitoring of marine environmental quality in the Western Indian Ocean.UNEP, Nairobi, Kenya, 86 pp.

UN-HABITAT. (2008). Constructed Wetlands Manual.UN-HABITAT Water for Asian Cities Programme Nepal, Kathmandu.

UNITED NATIONS ENVIRONMENT PROGRAMME, NAIROBI CONVENTION SECRETARIAT AND COUNCIL FOR SCIENTIFIC & INDUSTRIAL RESEARCH. (2021a). Western Indian Ocean: Situation Assessment on Marine Pollution and Coastal & Marine Water Quality Management. UNEP, Nairobi, Kenya, 61 pp.

Vymazal J., Brix H., Cooper P.F., Green M.B., Haberl R. (1998) Constructed Wetlands for Wastewater Treatment in Europe. Backhuys Publishers: Leiden, The Netherlands.

Vymazal, J. (1998). Removal mechanisms and types of constructed wetlands. Constructed wetlands for wastewater treatment in Europe, 17-66.

Vymazal, J. (2001). Types of constructed wetlands for wastewater treatment: their potential for nutrient removal. Transformations of nutrients in natural and constructed wetlands, 1-93.

Vymazal, J., and Kröpfelová, L. (2008). Wastewater treatment in constructed wetlands with horizontal sub-surface flow (Vol. 14). Springer science & business media.

Wallace, S.D., and Knight, R.L. (2006). Small Scale Constructed Wetland Treatment Systems.Feasibility, Design Criteria, and O&M Requirements, Water Environ. Res. Foundation, Alexandria, Virginia.Wat. *Sci. Tech*. 51(9): 173-175.

Wieder, R. K. (1989). A survey of constructed wetlands for acid coal mine drainage treatment in the eastern United States. *Wetlands*, 9, 299-315.

Younger, P. L., Banwart, S. A., Hedin, R. S., Younger, P. L., Banwart, S. A., and Hedin, R. S. (2002). Mine water hydrology (pp. 127-270). Springer Netherlands.

Zuñiga, (2020). What are nature-based solutions and why do they matter?.

This page is intentionally blank

Chapter 4: Policies, Laws, and Institutions Related to Constructed Wetlands

By Deogratius Mulungu and Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

The adaptation and thus the application at scale of any technology including CW, requires the enablers space and landscape for its support, encouragement, and promotion. The enablers in terms of policies, legislation and institutional frameworks provide the strategic direction through which the technology must effectively operate. This chapter discusses the existence, relevance, appropriateness and adequacy of the enabling environment in the WIO region which supports the adaptation and uptake of this rather timely technology at this global pressing pollution crisis.

4.1 Introduction

The inadequate and lack of appropriate and effective regulation and strategic planning framework of urban growth in African cities have led to severe environmental challenges such as wastewater pollution (UNEP *et al.*, 2022). The problem of urban pollution is a growing environmental concern with the major drivers being economic development, urbanization, and rapid increase of population (UNEP *et al.*, 2022). The same phenomenon is being experienced in most of the countries in the WIO region. It is therefore important to have sound enabling environment and an integrated approach for wastewater and faecal sludge management including climate change adaptation strategies to support decision making in solving urban water pollution challenges.

This chapter provides contextual global, regional, and national information on the available policies, laws and institutions related to CW technology application and its adaptation. This chapter presents institutional arrangements necessary in prioritizing policy framing, technology development, infrastructure development, and targeted behaviour change strategies for the aim of creating enabling environment for safely managed sanitation. The relevant enabling environment for planning, design, construction, operation and maintenance of CW contributes to the attainment of four of the 17 Sustainable Development Goals (SDGs) such as end poverty (SDG 1), ensure healthy lives and well-being for all at all ages (SDG 3) by reducing exposure to unsafe hazardous chemicals, water and soil contamination, and pollution (environmental health), safely managed sanitation for all (SDG 6) and decent work and economic growth (SDG 8) by improving living standards. The SDG2030 presents a global urgent call for action to reduce poverty, protect the planet and realise prosperous and peaceful life for all citizens on the planet.

4.2 Key International and Regional Arrangements

Several countries in the WIO region are signatories to international conventions or agreements linked to the combatting and prevention of marine pollution (Table 4.1). Most of these conventions and agreements relate to pollution from shipping, although, the United Nations Convention on the Law of the Sea (UNCLOS, 1982) addresses pollution of the marine environment more generally.

Agenda 2030 and its Sustainable Development Goals (SDGs) have a central, overarching aim of ensuring environmentally sustainable and socially equitable development, including the marine environment. Specifically, SDG 14: *Conserve and sustainably use the oceans, seas and marine resources for sustainable development* is relevant to marine pollution where target 14.1 is aimed at *preventing and significantly reducing marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution.*

The Convention of Biological Diversity (CBD) also sets overarching targets for environmental biodiversity protection (including the marine environment). Specifically, the Aichi Biodiversity targets aim to (*https://www.cbd.int/sp/targets/*) aim to:

- Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society;
- Reduce the direct pressures on biodiversity and promote sustainable use;
- Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity;
- Enhance the benefits to all from biodiversity and ecosystem services;
- Enhance implementation through participatory planning, knowledge management and capacity building.

Regional initiatives under the Nairobi Convention and WIOMSA which specifically address marine pollution include the following:

- Western Indian Ocean Land-based Activities (WIO-Lab) Programme which produced.
    - Guidelines for the Establishment of Environmental Quality Objectives and Targets in the Coastal Zone of the Western Indian Ocean (WIO) Region (UNEP *et al.*, 2009a);
    - Towards a Protocol for long-term monitoring of marine environmental quality in the Western Indian Ocean (UNEP *et al.* 2009b);
    - Regional Synthesis Report on the Status of Pollution in the Western Indian Ocean Region (UNEP *et al.* 2009a);
- Protocol Concerning Co-operation in Combating Marine Pollution in Cases of Emergency in the Eastern African Region (www.unenvironment.org/nairobiconvention/who-we-are/protocols);
- WIO Action Plan on Marine Litter (UN Environment, 2018);
- African Marine Litter Monitoring Manual (Barnardo and Ribbink, 2020);
- WIO Marine Highway development and Coastal and Marine Contamination Prevention Project (2020);
- Regional oil spill preparedness in eastern Africa and WIO (UNEP *et al.*, 2020 a and b).

Other overarching regional initiatives that address aspects on marine pollution, amongst others, include (UNEP *et al.*, 2022):

- Protocol for the Protection of the Marine and Coastal Environment of the Western Indian Ocean from Land-Based Sources and Activities (LBSA Protocol);
- Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities (WIOSAP)
- Western Indian Ocean Large Marine Ecosystems Strategic Action Programme Policy Harmonisation and Institutional Reforms (SAPPHIRE);
- African, Caribbean, and Pacific (ACP) Countries Capacity Building of Multilateral Environmental Agreements project (MEAS

Table 4.1: Key International and regional conventions/agreements applicable to marine water quality management, indicating signatory countries (UNEP et al., 2022)

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
International Convention on Civil Liability for Oil Pollution Damage (CLC) (1969)	Ensures adequate compensation to persons who suffer oil pollution damage resulting from maritime casualties involving oil-carrying ships, placing the liability on owners of the ships (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx*)	•	•	•	•	•		•		•	•
International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (INTERVENTION) (1969)	The Convention affirms right of coastal states to take measures on high seas to prevent, mitigate or eliminate danger to its coastline or related interests from pollution by oil or the threat thereof, following upon a maritime casualty (*www.imo.org/en/About/Conventions/Pages/International-Convention-Relating-to-Intervention-on-the-High-Seas-in-Cases-of-Oil-Pollution-Casualties.aspx*)			•	•		•			•	•
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) and London Protocol (1996)	Prohibiting the dumping of certain hazardous materials. In addition, a special permit is required prior to dumping of a number of other identified materials and a general permit for other wastes or matter. (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx*)		•			•		•		•	•
	In 1996, Parties adopted a Protocol to the Convention. It prohibits all dumping, except for possibly acceptable wastes on the so-called 'reverse list'		•							•	

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
International Convention for Prevention of Pollution from Ships (MARPOL) (1973)	Main international convention covering prevention of pollution by ships from operational or accidental causes (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx*):										
	Annex I: Regulations for the Prevention of Pollution by Oil	•	•	•	•	•		•		•	•
	Annex II: Control of Pollution by Noxious Liquid Substances	•	•	•	•	•		•		•	•
	Annex III: Harmful Substances Carried by Sea in Packaged Form	•	•	•	•	•				•	•
	Annex IV: Sewage from Ships	•	•	•	•	•					•
	Annex V: Garbage from Ships	•	•	•	•	•				•	•
	Annex VI: Air Pollution from Ships										
United Nations Convention on the Law of the Sea (UNCLOS) (1982)	This convention is cornerstone of ocean governance at the national, regional, and global levels. Section 5 addresses prevention of pollution of the marine environment (*www.iucn.org/theme/marine-and-polar/our-work/international-ocean-governance/unclos*)	•	•	•	•	•	•	•		•	•
Regional Seas Programme: Nairobi Convention (1985)	Partnership between governments, civil society and private sector, working towards a prosperous Western Indian Ocean Region. This Convention offers a regional legal framework and coordinates efforts of member states to plan and develop programmes that strengthen their capacity to protect, manage and develop their coastal and marine environment (including marine water quality management) (*www.unenvironment.org/nairobiconvention/*)	•	•	•	•	•	•	•	•	•	•

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC) (1990)	Require parties to establish measures for dealing with pollution incidents, either nationally or in co-operation with other countries (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx*)					•		•			
Convention on Biological Diversity (1993)	This convention has 3 main objectives (1) conservation of biological diversity, (2) sustainable use of the components of biological diversity, (3) fair and equitable sharing of the benefits arising out of the utilization of genetic resources (*www.cbd.int/convention/*)	•	•	•	•	•	•	•		•	•
International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND) (1996)	Under this Convention, victims of oil pollution damage may be compensated beyond level of ship owners' liability (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx*).	•	•	•	•	•		•		•	•

CONVENTION/ AGREEMENT	DECRIPTION	Comoros	Kenya	Madagascar	Mauritius	Mozambique	Reunion (France)	Seychelles	Somalia	South Africa	Tanzania
International Convention on Civil Liability for Bunker Oil Pollution Damage (BUNKER) (2001)	The Convention ensures adequate, prompt, and effective compensation availability to persons who suffer damage caused by spills of oil, when carried as fuel in ships' bunkers. (*www.imo.org/en/About/Conventions/Pages/International-Convention-on-Civil-Liability-for-Bunker-Oil-Pollution-Damage-(BUNKER).aspx)*		•		•		•				
Stockholm Convention (2001)	Convention on Persistent Organic Pollutants is a global treaty to protect human health and the environment from chemicals that remain intact in the environment for long periods (*www.pops.int/Home/tabid/2121/Default.aspx*)	•	•	•	•	•	•	•	•	•	
International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM) (2004)	This Convention aims to prevent spread of harmful aquatic organisms from one region to another, by establishing standards and procedures for management and control of ships' ballast water and sediments (*www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx)*.									•	
2030 Agenda for Sustainable Development (2015)	Adopted by UN member states as an agenda for people, planet and prosperity. Seventeen Sustainable Development goals were identified of which some are relevant to marine pollution prevention (*e.g.* SDG 14) (*www.un.org.za/sdgs/2030-agenda/*).	•	•	•	•	•	•	•	•	•	•

4.3 Overview of National Arrangements

Legislation pertaining marine pollution typically comprises that which deals with pollution from land (*e.g.* wastewater discharges), dumping at sea, shipping (maritime transport) and offshore exploration/mining. A brief overview of legal frameworks, policies and management structure pertaining to marine water quality (or marine pollution) in the WIO countries is provided below.

4.3.1 Comoros

The Constitution (2001) of the Union of the Comoros proclaims, "the right to a healthy environment and the duty of all to safeguard that environment", with Article 18 of its Environmental Code (1994) stipulating that the State must ensure the protection of the soil and subsoil, water resources and the marine environment, the atmosphere and biological diversity (ASCLME 2012a).

The Framework Law on the Environment (No. 94-018/AF) was proclaimed in 1994. This Law (as amended in 1995) provides general principles on all the aspects of environmental protection such as pollution, impact studies, terrestrial and marine environment protection and protected areas. Under this framework law other decrees and orders were established, including the decree on impact studies and the decree on coastal zone monitoring as well as orders on the protection of the mangroves, the harvesting of sea cucumbers, the protected areas and the extraction of sea sand and corals.

The Comoros has developed several operational plans to deal with disasters, including a National Action Plan against Oil Spills at Sea (POLMAR) (2010) that defines administrative organisation and intervention techniques at sea and along the coast as well as the identification of responsibilities of the parties involved and their respective companies (ASCLME 2012a; UNEP/OCHA, 2013).

At national level, issues concerning the environment are managed by the National Directorate of Environment (DNE), the National Directorate of Fisheries, the National Institute of Applied Research Fisheries and Environment (INRAPE) and almost all the Ministries (*e.g.* Public Finance, Budget, Economy and Planning, Transport and Tourism, Urban planning and Housing, Public Health and Population, Education and Justice). At the island level, responsibilities of regional departments of the environment ministry include the enforcement of regulations for protecting the natural environment (ASCLME 2012a). As far as could be established the Comoros does not have a national marine pollution monitoring programme (Jackson, 2011).

4.3.2 Kenya

Kenya's Environmental Management and Coordination Act (No 8 of 1999, as amended 2015) (ECMA) explicitly addresses the management and control of the pollution in the coastal and marine environment. For example, Section 55 stipulates that the Minister responsible for environmental matters shall, in consultation with the relevant lead agencies, issue appropriate regulations to prevent, reduce and control pollution or other forms of environmental damage in the coastal zone. Also, those regulations shall provide for the control and prevention of pollution of the marine environment from land-based activities and sources (ASCLME 2012b).

The Merchant Shipping Act (2009) consolidates ship-related legislation and provides for the prevention of pollution. For example, Section 410 allows for regulations on marine pollution, including giving effect to relevant international conventions (Jackson, 2011).

Under the ECMA, the Ministry of Environment and Forestry has a wide range of powers regarding pollution control. The National Environment Management Authority (NEMA) was established under this act and has general powers with respect to enforcing other government agencies to fulfil their environmental responsibilities, including management of pollution. Other departments and institutions that also fulfil key roles on marine pollution management and control include (Jackson, 2011):

- Ministry of Local Government (local authorities responsible for garbage collection and effluent treatment and disposal);
- Ministry of Transport and Communication (Kenya Ports Authority is responsible for ports and stores oil spill response equipment);
- Ministry of Health (Mombasa laboratories conduct marine pollution monitoring);
- Kenya Marine Fisheries Research Institute (KMFRI) (research, monitoring and advice on marine pollution).

4.3.3 Madagascar

In Madagascar the concept of sustainable development underpins environmental legislation and policy, for example the Decree relating to ensuring the environmental suitability of investments (MECIE) (No. 2004-167). In 2008 the National Office of the Environment (ONE) was established specifically to administer this Decree to ensure that economic activities and development are not detrimental to the environment. The ONE achieves this through a number of interventions, including the management and prevention of pollution, and monitoring of the marine environment. The Regulations of integrated management of coastal and marine areas in Madagascar (Decree 2010-137) also address aspects of coastal and marine pollution control and management (ASCLME 2012c).

In terms of Law No. 99-021 pertaining to the management policy for the control of industrial pollution, all industrial developments require authorisation prior to commissioning. Effluent quality standards that must be adhered to before discharge into surface waters are set out in Decree 2003/464, as well as minimum standards for metals in sewage sludge (Walmsley and Patel, 2012). The Organe de Lutte contre les Evénements de Pollution marine (OLEP) has been mandated to oversee the management and control of oil pollution in the marine environment (Decree 2004-994) (ASCLME 2012c).

4.3.4 Mauritius

The Environment Protection Act (No 19 of 2002, as amended) provides the policy framework for the preservation and conservation of the coastal zone in an integrated manner through the enforcement of environmental standards, particularly those pertaining to the control and prevention of pollution. The Guidelines on Coastal Water Quality (Government Notice No 620 of 1999) form part of the secondary legislation issued under the Environmental Protection Act of 2002. Other regulations under the Environmental Protection Act of 2002 include Standards for effluent discharge into the Ocean (Government Notice No 45 of 2003). The Pollution Prevention and Control Division of the Ministry responsible for the Environment carries out regular monitoring of environmental hotspots to prevent environmental pollution and degradation. Advice is also given on measures to prevent air, noise and water pollution and appropriate solid waste management systems (*https://environment.govmu.org/*).

Pollution from ships is dealt with under the Merchant Shipping Act (No 26 of 2007) and the Merchant Shipping Regulations (2019) and promulgated under the Act by the Ministry responsible for shipping (*https://blueconomy.govmu.org/*). Mauritius has prepared both a National Oil Spill Contingency Plan and the Port Louis Harbour Oil Spill Response Plan, providing frameworks for oil spill preparedness and response in the country (Mauritius Government, 2011).

The Laboratories Division of the Ministry responsible for Fisheries conducts long-term monitoring of coastal water quality to ensure compliance with the Coastal Water Quality Guidelines. Long-term monitoring of coliform bacteria at public beaches is conducted while fish samples are also tested for the presence of ciguatoxin and ciguatera fish poisoning. Long-term monitoring of harmful marine microalgae is also conducted. The division comprises three laboratories, namely the Marine Chemistry, Marine Microbiology and Fish Toxicity laboratories (*https://blueconomy.govmu.org/*).

4.3.5 Mozambique

The Constitution of the Republic of Mozambique (2004) addresses matters relating to the environment and quality of life including the preventing and controlling of pollution. The Environment Law (No. 20/97), administered by the Ministry for Environmental for Coordination of Environmental Affairs (MICOA), is an umbrella law for environmental matters and an important instrument for the enactment of specific regulations (Wamsley and Patel, 2012). With specific reference to coastal and marine pollution these include:

- Regulation on Standards for Environmental Quality and Effluent Discharges (Decree no. 18/2004, Decree no. 67/2010);
- Regulation for the Management of Solid Municipal Waste (Decree no. 94/2014), revoked (Decree no. 13/2006);
- Regulation for the Management of Hazardous Waste (Decree no. 83/2014);
- Shipping and harbour operations are dealt with under the Sea Act (Law no. 4/1996); administered by Mozambican Dredging Company Mozambique Ports and Railways Company (Wamsley and Patel, 2012). Specific regulations pertaining to pollution control include
    - Regulations for Harbour Operations (Portaria no. 18630/1965);
    - Regulation for the Prevention of Pollution and Marine and Coastal Environmental Protection (Decree no. 45/2006).

Management and control of petroleum operations are dealt with under the Petroleum Law (Law no. 3/2001), including Environmental Regulations for Petroleum Operations (Decree no. 56/2010) and administered by Ministry of Mineral Resources and National Petroleum Institute (INP) (Wamsley and Patel, 2012).

4.3.6 Reunion (France)

Reunion is a department of France and part of the Eurozone. It is therefore understood that France's legislation pertaining to marine pollution management and control apply. In 2000, France adopted its Environmental Code to reorganise the country's environmental legislation, including those pertaining to pollution prevention (Alogna, 2018).

With specific reference to pollution prevention and control, the Law on water and aquatic environments (Law 2006-1772) are important, reflecting European requirements such as the Water Framework Directive (Directive 2000/60/EC). The legal regime to protect the marine environment from industrial pollution (or any other type of pollution) includes the Law of on installations classified for the purposes of environmental protection (Law 76-663) (Alogna, 2018).

4.3.7 Seychelles

In the Seychelles the Environmental Protection Act (No 9 of 1994) is the framework environmental law providing for the protection, preservation, and improvement of the environment and for the control of hazards to human beings, other living organisms and property. It also provides for the coordination, implementation, and enforcement of policies pursuant to the national objectives on environment protection. For example, it prohibits the discharge of any effluent, or throwing, depositing or placing any polluting, or hazardous substance or waste in any watercourse or in the territorial waters without authorisation. This Act is administered by the Ministry responsible for the Environment. Specifically, the Standards and Enforcement Section is responsible to ensure that no harmful chemicals are discharged into the environment and are disposed of as permitted, while the Landscape and Waste Management Agency are responsible for monitoring the disposal of waste in all forms (*www.meecc.gov.sc/*).

The Merchant Shipping Act (No 13 of 1992, as amended) deals with a wide variety of matters relating to shipping in Seychelles waters including marine pollution. Regulations pertaining to pollution from shipping include:

- Merchant Shipping (Oil Pollution Preparedness and Response) Regulations (2001) giving legal status to Oil Pollution Preparedness, Response and Co-operation (OPRC), the Convention on Civil Liability (CLC) the Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (FUND);
- Maritime Zones (Marine Pollution) Regulations (1981) provide for the protection and preservation of the marine environment and the prevention and control of marine pollution.

The Seychelles Maritime Safety Authority (SMSA) is the regulatory and supervisory authority within the current Ministry of Tourism, Civil Aviation, Ports and Marine that has been delegated responsibility to deal with shipping activities (*http://www.seymaritimesafety.com/*).

The Seychelles Ports Authority, a parastatal organisation under the current Ministry of Tourism, Civil Aviation, Ports and Marine, is responsible for administration, regulation and control of the country's commercial ports. Activities are regulated by the Harbour Act and Regulations (1932 & 1933, amended in 1988) which cover traffic movements, pollution, waste management and ballast water discharge (*https://www.pemc.sc/seychelles-port-authority-spa*).

4.3.8 Somalia

In Somalia, the Ministry of Fisheries and Marine Resources has jurisdiction to control pollution of marine (fishing) waters under the Fisheries Law (No 23 1985, as reviewed in 2016). Article 35 prohibits any intentionally or unintentionally dumping of any polluting substances or wastes into the fishing waters that may affect marine resources, birds, the environment and human beings, disrupt fishing activities or pose a threat to sea navigation (*https://mfmr.gov.so/en/legislations/*).

The Ministry of Ports and Marine Transport promotes sustainable development of the maritime transportation sector and to ensure maritime safety and protection of the marine environment, amongst other responsibilities supported by two agencies, namely the Somali Port Authority Agency and the Somali Shipping Line Agency (*https://mpmt.gov.so/*).

The Petroleum Environmental Regulations (2017) promulgated under the Petroleum Law (No. XGB/712/08) sets out the requirements for oil and gas exploration to prevent and control pollution. Until the Somalia Petroleum Authority is established, the Ministry of Petroleum and Mineral Resources will administer these regulations (*https://mopmr.gov.so/resources/petroleum/*). The Ministry of Petroleum and Mineral Resources also is in the process of a Mining policy that will pave the way for regulatory frameworks pertaining to mining (*https://mopmr.gov.so/resources/mining/mining-policy/*).

4.3.9 South Africa

Environmental provisions are included in the Bill of Rights in the Constitution of South Africa Act (No. 108 of 1996) giving everyone the right an environment that is not harmful to their health or well-being and to have the environment protected, for the benefit of present and future generations (Walmsley and Patel, 2012).

Coastal and marine water quality (or pollution) is governed under a number of key pieces of legislation (Taljaard *et al*., 2019). Land-based pollution is controlled under the National Environmental Management: Integrated Coastal Management Act (No 24 of 2008) (ICM Act) by the Department responsible for the Environment (Branch: Oceans and Coasts). A number of policies, guidelines and regulations pertaining to the management and control of coastal pollution have been published under the ICM Act including:

- National Guideline for the Discharge of Effluent from Land-based Sources into the Coastal Environment (DEA, 2014b);
- Coastal Waters Discharge Permit Regulations (DEA, 2019);
- Recreational water quality guidelines for coastal waters (DEA, 2012a);
- Coastal water quality guidelines for natural environment and marine aquaculture (under revision).

Land-derived effluent discharges to coastal waters are subject to permitting and mandated operators to perform routine monitoring. Wastewater discharges to estuaries are also controlled under the National Water Act (No 36 of 1998) (classified as water resources under this Act).

Monitoring of environmental quality pertaining to human health (beach water quality) is delegated to metropolitan and district municipalities under the National Heath Act (No 61 of 2003). However, only a few of the larger local authorities have resources to perform routine monitoring (DEA, 2014b).

The ICM Act also controls dumping of waste at sea under the jurisdiction of the Department for the Environment (Branch: Oceans and Coasts), giving legal status to the London Convention and its 1996 Protocol. A National Action List: Screening of dredged material proposed for marine disposal (DEA 2012b) provides guidance on the quality limits for dumping of dredge spoil to sea.

To assist with the implementation of integrated coastal management (including coastal water quality), coastal management programmes and coastal committees are mandated under the ICM Act. The first national coastal programme was published in 2014 (DEA 2014a), followed by several provincial and municipal coastal management programmes. A national ministerial working group acts as the national coastal committee, with several provincial and municipal committees also in operation, although some challenges remain (Sowman and Malan, 2018).

To build capacity in coastal pollution monitoring the Government of South Africa established a National Pollution Laboratory in 2018, hosted by the Walter Sisulu University (Eastern Cape Province). Currently pilot testing is undertaken at designated sites along South Africa's coast (*www.wsu.ac.za/waltersisulu/index.php/wsu-hosts-national-pollution-lab/*).

Pollution from shipping is regulated through the Marine Pollution (Prevention of Pollution from Ships) Act (No 2 of 1986) which, together with regulations, gives legal status to the MARPOL Convention and the Annexes which South Africa has ratified. Accidental pollution from ships is dealt with under the Marine Pollution (Intervention) Act (No 64 of 1987) and the Marine Pollution (Control and Civil Liability) Act (No 6 of 1981, as amended). The responsibility of shipping falls with the Department responsible for Transport. However, responsibilities for day-to-day management of shipping activities has been delegated to the South African Maritime Safety Authority (SAMSA) and includes ensuring the safety of life and property at sea and the prevention and combating of pollution of the marine environment by ships (Jackson, 2011). While SAMSA is responsible for the implementation of shipping legislation, the responsibility for matters relating to the combating of pollution is assigned to the Department responsibility for the Environment (Branch: Oceans and Coasts). The National Ports Act (No. 12 of 2005) addresses pollution matters in ports through the National Ports Authority.

Environmental matters pertaining of offshore exploration and mining activities are regulated by the Department responsible for Minerals under the Mineral and Petroleum Resources Development Act (No. 28 of 2002) which requires holders of exploration and mining permits to manage and remedy environmental impacts (including pollution) in accordance with the National Environmental Management legislation and in consultation with relevant government agencies (DEA, 2014a).

4.3.10 Tanzania

The Constitution of the United Republic of Tanzania (1977) links a healthy environment with the wellbeing of its citizens and call on the public to ensure that natural resources of the country are managed properly obliging every person to safeguard and protect the natural resources, to combat all forms of misappropriation and wastage, amongst other matters (Walmsley and Patel, 2012).

The Environmental Management Act (2004) provides a framework for the regulation of environmental issues in general, including Pollution Prevention and Control and Waste Management. Several regulations relevant to pollution control have been issued under this Act, including (Jackson, 2011):

- Environmental Management (Water Quality Standards) Regulations (2007);
- Environmental Management (Solid Waste Management) Regulations (2009);
- Environmental Management (Hazardous Waste Control) Regulations (2009).

The primary responsibility for marine pollution on mainland Tanzania lies with the National Environment Management Council (NEMC) (*www.nemc.or.tz/*). The NEMC has sole responsibility for control of land-based sources of pollution, and shares responsibilities on other matters pertaining to pollution of the marine environment.

Together with the NEMC the Tanzania Ports Authority (established under the Tanzania Ports Act – 2004) controls pollution in ports and harbours on mainland Tanzania, while the Zanzibar Ports Corporation fulfils this function in Zanzibar's main ports (Jackson, 2011).

The Merchant Shipping Act (No.21 of 2003) provides for pollution prevention and protection of the marine environment and marine security (Guromo 2017). Regulations under this Act include:

- Merchant Shipping (Prevention of Oil Pollution) Regulations (2012), providing technical and detailed guidelines for prevention of marine oil pollution.

- Merchant Shipping (Oil Pollution Preparedness, Response and Co-operation) Regulations (2012) prescribing requirements for harbours, oil handling facilities, and offshore installations.

The National Marine Oil Spill Response Contingency Plan (2016) is the national response to OPRC (1990) requirements, executed under the National Marine Oil Spill Coordinating Committee. The plan covers oil pollution response to the lakes and rivers but does not cover response to oil pollution originating from land-based activities and sources (Guromo, 2017).

Petroleum exploration and development in Tanzania is governed under the Petroleum Act (No 21 of 2015). Part vii of the Act addresses environmental principles and liability towards pollution prevention. The Energy and Water Utilities Regulatory Authority (EWURA) is an autonomous multi-sectoral regulatory Authority that is obliged to comply and enforce the Petroleum Act (2015) (*https://www.ewura.go.tz/home/)*.

4.4 Conventions

Various conventions exist which indirectly promote and encourage the use of CW technology for water pollution abatement. This section covers water governance aspects and the relationship with hydrological principles of water flow in aquifer (unconfined and confined) with surface (river basins or watercourses) and groundwater interactions that impact inclusion of constructed wetland issues in various international conventions. These conventions and soft laws (legal arrangements) create important precedence to principles for cooperation and frameworks for different agreements to be made later for constructed wetlands at an international stage.

The UN Watercourses Convention: Convention on the Law of the Non-navigational Uses of International Watercourses 1997 is a framework convention governing international watercourses and it is the only treaty governing shared freshwater resources that is of universal applicability. The key points of the convention include equitable and reasonable utilization and participation; taking all appropriate measures not to cause significant harm; Protection of ecosystems of an international watercourse.

The Draft articles on the Law of Transboundary Aquifers 2008 was prepared by the International Law Commission (ILC) and adopted by UN General Assembly in 2008. It improved the scope of other conventions such as the United Nations Convention Watercourse (McCaffrey, 2009). Among others, it accurately and most usefully reflects the hydrology of aquifers (not groundwater in general but the aquifer system) including regulation of fossil aquifers and by regulating all groundwater system in an integrated framework emphasizing on the protection and preservation of aquifers (Quadri, 2015). However, Devlaeminck, (2021) indicated that the 2008 Draft Articles on the Law of Transboundary Aquifers have yet to be fully adopted by the international community and there are areas to be revisited. In relation to CW, the discharge can have effects on aquifers in terms of recharge and pollution resulting in groundwater water quality issues.

The African convention on the conservation of nature and natural resources 2003 is a continent-wide agreement (revised) signed in Maputo in 2003 and entered into force in 2016. It has broad objective of encouraging conservation, utilisation and development of soil, water, flora and fauna for the present and future welfare of mankind, from an economic, nutritional, scientific, educational, cultural and aesthetic point of view. It covers abroad aspects including quantitative and qualitative management of natural resources such as soil and land, air and water and biological resources. It takes on board processes and activities affecting the environment and natural resources, procedural rights and provides mechanisms and secretariat to assist its implementation. Also, it demands cooperation in case of its implementation requirements and when transboundary effects may occur (Steiner, 2009). The Parties shall take all necessary measures for the protection, conservation, sustainable use and rehabilitation of vegetation cover including wetlands. For the land and soils, The Parties they shall ensure that non-agricultural forms of land use, including but not limited to public works, mining and the disposal of wastes, do not result in erosion, pollution, or any other form of land degradation (AU, 2016).

The Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat is an international treaty for the conservation and sustainable use of Ramsar sites (wetlands). It is also known as the Ramsar Convention, after the Iranian city in which it was adopted in 1971. The Convention on Wetlands provides the framework for international cooperation and national action for the conservation and wise use of wetlands and their resources. Almost 90% of UN member states are Ramsar Contracting Parties (Ramsar, 2014; Rica, 2015).

The Conference of the Contracting Parties (COP) as representatives of the contracting parties and the policy-making organ of the convention meets every three years and promotes policies and guidelines to advance the objectives of the Convention. The Convention has three pillars: wise use of all wetlands, designate the list of Wetlands of International Importance (the "Ramsar List") and ensure their effective management and cooperate internationally on wetland issues. The Convention uses a broad definition of wetlands. It includes all lakes and rivers, underground aquifers, swamps and marshes, wet grasslands, peatlands, oases, estuaries, deltas and tidal flats, mangroves and other coastal areas, coral reefs and all human-made sites such as fishponds, rice paddies, reservoirs and salt pans. In this case, constructed wetlands fall under human-made sites. For example, in Tanzania, there are biological important areas of Ramsar wetlands called Ihefu and other protected reserves such as Ruaha National Park (RNP), Kitulo, Mpanga Kipengele within the Great Ruaha River catchment, which comprise nearly twice number of biodiversity compared to the whole Europe (Williams *et al*., 2010). Other designated four wetlands as RAMSAR sites are: Rufiji- Mafia-Kilwa Marine (2004); Malagarasi – Muyowosi (2000); Lake Natron Basin (2001) and Kilombero Valley Floodplain (2002) (URT, 2021).

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 is commonly called the "London Convention" or "LC '72" and also abbreviated as Marine Dumping. The London Convention was adopted in 1972 and came into force in 1975. It is an international treaty that created a global system to protect the marine environment from pollution caused by ocean dumping. This Convention ensures that the few materials that are permitted for ocean disposal are carefully evaluated to make sure that they will not pose a danger to human health or the environment and that there are not more feasible alternatives for their reuse or disposal (EPA, 2022). Its objective is to promote the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter. The Convention was later replaced by the London Protocol (Sec. 4.2.3).

The International Plant Protection Convention (IPPC) is a 1951 multilateral treaty overseen by the UN Food and Agriculture Organization (FAO) that aims to secure coordinated, effective action to prevent and to control the introduction and spread of pests of plants and plant products. The Convention extends beyond the protection of cultivated plants to the protection of natural flora and plant products. It also takes into consideration both direct and indirect damage by pests, so it includes weeds.

The Convention created a governing body consisting of each party, known as the Commission on Phytosanitary Measures (CPM) established in 2005, which oversees the implementation of the convention with a strategic framework for capacity building, protection of environment and ecosystems, and facilitation of trade. The convention is recognized by the World Trade Organization's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (the SPS Agreement) as the only international standard setting body for plant health. The same applies to the Southern African Development Community (SADC) Protocol on Trade (SADC, 2008). Under the IPPC is Regional Plant Protection Organizations (RPPO) such as the Inter-African Phytosanitary Council (IAPSC). These are an intergovernmental organization responsible for cooperation in plant protection. The African Union (AU)-IAPSC established in 1954 is mandated to coordinate and provide support to the protection of plant resources for the welfare and economic development of the Member States of the AU. It focuses on robust plant health systems and reduced pest risks, which contribute to better livelihoods, enhanced trade and biodiversity preservation in Africa.

While the IPPC's primary focus is on plants and plant products moving in international trade, the convention also covers research materials, biological control organisms, germplasm banks, containment facilities, food aid, emergency aid and anything else that can act as a vector for the spread of plant pests for example, containers, packaging materials, soil, vehicles, vessels, and machinery. In this case, reeds or microphytes and on their harvests from constructed wetlands could be an issue of concern. The IPPC places emphasis on three core areas: international standard setting, information exchange and capacity development for the implementation of the IPPC and associated international phytosanitary standards.

The Convention on Biological Diversity (CBD) is the international legal instrument and multilateral treaty for "the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources". Its overall objective is to encourage actions, which will lead to a sustainable future. The Convention on Biological Diversity covers biodiversity at all levels: ecosystems, species, and genetic resources. It also covers biotechnology, including through the Cartagena Protocol on Biosafety. The CBD's governing body is the Conference of the Parties (COP), which meets every two years to review progress, set priorities and commit to work plans. The Jakarta Mandate is an associated instrument, which provides specific requirements for marine biodiversity conservation and identifies five key areas: integrated coastal management (ICM), sustainable use of living resources, Marine Protected Areas (MPAs), mariculture and alien species (www.biodiv.org). The International Day for Biological Diversity is held every year on 22 May.

4.5 International/ Regional Strategies and Projects

4.5.1 Strategies

Most of the regional strategies are organised around the regional economic integration communities or blocks presented in Sect.

4.5.2 Projects

There are a number of projects related to constructed wetlands. The Nairobi Convention Secretariat is implementing several projects within the Western Indian Ocean region as indicated hereunder.

The Implementation of the Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities (WIOSAP) project is intended 'to reduce impacts from land-based sources and activities and sustainably manage critical coastal-riverine ecosystems through the implementation of the WIO-SAP priorities with the support of partnerships at national and regional levels. The WIOSAP project subscribes to the Nairobi Convention, and it presents an opportunity to the governments in the region and their conservation partners to jointly implement strategies of protecting the coastal and marine ecosystems from land-based sources and activities to provide essential goods and services on sustainable basis. The project was funded by the Global Environment Facility for the project period 2016 – 2021. It strives to reduce these land-based stresses by protecting critical habitats, improving water quality, and managing river flows. The participating countries are Comoros, Kenya, Mauritius, Madagascar, Mozambique, Seychelles, Somalia, United Republic of Tanzania, Republic of South Africa and France – Non-project beneficiary and was implemented by UNEP and executed by the Nairobi Convention Secretariat.

The Constructed Wetland Technology as Nature-based Solution for Sustainable Municipal Wastewater Treatment in Western Indian Ocean (WIO) Region project has the objective of publishing a book on constructed wetland technology as a wastewater treatment solution for WIO region. The published book will be one of tools that WIOSA can used to help in pollution control from land-based activities and sources and management of municipal wastewater while drawing the regional CWs experiences and expertise. The project is being implemented by the University of Dar es Salaam (UDSM) and the Western Indian Ocean Marine Sciences Association (WIOMSA) in collaboration with the University of Dodoma (UDOM). The project is being funded by the WIOMSA for the period June 2021 - June 2023.

The WIO Marine Biodiversity Conservation Project funded by NORAD aims to implement the Jakarta Mandate and has identified MPAs as a priority theme for focus. The project on capacity building in MPA management in the WIO region is aimed at providing training in skills, techniques, and tools necessary for effective management of MPAs in the region. The project is supported by the Coastal Zone Management Centre (CZMC) of the Netherlands and implemented in collaboration with WIOMSA.

The Nairobi Convention's "Western Indian Ocean Large Marine Ecosystems Strategic Action Programme Policy Harmonisation and Institutional Reforms (SAPPHIRE) project", promotes policy and institutional reform to help improve the management of the Western Indian Ocean Large Marine Ecosystems (LME), also known as the Entire regions of the world's oceans. It builds capacity among governments, communities, partners, intergovernmental organizations and the private sector in sustainable resource management and ocean governance. The project is funded by the Global Environment Facility for the project period 2017 – 2023. It is being implemented in Comoros, France, Kenya, Mauritius, Madagascar, Mozambique, Seychelles, Somalia, United Republic of Tanzania, and Republic of South Africa by UNDP and executed by UNEP-Nairobi Convention (Secretariat).

4.6 International and Regional Institutional Framework

Institutional arrangement is important and necessary for governance of the water resources related to constructed wetlands.

4.6.1 Western Indian Ocean (WIO) Region

The significant and one single most important WIO project is the Western Indian Ocean region consisting of 10 countries: Somalia, Kenya, Tanzania, Mozambique, South Africa, Comoros, Madagascar, Seychelles, Mauritius, Réunion (France). The WIO is being degraded by activities that harm marine life, undermine coastal communities, and negatively affect human health. These threats make it more important than ever for governments in the region to work together to strengthen protection of the ocean. As a result, the Nairobi Convention was signed by WIO countries: Comoros, France, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, Somalia, Tanzania, and the Republic of South Africa.

The COP is the main decision-making body of the Nairobi Convention, composed of experts from each country where policies and strategies are agreed on to continue the protection, management, and development of the Western Indian Ocean. The above showed that in the span of 14 years (1989-2003) ten countries recognized the need to protect, manage, and develop the Western Indian Ocean.

In 2010, the Conference of Parties, Contracting Parties adopted the following as part of legal instruments:

- Protocol for the Protection of the Marine and Coastal Environment of the Western Indian Ocean from Land-Based Sources and Activities;
- Amended Nairobi Convention for the Protection, Management, and Development of the Marine and Coastal Environment of the Western Indian Ocean.

To address emerging issues in the region, the COP has also established expert groups and task forces, such as the Mangrove Network, the Coral Reef Task Force, Marine Turtle Task Force, the Forum for Academic and Research Institutes (FARI), and the Legal and Technical Working Group.

4.7 National Institutional Frameworks

The institutional arrangement with legal framework in place provides mechanisms to manage water resources and the environmental issues. The following are the institutional frameworks for the countries, which involves different sectors of governing bodies:

4.7.1 Institutional Framework in Kenya

At the national level, responsibilities for sanitation are divided between the Ministry of Health and the Ministry of Water and Sanitation (GLAAS, 2019). The Water Sector Strategic Plan (WSSP) 2009–2014, which brought together policies and plans from all relevant stakeholders, indicated that the sanitation sector is under the responsibility of the Ministry of Health and the Ministry of Water and Sanitation (GoK, 2009); and the Ministry of Environment and Natural Resources (GoK, 2016).

Figure 4.1 gives the representation of the institutional framework of the water sector under the Ministry of Water, Sanitation and Irrigation (MoWSI).

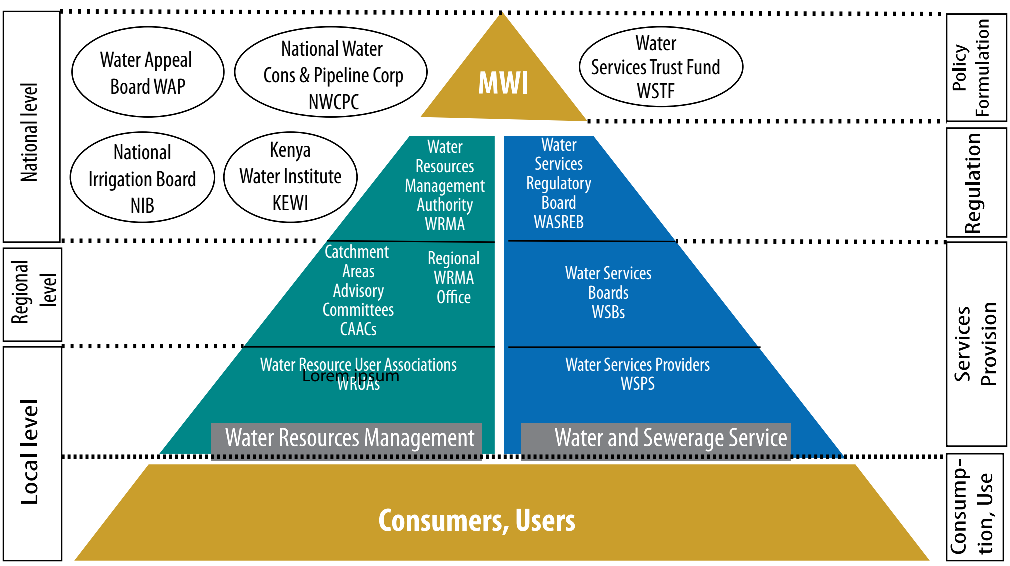


Figure 4.1: A schematic representation of the institutional framework for the water sector under the Water Act 2002 (MoWI, 2007).

The Ministry of water, sanitation and irrigation is in charge of water affairs and deals with policy and strategy formulation, development of legislation, mobilization of funds, coordination and monitoring. There are three sub-sectors: WRM, WSS and WSTF. This is particularly crucial for areas like pollution of raw water sources, issuing of extraction permits, clustering of WSS systems, etc. The WASREB regulates water service provision; the WSBs oversee assets and contracting WSPs for WSS from the public, private, community and civil society sectors while the WRMA oversees WRM (RoK, 2013). All these institutions report to boards that represent different stakeholders' interests. The Catchment Areas Advisory Committee (CAACs) is an advisory body to WRMA for the regulation of water resources issues at the regional level. The subregional offices of WRMA provide water resources management (WRM) services at subregional level under the regional offices of WRMA (RoK, 2013).

The MoWSI has several state corporations and water work development agencies. The corporations are: Regional Center on Groundwater Resources, Education, Training and Research, National Irrigation Board, Water Sector Trust Fund, National Water Harvesting and Storage Authority, Water Resources Authority, Kenya Water Institute, Water Services Regulatory Board, Hydrologists Registration Board, Water Appeal Board, and Imarisha Naivasha. The water works development agencies are: Athi Water Works Department Agency, Central Rift Water Works Development Agency, Tana Water Works Development Agency, Tanathi Water Works Development Agency, Coast Water Works Development Agency, Lake Victoria South Water Works Development Agency, Lake Victoria North Water Works Development Agency, Northern Water Works Development Agency and North Rift Water Works Development Agency.

4.7.2 Institutional Framework in Mauritius

The **Ministry of Energy and Public Utilities** is responsible for the water sector in Mauritius. It formulates policies and strategies for the mobilization and conservation of water resources and management of supply and distribution of water. The Water Resources Unit operates under the auspices of the Ministry and is responsible for the implementation of water mobilization projects and water resources administration.

The Central Water Authority (CWA) is administered and controlled by a Central Water Board (CWB). The CWA operates under the auspices of the Ministry of Energy and Public Utilities. It is responsible for the control, development and conservation of water resources and the treatment and distribution of water to domestic, industrial, and commercial purposes throughout Mauritius. The CWA is mainly responsible for the treatment and distribution of potable water for domestic, commercial, and industrial usage (*http://cwa.govmu.org*).

In the wastewater sector, the Wastewater Management Authority (WMA) operates under the auspices of the Ministry of Energy and Public Utilities. The core service of the WMA is the collection and treatment of domestic, commercial and industrial wastewaters for disposal to an environmentally acceptable quality, ensuring the country's sustainable development through the provision of appropriate water pollution standards, wastewater control systems and management services to the entire population of Mauritius (*https://www.wmamauritius.mu/*).

The Utility Regulatory Authority (URA) is an independent body set up by the Government of Mauritius and its role is to regulate the utility services, namely electricity, water and wastewater. Its objectives are to ensure the sustainability and viability of the utility services; protect the interests of consumers; promote efficiency in both operations and investments in respect of utility services; and promote fair competition in the utility services industry (*https://publicutilities.govmu.org/*).

The Ministry of Environment, Solid Waste Management and Climate Change, among others, preserves the beaches through integrated coastal zone management; and devises effective waste management policy to minimize the negative impacts of solid and hazardous wastes. It has several departments among others: policy planning, environmental assessment, EIA/PER monitoring, environmental law and prosecution integrated coastal zone management, pollution prevention and control, and sustainable development (*https://environment.govmu.org/*). The Solid Waste Management Division in the ministry is responsible for the protection of the environment and public health through a proper management of solid waste and hazardous waste. Also, the Climate Change Information Centre (CCIC) deals with climate change adaptation functions and information services.

4.7.3 Institutional Framework in Seychelles

The Ministry of agriculture, climate change and environment govern different public bodies that deal with water management, protected area management, botanical gardens management, waste and energy issues. The Ministry is under the leadership of the Minister, who is responsible for the Environment and Energy and Climate Change Departments. These Departments are responsible for the development of policy and regulatory frameworks whilst the authorities and agencies (*i.e.*, NBGF, LWMA, PUC, SNPA, SEC and NMS) are the arm length of the Ministry with the responsibility to put these policies into practice. The Environment Department has two divisions: Waste, Enforcement and Permit Division, and Biodiversity and Conservation Management Division. The Energy and Climate Change Department has the responsibility for energy, water and other related issues pertaining to climate change. The relevant authorities and agencies are briefly explained hereunder.

Public Utilities Corporation (PUC) is a government parastatal, which provides electricity, water, and sewerage services in Seychelles. Its mission is to provide an efficient, safe and reliable supply of electricity and treated water, to treat and dispose wastewater, paying due regard to the environment and customers' interests. Landscape and Waste Management Agency (LWMA) is the Agency responsible for the management of waste in the Seychelles and for implementing policies that deals with waste and sewage management. LWMA supervises the work of the contractors to ensure that waste is properly collected, treated and disposed at the Landfill. The agency puts a lot of efforts in promoting public sensitization especially regarding good waste management practices and promulgation of the 3 R's (Reduce, Recycle and Reuse).

The Town and Country Planning Authority as an inter-ministerial body created under Town and Country Planning Act and are responsible for the approval of all land development proposals in Seychelles. Accordingly, any developments on constructed wetlands need approval from the authority.

4.7.4 Institutional Framework in Tanzania

In Tanzania, the relevant ministries related to constructed wetlands include the Ministry of Water, State Ministry for Environment under the Vice President's office and Ministry of Health.

Tanzania incorporated Integrated Water Resources Management (IWRM) in her policy frameworks and strategies since 2000s to create Institutional Water Management Framework (IWMF) that provides space for various stakeholders from national to community level to participate into governing water resources (URT, 2020).

In Tanzania, River Basin Organizations (RBOs) are acknowledged by the Institutional Water Management Framework (IWMF) for implementing participatory governance to water resources management under the ministry of water (Figure 4.2). The IWMF comprised of the National Water Board (NWB) which is inter/multisectoral advisor board; autonomous bodies such as Basin Water Boards (BWBs), which operate at the basin level, Catchment Management Committees or Catchment Water Committees (CWCs), which operates in the catchment level, Sub-Catchment Water Committees (SCWCs) operating in the sub-catchment level and Water User Associations (WUAs) operating in the community levels and Local Government Authorities (LGAs) are represented in all levels (URT, 2009)as it accounts for 45% of GDP and is the source of livelihood for more than three-quarters of the population. The majority of the population is still rural although urbanization increased in the last three decades to reach 38%. Currently the rate of urbanization is slowing down. The population is very young, as 43% of Tanzanians are below 15 years of age. Life expectancy, now 46 years on average, has decreased

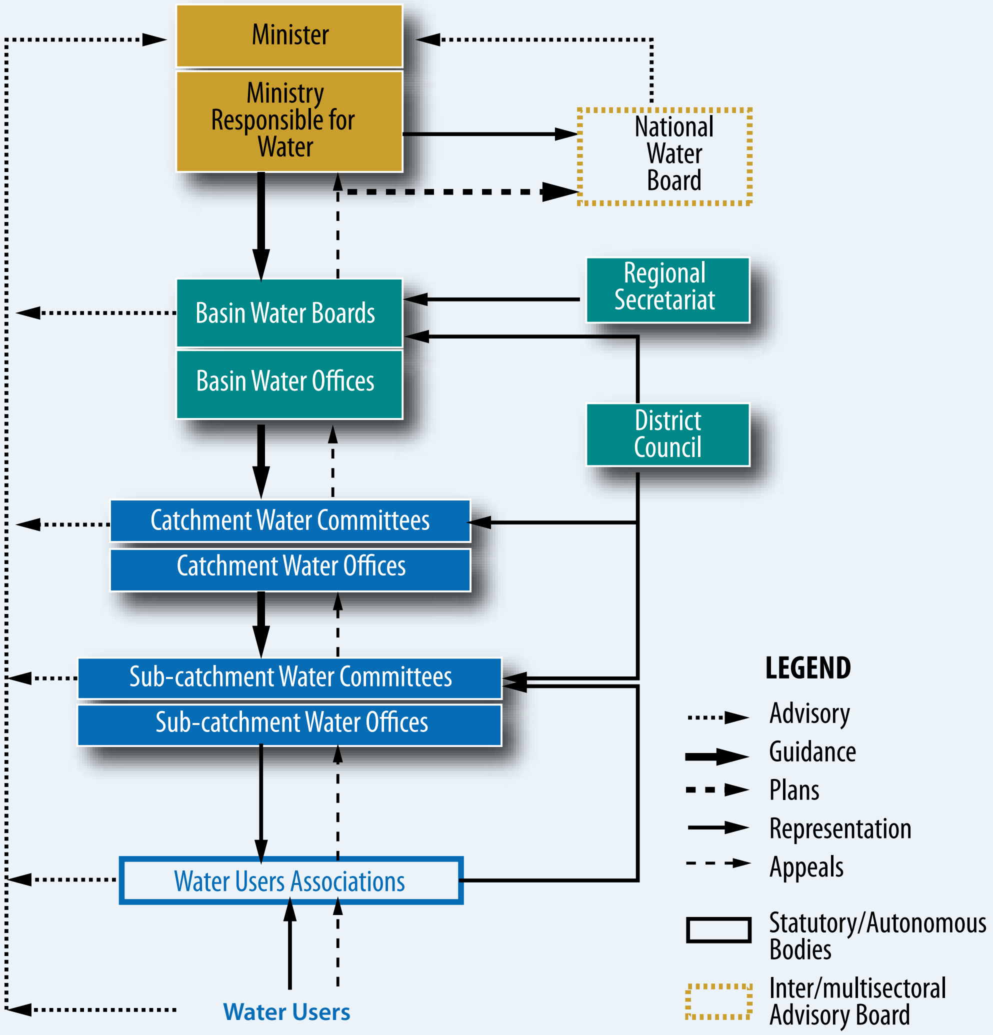


Figure 4.2: Institutional Water Management Framework (IWMF) in Tanzania (Source: Kabogo et al., 2017)

in the past 20 years, probably due to increasing HIV/AIDS prevalence, which affects around 7% of the adult population. Although improvement was observed during the last decade, infant and underfive mortality rates remain high. Eighty percent of the population has physical access to health facilities, but user fees and poor quality of services, mainly due to lack of skilled health personnel, reduce the effectiveness of the health system. However, immunization coverage among infants is very high. Poor sanitation conditions are common both in the rural and urban areas, while access to safe water is a problem mainly for rural inhabitants. In the rural population, poverty is widespread, as approximately 40% of the population are below the basic needs poverty line, while in the urban areas approximately a quarter of the population is poor. The diet is based on cereals (maize and sorghum.

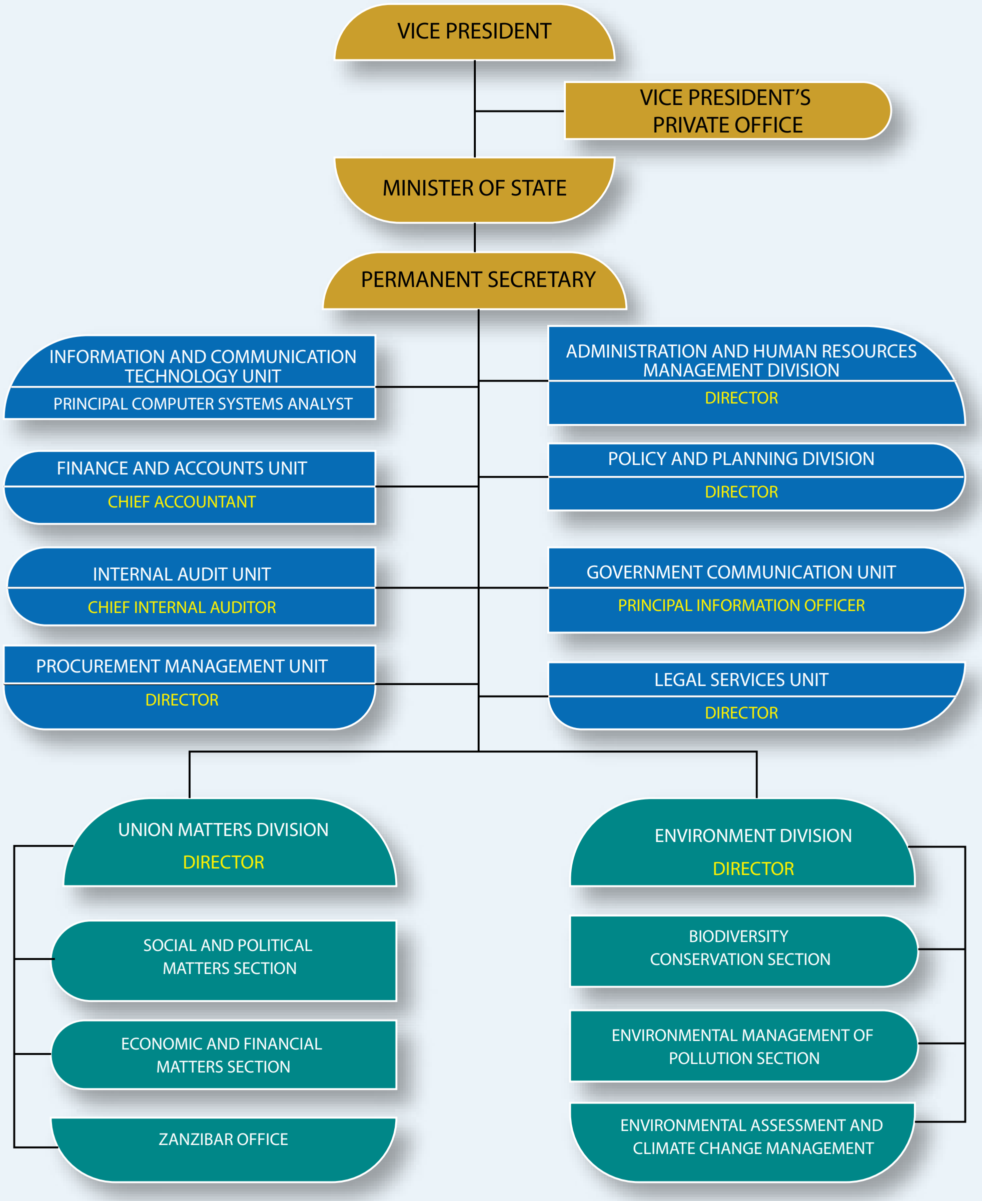
In the ministry of water, wastewater management is handled through urban water supply and sanitation authorities (WSSAs) and rural water supply and sanitation agency (RUWASA). The urban WSSA is organized for a city, municipality, regional and district headquarters, town councils as well as national projects water authorities. While in the large rural area, there is an organization from the national, regional, district to the lower levels through the RUWASA governance structure. In terms of the organization structure, the ministry of water with its water supply and sanitation division oversees the WSSAs through the Board of Directors and managing directors of the respective WSSAs.

The WSSAs are regulated by the Energy and Water Utilities Regulating Authority (EWURA) under the directorate of water and sanitation. The functions of EWURA include among others, licensing, tariff review, monitoring performance and standards with regards to quality, safety, health and environment in water and energy sectors.

Section 28 of the *Water Supply and Sanitation Act, 2019* and *EWURA Act Cap 414 2006*, provide mandates to EWURA, to perform both technical and economic regulation of water supply and sanitation services in Tanzania, in order to protect stakeholders' interests; ensuring sustainability of service providers' financial viability and promoting availability of regulated services to all consumers including low income and disadvantaged.

The Water Supply and Sanitation Act No.5 of 2019, among other things, established The Rural Water Supply and Sanitation Agency (RUWASA) which took over mandates that were previously vested to PO-RALG, Regional Secretariats (RSs) and Local Government Authorities (LGAs). The transferred mandates involve ensuring the provision of water services to rural communities, small towns, and district headquarters. The Act also transferred accountability of officers responsible for water service provisions from PO-RALG, RSs and LGAs to the Ministry of Water. RUWASA has offices at Headquarters, Regional and District levels as opposed to previous structure which compose of office at LGA's level and RSs.

Waste management is continuously evolving in developing countries including Tanzania. The Government of Tanzania considers environmental management as a priority agenda. There is an institutional arrangement to deal with waste and wastewater management. In Tanzania, the environmental matters are overseen by the Ministry of State under the Vice President's Office, Union and Environment (Figure 4.3). The Minister of State for Environment is the head of the Ministry of State in the Vice President's Office.



.

Figure 4.3: Policies, Laws, and Institutions Related to Constructed Wetlands-21: The Organization structure of the Vice President's Office (VPO).

The environment division has the objective of providing overall policy guidance, coordination, expertise and services for sustainable environmental management and development. Among other functions, it oversees the operations of the National Environment Management Council (NEMC). NEMC was established with a broad mandate in response to the national need for such an institution to oversee environmental management issues and implement the resolutions of the Stockholm Conference on Environment and Development of 1972, which called upon all nations to establish and strengthen national environmental Councils to advise governments and the international community on environmental issues. EMA 2004 gives NEMC mandates to undertake enforcement, compliance, review and monitoring of environmental impacts assessments, research, facilitate public participation in environmental decision-making, raise environmental awareness and collect and disseminate environmental information. Accordingly, the objective of NEMC is to undertake environmental enforcement, compliance, review and monitor environmental impact statements, research and awareness rising. In this case, CW needs to comply with environmental standards and requirements.

4.8 National Policies and Strategies

In this section, policies for water resources and environmental management in relation to constructed wetlands are discussed.

4.8.1 Policies and Strategies in Kenya

Both the Ministry of Health (MoH) and the Ministry of Water, Sanitation, and Irrigation (MoWSI) are involved in sanitation in Kenya; each ministry has policies that affect sanitation in the country. The National Water Policy of Kenya currently known as the National Policy on Water Resources Management and Development (NWP) 1999 (RoK, 2013). The policy aims at achieving sustainable development and management of the water sector by providing a framework in which the desired targets/goals are set, outlining the necessary measures to guide the entire range of actions and to synchronise all water-related activities and sectors.

A strategy to operationalize the water policy was developed in 2007, followed by a Sector Investment Plan (SIP) in 2009 (MoWI, 2007). In the sanitation subsector, an environmental sanitation and hygiene policy was published in 2007, and the accompanying strategy and investment plan are in development (Ministry of Health, 2007). The Kenya Environmental Sanitation and Hygiene Policy 2016-2030 replaces the National Environmental Sanitation and Hygiene Policy of 2007. The policy focuses on a range of complementary strategies devoted to ensuring universal access to improved sanitation and clean and healthy environment by increasing the proportion of the population with access to improved sanitation to 100% by 2030. Importantly, the Kenya Environmental Sanitation and Hygiene (KESH) Policy 2016-2030 (GoK, 2016) mentioned and gave emphasis on less energy intensive technologies among others constructed wetlands. The Kenya Environmental Sanitation and Hygiene Strategic Framework (KESSF) 2016-2020 provides the framework for implementation of the KESH Policy 2016-2030 and is guided by the Kenya Health Policy 2012-2030, which targets to attain the highest level of health commensurate with that of a middle-income economy. It conveys the strategic interventions necessary for achieving open defecation free Kenya by 2020 as well as universal access to improved sanitation and a clean and healthy environment for all by 2030.

In accordance with Kenya's 2010 Constitution, long-term development plan, Vision 2030, and international commitments, the Kenya Health Policy, 2014–2030 provides guidelines for ensuring a significant improvement in Kenya's overall health status. Under the government's direction, it demonstrates the commitment of the health sector to achieving the highest possible health standards in a way that meets the needs of the population (GoK, 2014).

The National Water Services Strategy (NWSS) was derived from the water sector policy. The strategic framework for the water services subsector is provided by the NWSS, which spans the years 2007 to 2015. The National Water Master Plan 2030 launched in 2014 facilitates planning for development and management of water resources of Kenya. It considers water reliability and quality, climate change and transfer of technology in the management of water resources (RoK, 2013). It aligns with the Kenya Vision 2030 aiming to ensure that improved water and sanitation are available to all.

The Ministry of Water and Sanitation Strategic Plan 2018–2022 detailed priority projects or developments that will be implemented during the period. The implementation of the strategic plan shall help the country to achieve universal access contributing to meet the national development goals and Sustainable Development Goals (SDG) No. 6 (GoK, 2018). The Water Resources Authority Strategic Plan 2018 – 2022 by the Water Resources Authority (WRA, 2019) presents the mechanism of WRA to regulate the management and use of water resources in Kenya. It is the key operational planning document for the WRA detailing organizational objectives, activities, resource needs, and monitoring and evaluation approaches during the period 2018-2022.

The National ODF Kenya 2020 Campaign Framework 2016–2020 aims to eradicate open defecation and to declare 100% villages and Kenya open defecation (ODF) by 2020 (RoK, 2016). It also aimed at increasing awareness of and access to available sanitation solutions and technology options. This was to be achieved through the development of key sanitation stakeholders' capacities, the creation of an efficient monitoring and evaluation system, the mobilization of partners and the media to support the campaign goals, the facilitation and assistance of County Governments in achieving their respective ODF targets, the engagement and enabling of the private sector to effectively respond to the demand created for sanitation materials and products, and the mobilization of resources. This Campaign Framework was aligned with the Kenya Environmental Sanitation and Hygiene Policy (KESHP) 2015-2030 and the Kenya Environmental Sanitation and Hygiene Strategic Framework (KESSF) 2015-2020.

The African Ministers' Council on Water (AMCOW) developed the African Sanitation Policy guidelines, which were adopted in the formulation of Kenya's National Sanitation Management policy. Kenya is the first nation in Africa to do so. The goal of the National Sanitation Management Policy (NSMP) is to provide an enabling policy framework that improves universal access to equitable, sustainable, and safely managed sanitation services throughout the service chain. This will help the Kenyan government's efforts to ensure that everyone has access to safely managed sanitation by 2030. This gives NSMP the institutional foundation it needs to fulfil Kenya's commitments to achieving SDG 6.2. A Multi-Stakeholder Steering Committee led by the Principal Secretary of the Ministry of Health was in charge of the overall consultative and participatory development of the NSMP.

The National Environment Policy (NEP) 2013 aims to provide a framework for an integrated approach to sustainable management of Kenya's environment and natural resources. In particular it proposes to strengthen: legal and institutional framework, integrated environmental management, research and capacity development, new environment management tools, collaboration and cooperation and partnerships in environment management, domestication, co-ordination and maximisation of benefit from Strategic Multilateral Environment Agreements, and intended climate change-related policy actions. It establishes governmental responsibilities for water quality protection, including the development of basin management plans, emphasizing wetland protection, and promotes user and polluter-pays principles.

The National Water Master Plan (NWMP) 2014 creates detailed national level plan for development and use of water resources by 2030. Other strategies and plans include:

- Environmental Sanitation Strategy and Action Plans (ESSAPs);
- Urban Strategic Environmental Sanitation Investment and Financing Plan (USESIFP);
- Urban Environmental Sanitation and Hygiene Strategic and Action Plans (UESHSAPs);
- Water and Sanitation Programme (WSP);
- Water and Sanitation Programme Africa Region (WSP-AF); and
- Water Sector Strategic Plan (WSSP).

4.8.2 Policies and Strategies in Mauritius

Water and Energy for all has been one of the key policies of the government for many years. Our challenge for the future is to accelerate the absorption of renewable energy and introduce nationwide energy efficiency measures including the regulation of the standard of electric appliances entering the country. The work of the Ministry is governed by the Seychelles Sustainable Development Strategy 2012-2020, the National Waste Strategy, the National Biodiversity Strategic Action Plan, the Climate Change Strategy, the National Energy Policy, the Water Master Plan and other policy documents.

4.8.3 Policies and Strategies in Seychelles

The water resources of Seychelles are at risk from pollution and other environmentally harmful activities. Several rivers and streams are polluted by discharges from septic tanks (domestic and agricultural), civil works and the dumping of waste. Therefore, relevant policies are in place to meet the national policy priorities for environmental and water resources management at all levels.

The Seychelles Wetlands Policy and Action Plan 2019-2022 was established with the intention to regulate the developments in and around the wetland areas and support EIA process through its classification system. It provides framework for allocating water resources among many users, appropriate measures to sustainably manage and protect catchment forests, adoption of necessary measures to prevent and control pollution (point and non-point sources) of ground and surface waters, following a source-to sea approach to the management of water resources and prevent negative impacts on the coastal and marine environment, and management of wetlands and rivers including climate adaptation and management (GoS, 2019). However, constructed wetlands for the purpose of wastewater treatment were not covered. Water reservoirs as constructed wetlands were the only ones featured.

The National Water Policy 2017 provides a general framework for the water sector to achieve the following objectives: manage the country's water resources on an equitable and sustainable basis; ensure the availability of good quality water to all sectors of the economy; promote efficient consumption of water; maintain performance of water supply services by applying modern management practices; develop an appropriate legal, regulatory and institutional framework for the optimal, integrated management of the country's water resources.

The National Integrated Water Resource Management (IWRM) Plan 2017 endorses IWRM approach. Together, the policy and plan provide the basis for sustainable, equitable, and coordinated development. They will also support the cross-sectorial management of water, land, coastal, and estuarine environments that impact the ocean and related resources in this island state.

The Seychelles Strategic Land Use and Development Plan 2015 is a multi-sectorial policy document, which sets out the long-term spatial planning framework for the country up to 2040. It provides a tool for coordinated decision-making and investment, helps ensure that infrastructure provision is aligned with growth locations, and guides the amount and location of development. The Plan has identified strategies for enhancing agricultural production and protecting environment and agricultural land (GoS, 2015).

The Seychelles Sustainable Development Strategy (SSDS) 2012-2020 is a national plan that includes national priorities for sustainable development and outlines a path for putting those priorities into action. Through an innovative, knowledge-driven approach, the Strategy aims to contribute to the realization of the nation's economic, social, and cultural potential while being mindful of the need to preserve the Seychelles' natural environment and heritage for present and future generations. The Strategy particularly stresses the significance of encouraging efforts to adapt and investments in renewable energy. Estimates are made of the resources required to achieve these objectives and preserve biodiversity.

Solid waste master plan (2003-2010) was planned to be updated and the proposed 2011–2020 Solid Waste Master Plan to complement SSDS main objectives and programmes, specifically for waste management. By 2016, this updated Solid Waste Master Plan had not yet been developed (Lai *et al*., 2016). To handle waste, the Landscape & Waste Management Agency (LWMA) was established in 2009; clean streets, rivers, beaches, and other facilities; and oversee the improvement of public landscapes in Seychelles. In addition, it is LWMA's responsibility to provide the environment minister with advice regarding waste management plans and laws, including Land Waste Management Strategy (RoS, 2020).

Other strategies and plans in Seychelles include the following:

- Public Utilities Corporation Act (Cap 196) “regulates the use of water throughout the country as well as sewage disposal systems both public and private”;
- Sanitation master plan (2010-2025) will contain the main strategy for sanitation services in the Republic of Seychelles;
- Seychelles water supply development plan (2008-2030) “to ensure availability of adequate and affordable water up to the year 2030 to meet needs of the population, industry and tourism”;
- Seychelles National Climate Change Strategy “minimise the impacts of climate change through concerted and proactive action at all levels of society””.

Through coordinated and proactive action at all levels of society, the Seychelles National Climate Change Strategy 2009 aims to reduce the effects of climate change. It identifies five strategic goals: 1) to improve comprehension of the effects and appropriate responses of climate change; 2) to put in place measures to adapt, build resilience, and reduce vulnerability to the effects of climate change; 3) to achieve sustainable energy security by reducing greenhouse gas emissions; 4) to incorporate climate change into national policies, strategies, and plans; and 5) to build capacity and social empowerment at all levels to respond appropriately to climate change. Environment Protection Act (Cap 71) – “provides for the protection, improvement and preservation of the environment and for the prevention, control and abatement of environmental pollution.”

State Land and River Reserves Act (cap 228) – “makes provision for the management and alienation of State land, for the appointment of forest rangers and for the protection of State lands and River Reserves.” Seychelles Sustainable Development Strategy (2012-2020) - “sets the plan for the implementation of priorities for government, the private sector and the public at large with the final goal of improving sustainable development management in the Seychelles”.

Environmental management in Seychelles is guided by the second Environment Management Plan of Seychelles (EMPS 2000 - 2010), which has the following goal: “the promotion, coordination and integration of sustainable development programmes that cut across all sectors of society in the Seychelles”. The EMPS covers economic sectors (fishery, agriculture, forestry, and tourism), infrastructure (transport, water, sanitation, solid waste) and regulation as well as capacity building.

4.8.4 Policies and Strategies in Tanzania

The National Water policy of 2002 indicated that safe drinking water and good sanitation practices are basic considerations for human health. The use of contaminated sources poses health risks to the population as evidenced by the incidences of water borne diseases such as diarrhoea and cholera. It covers water resource management, supply, and sewerage. It provides guidance on three main issues: (i) Water Resources Management, (ii) Rural Water Supply, and (iii) Urban Water Supply and Sewerage. The policy stresses on integration of water supply and sanitation and hygiene education to improved health and conditions of people in urban and rural areas.

One of the policy issues for Water Resources Management includes improving the management and conservation of ecosystems and wetlands. On the other hand, the policy issue for urban water supplies and sewerage includes protecting water source areas and infrastructure such as treatment plants. Also, to ensure compliance with standards and guidelines for treatment processes for safety and health reasons. Also, to develop least cost technologies for wastewater treatment and recycling and have a wastewater treatment system which is environmentally friendly. In responding to the water policy's participatory management of water resources at all levels, the ministry of water had produced the Tanzania Water Resources Atlas (URT, 2019), which provides information to the community and for evidence-based decision making. The National Environmental Policy of 2021 came into force in 2022 following the review of the National Environmental Policy of 1997. Among others, it incorporates control of electronic wastes, climate change matters, control use of modern biotechnology and chemicals, invasive species like weeds in water as well as control of pollution at oil and gas extraction activities in the country. This follows the emerging increasing environmental challenges due to economic, social, and environmental developments in the world. The policy included other areas of urgent attention among others land degradation reducing soil productivity and lack of accessible good quality water for urban and rural dwellers. The above is with the objective of ensuring sustainability, security and equitable use of resources for meeting the basic needs of the present and future generations without degrading the environment or risking health or safety. The policy gave the definition of wetlands to include natural and artificial ones whether permanent or temporary.

The National Health Policy 2007 aims to reduce the burden of disease, maternal and infant mortality and increase life expectancy through, among other interventions, to facilitate promotion of environmental health and sanitation, and control of communicable diseases. The Community Development Policy 1996 recognizes the essence of sufficient clean and safe water, clean and healthy environment as critical elements for community development. The Tanzania Development Vision (TDV) 2025 (developed in 1999) and National Five-Year Development Plan I (FYDP I, 2011/2012-2015/2016) and II (FYDP II, 2016/2017-2020/2021) are among the initiatives of Tanzania Government to meet the Sustainable Development Goals (SDGs) by accelerating access to improved (now safely managed) sanitation and hygiene. The National Five-Year Development Plan I (2011/2012-2015/2016) and II (2016/2017-2020/2021) also cascading the targets for water, sanitation, and hygiene, which aimed at achieving 90% and 80% of urban and rural population, respectively with access to safe water and sanitation by 2020/2021. The National Water Sector Development Strategy 2006-2015 geared to a prioritized, timely, and appropriate interventions to address the challenges in the water sector in the process of achieving all of the goals outlined in the National Strategy for Growth and Reduction of Poverty by 2010, the Millennium Development Goals (MDGs) by 2015, and contributing to the Tanzania Development Vision goals by 2025. Through a straightforward and manageable institutional arrangement, the Strategy results in a reorganization and increase of sector financing.

The preparation of the following three sub-sector programs has been guided by the National Water Sector Development Strategy (NWSDS); the Water Resources Management Program (WRMP), the Urban Water and Sewerage Program (UWSSP), and the Rural Water Supply and Sanitation Program (RWSSP). The Water Sector Development Program (WSDP) 2006-2025 brings together the three parts, including improving MoW's overall management; Using a Sector-Wide Approach to Planning (SWAP), the Drilling and Dam Construction Agency (DDCA), the Water Resources Institute (WRI), and the Maji Central Stores (MCS) Agencies. The government has implemented SWAP that emphasizes community demand, decentralized management through local governments and water user-specific entities or authorities, central government facilitation, and private sector service delivery. SWAP unifies the three subsectors water resources management, urban water supply and sewerage, and rural water supply under a single, comprehensive investment and regulatory framework. The SWAP is a direct response to the National Water Policy (NAWAPO). The WSDP's three-year transitional period of preparation began in 2003 with the intention of: i) Establish the framework for a SWAP; ii) Come up with the necessary investment strategy; iii) increase capacity at all levels for providing services and managing water resources; and (iv) establish the necessary regulatory framework for the ongoing provision of nationwide water supply services.

The National Strategy for Accelerating Sanitation and Hygiene for All (NASSHA) (2020 - 2025) is a guiding framework for sanitation promotion in the country for the stated period. It is a national initiative to promote innovation and new approaches to sustain gains and expand sanitation services. NASSHA stems on equity and equitable services, integrated management, Behaviour Change and Communication (BCC), and sustainable sanitation. It is expected that the strategy will serve a valuable reference for designing planning, implementation, and monitoring and evaluation of sanitation and hygiene programme across the Country. This National Strategy describes Tanzania's vision for accelerating access to sanitation and hygiene for all over the next five (5) years. It also describes the leadership and enabling environment that will help ensure the timely implementation of initiatives.

Other efforts to improve access to sanitation and hygiene were streamlined through the National Sanitation Campaign (NSC) implemented under the Water Sector Development Programme (WSDP). WSDP is a twenty-year nationwide programme for improving the provision of water supply and sanitation services, and integrated water resource management, across Tanzania. The Phase II (WSDP II) runs from 2016 to 2021.

4.9 National Legal Framework

The legal framework together with institutional arrangement provides mechanisms to manage water resources and the environment. The following are the legal frameworks for the countries.

4.9.1 Legal Framework in Kenya

Kenya has established the whole bunch of acts geared towards promoting and use of CW technology. The section below provides for the brief account of these legal instruments.

The Environmental Management and Coordination Act (EMCA) of 1999 is the framework law on environmental management and conservation. EMCA establishes, among others the following institutions: National Environment Management Authority, Public Complaints Committee, National Environment Tribunal, National Environment Action Plan Committees, and County Environment Committees. Subsequently, the Environmental management and co-ordination (Amendment) Act of 2015 among others broadened the definition of wetlands to include natural and artificial ones whether permanent or temporary.

The main purpose of the Environmental Management and Co-ordination (wetlands, riverbanks, lakeshores, and seashores management) Regulations of 2009 is to provide for the conservation and sustainable use of wetlands and their resources in Kenya. Environmental Impact Assessment and Environmental Audit as required under the EMCA shall be mandatory for all activities likely to have adverse impact on the management of wetlands. The Environmental (impact assessment and audit) Regulations of 2003) prescribes that the goal of an EIA is to ensure that decisions on proposed projects and activities are environmentally sustainable. It guides policy makers, planners, stakeholders, and government agencies to make environmentally and economically sustainable decisions.

The objective of Water Quality Regulations No. 121 of 2006 and Environmental Management and Co-ordination (water quality) Regulations of 2006 is to prohibit discharge of effluent into the environment contrary to the established standards. The regulations further provides guidelines and standards for the discharge of poisons, toxins, noxious, radioactive waste, or other pollutants into the environment in line with the Third Schedule of the regulations. The regulations have standards for discharge of effluent into the sewer and aquatic environment. While it is the responsibility of the sewerage service providers to regulate discharges into sewer lines based on the given specifications, NEMA regulates discharge of all effluent into the environment.

The Waste Management Regulations of 2006 covers application and renewal for license to own waste treatment or disposal site; application and renewal for license to transport waste; general guidelines for waste management license application**.** The Water Act 2002 of Kenya was developed based on the National Policy on Water Resources Management and Development (NWP) 1999. The Water Act 2016 technically repeals the Water Act 2002. The Act presents several changes in the water sector with the aim of improving services. It provides for the regulation, management and development of water resources, water, and sewerage and for other connected purposes.

The Water Act, 2016 establishes the regulatory structure for water resources management, defines stakeholders' responsibilities at the national, basin, and county level, and establishes Basin Water Resource Committees (BWRC). The Water (Services Regulatory) Rules, 2012are made by the Minister for Water under section 110 of the Water Act, 2002, concern the operations regarding the provision of water services by water service boards and other operators or their agents. Each water service board shall apply to the Regulatory Board for the issuance of a license. The Board may issue a provisional license or a full license.

The Public Health Act Cap 242, 1986 (revised 2012) concerns the assurance of public health in Kenya and sets down rules comparative with, in addition to other things, food hygiene and protection of foodstuffs, the keeping of animals, protection of public water supplies, the counteraction and annihilation of mosquitos and the reduction of annoyances including irritations emerging from sewerage. The Act establishes the Central Board of Health and a district health management board in each district. It additionally lays out functions of health authorities. The functions of the Board shall be to advise the Minister upon all matters affecting the public health. The Minister may make Rules concerning port health matters.

The County Governments Act, 2012 accommodates the political decision, working, control of, undertakings and powers, and so on of county legislatures as accommodated under Article 176 of the Kenya Constitution. It likewise accommodates a wide assortment of issues connecting with public administration at local level like community participation, access to information, public communication and the protection of minorities. Its targets include facilitation of the development of an even arrangement of settlements and guaranteeing useful utilization of scarce land, water and different assets for economic, social, ecological and different functions across a county; and the accomplishment and upkeep of a tree cover of no less than 10% of the land.

The Environmental Management and Co-ordination Act, 2012 provide rules relative to the use and discharge of water for domestic, agricultural, and industrial purposes, make provision for the protection of water resources from pollution and define water quality standards. Environmental Management and Co-ordination (Wetlands, Riverbanks, Lake Shores and Sea Shore Management) Regulation, 2009 (Cap. 387) made under the Environmental Management and Co-ordination Act, 1999, make provision for the management, conservation and sustainable use of wetlands and wetland resources and the sustainable utilization and conservation of (resources on) riverbanks, lake shores, and the seashore. Environmental Management and Co-ordination (Waste Management) Regulations, 2006 (Cap. 387) define rules for the management of waste in general and for the management of solid waste, industrial waste, hazardous waste, pesticides and toxic substances, biomedical waste, and radioactive substances in particular. Environmental Management and Coordination (Water Quality) Regulations, 2006 (Cap. 387) provide rules relative to the use and discharge of water for domestic, agricultural, and industrial purposes, make provision for the protection of water resources from pollution and define water quality standards.

4.9.2 Legal Framework in Mauritius

The Environment Protection (Amendment) Act 2008 (No. 6 of 2008) makes a number of changes to the Environment Protection Act of 2002, including the definition of following: environmental law, the National Environmental Laboratory, the Multilateral Environmental Agreements Co-ordinating Committee, preliminary environmental reporting, the Environmental Impact Assessment (EIA) Committee, the Environmental Impact Assessment (EIA/PER Monitoring Committee), the response to a threat to the environment, noise standards, and the Minister's authority to make regulations.

The Wastewater Management Authority Act 2000 provides for the establishment of the Wastewater Management Authority and a legal framework for the wastewater sector. The Wastewater Management Authority Act regulations made by the Minister under section 47 of the Wastewater Management Authority Act 1. These regulations may be cited as the Wastewater (License for Discharge of Industrial Effluent into a Wastewater System) Regulations 2019. Also, the regulations made by Minister under section 47 of the Wastewater Management Authority Act. These regulations may be cited as the Wastewater (Registration of Wastewater Carriers and Disposal of Wastewater) Regulations 2006.

The Central Water Authority Act No. 20 of 1971 as amended by Act No. 3 of 2005 provides for the establishment and management of the Central Water Authority in Mauritius. It defines its functions and powers, contains rules relative to its internal organization and prohibits the construction of waterworks without the permission of the Authority and the discharge of polluted water into any canal, river, stream, lake, reservoir or lagoon.The Authority is established as a body corporate, which shall be responsible for the control, development and conservation of water resources (*i.e.*, surface and groundwater of Mauritius).

The Central Water Authority (Water Supply for Non-Domestic Purposes) Regulations 1992 provide rules relative to water supply by the Central Water Authority to a property for non-domestic purposes including supply water for irrigation of cultivations and breeding of livestock or poultry for commercial purposes.

The current legal framework in Mauritius for the environmentally sound waste management comprises the Environment Protection Act (EPA) of 2002, as amended in 2008, and the Local Government Act (LGA) of 2011 as amended in 2018. The following Regulations have been made under the EPA and the LGA:

- Environment Protection (Standards for hazardous wastes) Regulations 2001;
- Local Government (Dumping and Waste Carriers) Regulations 2021;
- Local Government Act (Registration of Scavenging Contractors) Regulations 2004;
- Environment Protection (Collection, Storage, Treatment, Use and Waste Oil) Regulations 2006;
- Local Government Act (Registration of Recycler and Exporter) Regulations 2013.

Climate Change Act 2020 (No 11 of 2020) is the Mauritius' framework climate law. Parts II, III and IV of the Act create climate-focused institutions and bodies and set their attributions.

4.9.3 Legal Framework in Seychelles

Public Utilities Corporation Act (Cap 196) – "regulates the use of water throughout the country as well as sewage disposal systems both public and private." The water resources management laws for the Seychelles originate from the pre-IWRM era and are both fragmented and outdated in the sense that they do not provide a basis for IWRM-based water management. The legal framework centres on the PUC Act and grants substantial powers to the PUC, establishing the PUC as de-facto resources manager, service provider and regulator. The legal framework also lacks clarity on aspects of catchment protection and management and makes little provision for stakeholder engagement in water resources management. Stakeholders therefore identify the revision of water management legislation as a priority. Legislation needs to be brought in line with IWRM principles and consolidated into one central national water Act. Other regulatory frameworks include:

- The Town and Country Planning Act (TCPA) is the primary instrument dealing with land use and development in Seychelles;
- State Land and River Reserves Act (SLRRA);
- State Land and River Reserves Act, 1903;
- Environment Protection Act, 1995.

Environment Protection Act (Cap 71) – "provides for the protection, improvement and preservation of the environment and for the prevention, control and abatement of environmental pollution".

State Land and River Reserves Act (Cap 228) – "makes provision for the management and alienation of State land, for the appointment of forest rangers and for the protection of State lands and River Reserves."

Public Health Act (Cap 189) – "provides competences to Ministry of Health in respect to chemical examination and bacteriological examination of any supply or source of supply of water which is or may be used for drinking or domestic purposes".

4.9.4 Legal Framework in Tanzania

In Tanzania, the following are the main legal instruments which are either directly or indirectly related to promoting and encouraging the use of CW technology for pollution control from land-based activities.

Water Resources Management (Amendment) Act, 2022 (No. 8 of 2022).This Act amends the Water Resources Management Act, 2009 (No. 11 of 2009) by, among other things, providing for the office of Water Basin Director and other institutional arrangements, powers of Water Basin Boards, Strategic Environmental Assessment, water use offences, and some other matters. It also inserts a definition of "court" and a new section on use of water without permit. This Act may be cited as the Water Resources Management (Amendment) Act, 2022, and shall be read as one with the Water Resources Management Act, 2009 hereinafter referred to as the "principal Act". The principal Act provides for institutional and legal framework for sustainable management and development of water resources; to outline principles for water resources management; to provide for the prevention and control of water pollution; to provide for participation of stakeholders and the public in implementation of the National Water Policy, repeal of the Water Utilization (Control and Regulation) Act and to provide for related matters.

The Environmental Management Act (EMA) 2004 provides for a legal framework for sustainable management of the environment, prevention and control pollution, waste management, environmental quality standards, public participation, environmental compliance and enforcement. Also, it has provision for various conservation and protection measures for areas such as inland waters, shoreline, wetlands, coastal zones, mountain areas and range lands and make provision with respect to biodiversity, protection of forest resources, promotion of conservation of wildlife and fisheries resources, protection of natural and cultural heritage, use of genetically modified organisms, prior informed consent procedures, etc. The Act requires the local Government Authorities to prescribe and issue guidance on how liquid waste from domestic and commercial premises is to be treated and finally disposed of both within the site and outside the premises. Under this Act the local government authorities are mandated to designate and ensure compliance with designated disposal ponds and sewage treatment facilities.

The Water Supply and Sanitation Act 2019 provide for sustainable management and adequate operation and transparent regulation of water supply and sanitation services with a view to give effect to the National Water Policy, 2002. It outlines legal mandates and responsibilities of water supply in urban, rural and at community level. It established Urban Water Supply and Sanitation Authorities (UWSSAs) in urban areas, Rural Water Supply and Sanitation Agency (RUWASA) and the Community Based Water Supply Organizations (COBWSOs). RUWASA is responsible for the development and sustainable management of rural water supply and sanitation related to faecal sludge emptying, transportation, treatment, and safe disposal.

The Water Supply and Sanitation (Registration and Operations of Community Based Water Supply Organizations) Regulations 2019 provide the guidance on the registration and operation of Community Based Water Supply Organizations. These Organizations shall be registered as per Subsection 9 (1) of these Regulations. According to these Regulations, every District Manager of Rural and Urban Water Supply and Sanitation Authorities (RUWASA) shall be the Registrar of community organization in the respective district engages in interventions for protection and conservation of water sources for sustainable water supply.

The Water Supply and Sanitation (Provision and Management of Sewage and

Wastewater Services), Regulations 2019 shall apply to any area designated and declared to be a water authority, clustered water authority, or to any person providing or using water supply and sanitation services. Sub-sections 4 - (1), (2) of the Regulations requires a water authority to develop and maintain sanitation works within its jurisdiction. Sanitation works shall involve infrastructure for collection, conveyance, and treatment of wastewater as well as disposal of effluent.

The Public Health Act 2009 provides for the promotion, prevention, and maintenance of public health, with a view to ensuring the provisions of comprehensive, functional and sustainable public health services to the general public and to provide for other related matters. Part iv (e) of the Act concerns the provision of adequate sanitary accommodation in every dwelling house and every public place; and Part iv (g) concerns the construction and maintenance of sewerage whereby Authorities are required to ensure efficient operation of sewerage system. The Act further controls the habit of urinating in the open space where, Section 174 (1) prohibits any person to have a natural call-in areas other than toilets built for that purpose. Generally, the Public Health Act works to ensure attainment of the main purpose of hygienically separating human excreta from human contact.

The Energy and Water Utilities Regulatory Authority (EWURA) Act 2001 empowers EWURA to regulate (licensing, setting standards of operation and to set rates and charges) and to establish water supply and sanitation authorities under the Water Supply and Sanitation Act. The Occupational Health and Safety Act 2003 require factories to make provisions for the safety, health, and welfare of persons at work in factories and other places of work. Part V of the Act provides for health and welfare, particularly provision of sanitary accommodation and safe drinking water. The Local Government Act 2002 spells out the requirements to the sanitation of buildings and the cleanliness of yards or compounds and as to the construction and maintenance of toilets and other sanitary structures.

4.10 Status and Challenges on Policy, Laws and Institutions Related to Constructed Wetlands

Generally, an attempt has been made across all the countries in WIO region to establish enablers for either directly or indirectly supporting, promoting or encouraging the use and adaptation of CW technology for preventing and controlling the pollution from land-based activities. These enablers exist at various levels at global (treaties, organizations), regional (protocols, agreements) and national (policies). However, the major concern is discrepancies in terms of appropriateness, relevance, and coherence within the countries and across the region. The observed challenges include:

- Institutional arrangement gaps, which relatively limit cooperation and management of water resources and sanitation across different fields or sectors;

- Limited and weak national regulations which can't adequately control the pollution of marine and coastal ecosystems from land based activities;
- Constructed wetlands technology map and system of data sharing in each country among institutions and stakeholders is not well articulated. This is important for managing potential problems before they occur and for the case of invisible water resources such as groundwater;
- Most of the policies (with the exception of that of Kenya) don't categorically and explicitly promote and encourage the use of nature-based solutions particularly the CW which are which are energy intensive technologies;
- Limited mainstreaming and alignment of international and regional frameworks into country's framework systems with, only Kenya aligned with the African Sanitation Policy guidelines in the formulation of the National Sanitation Management Policy;
- Outdated enablers which comprehensively need review for address the current and emerging topical issues including the nature based solutions;
- Lack of clarity, adequacy and appropriateness to clearly promote and encourage the use of nature-based solutions; and
- Lack of coherence and cohesion among enablers which need harmonization..

4.11 References

Alogna, I. (2018). Environmental law of France. In: Comparative Environmental Law and Regulation (Robinson NR, Burleson E and Lye L-H (Eds.) Publisher: Thomson-Reuters and Westlaw (www.academia.edu/37680496/Environmental_Law_of_France)

ASCLME. (2012a). National Marine Ecosystem Diagnostic Analysis. Comoros. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME. (2012b). National Marine Ecosystem Diagnostic Analysis. Kenya. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

ASCLME. (2012c). National Marine Ecosystem Diagnostic Analysis. Madagascar. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing).

AU. (2016). African convention on the conservation of nature and natural resources. African Union (AU) Headquarters, Addis Ababa, Ethiopia, 45pp.

Bank, W. (2015). East Asia's Changing Urban Landscape: measuring a decade of spatial growth. World Bank Group, Washington, DC.

Barnardo, T., and Ribbink, A. J. (2020). African Marine Litter Monitoring Manual. African Marine Waste Network. Sustainable Seas Trust

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA) (2014b). The National Coastal Management Programme of South Africa. Cape Town, South Africa.

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA). (2012b). Review and update of South Africa's national action list for the screening of dredge material proposed for marine disposal. Cape Town, South Africa (*https://www.environment.gov.za/sites/default/files/docs/nationalactionlist_marinedisposal_techni calreport.pdf*).

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA). (2014a). National Guideline for the Discharge of Effluent from Landbased Sources into the Coastal Environment. Pretoria, South Africa. RP101/2014 (*https://www.environment.gov.za/sites/default/files/legislations/nationalguideline_landbasedinflue nt_dischargecoastal_0.pdf*).

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA). (2019). Coastal Waters Discharge permit regulations 2019 (Government Gazette 42304, 15 March 2019) (*https://cer.org.za/wp-content/uploads/2019/03/Coastal-Waters-Discharge-Permit-Regulations.pdf*)

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (DEA. (2012a). South African Water Quality Guidelines for Coastal Marine Waters Guidelines for Recreational Use. Cape Town. *https://www.environment.gov.za/sites/default/files/legislations/water_qualityguidelines_0.pdf*

Devlaeminck, D. J. (2021). Reassessing the Draft Articles on the Law of Transboundary Aquifers through the lens of reciprocity. *International Journal of Water Resources Development*, 37(1), 162-177.

EPA. (2022). The London Convention.Accessed on 21st July 2022: *https://www.epa.gov/sites/default/files/2015-10/documents/lc1972.pdf*.

GLAAS (2019). Case studies on sanitation policy and planning frameworks: Kenya: Sanitation Policy and Planning Framework Case Study for Discussion. Accessed on 22nd Jul 2022: Microsoft Word - Kenya_Case Study DRAFT_Kenya_22August.docx (who.int)

GoK (2018). Ministry of Water and Sanitation Strategic Plan 2018-2022. Ministry of water and sanitation.

GoS (2015). Seychelles Strategic Land Use and Development Plan.Seychelles Planning Authority, Seychelles.

GoS (2019). Seychelles Wetland Policy and Action Plan 2019-2022. Government of Seychelles (GoS).

Government of the Republic of Kenya (2014). Kenya Health Policy 2014–2030. Ministry of Health.

Government of the Republic of Kenya (2016). National ODF Kenya 2020 Campaign Framework 2016/17-2019/20.Ministry of Health.

Government of the Republic of Kenya. (2009). The Water Sector Strategic Plan, 2009–2014. Ministry of Water and Irrigation.

Gurumo, T. S. (2017). Legal Framework for Marine Oil Pollution Control in Tanzania. *Advances in Social Sciences Research Journal*, 4(12).

Jackson, L. (2011). Marine pollution in the Agulhas and Somali Currents Large Marine Ecosystem. Report prepared for ASCLME Project (*https://nairobiconvention.org/clearinghouse/sites/default/files/7%20ASCLME%20Marine%20polluti on%20-%20Final.pdf*).

Kabogo, J. E., Anderson, E. P., Hyera, P., & Kajanja, G. (2017). Facilitating public participation in water resources management: Reflections from Tanzania. *Ecology and Society*, 22(4). *https://doi.org/10.5751/ES-09739-220426*

RoS (2020). Voluntary National Review 2020. Economic planning Department, Ministry of Finance, Trade, Investment & Economic Planning, Republic of Seychelles.

Lai, A., Hensley, J., Krütli, P., and Stauffacher, M. (2016). Solid waste management in the Seychelles: USYS TdLab transdisciplinary case study 2016. USYS TdLab Fallstudie.

McCaffrey, S. C. (2009). The International Law Commission adopts draft articles on transboundary aquifers. *American Journal of international law*, 103(2), 272-293.

Ministry of Health. 2007. National Environmental Sanitation and Hygiene Policy.

MoWI (2007). National Water Services Strategy 2007– 2015; and 2009.Sector Investment Plan for the Water and Sanitation Sector in Kenya.

MoWI (2007). The National Water Services Strategy (NWSS) (2007 – 2015). Republic of Kenya.

Quadri, E. (2015). The Law of Transboundary Aquifers in the Draft Articles of the International Law Commission and in the UN Convention on the Law of the Non-Navigational Uses of International watercourses.

Ramsar, (2014. Introducing the Convention on Wetlands. Accessed on 21th July 2022: Leaflet 2014_EN final.indd (ramsar.org).

Republic of Kenya. (2016). Kenya Environmental Sanitation and Hygiene Strategic Framework (KESSF) 2016–2020. Ministry of Health.

RoK. (2013). The project on the development of the national water master plan 2030.Final report volume - I Executive Summary. Ministry of environment, water and natural resources water resources management authority, Republic of Kenya (RoK), Japan International Cooperation Agency and Nippon Koei Co., LTD.

SADC. (2008). Sanitary and Phytosanitary (SPS) Annex to the SADC Protocol on Trade.Approved by the SADC Committee of Ministers of Trade on 12 July 2008, Lusaka, Zambia. *https://www.sadc.int/*.

Sowman, M., and Malan, N. (2018). Review of progress with integrated coastal management in South Africa since the advent of democracy. *African Journal of Marine Science*, 40(2), 121-136.

Steiner, A. (2009). An Introduction to the African Convention on the Conservation of Nature and Natural Resources (No. 56). IUCN.

Taljaard, S., Van Niekerk, L., and Weerts, S. P. (2019). The legal landscape governing South Africa's coastal marine environment–Helping with the 'horrendogram'. Ocean & coastal management, 178, 104801.

UN Environment (2018). Western Indian Ocean Regional Action Plan on Marine Litter. UN Environment/Nairobi Convention, Nairobi, vi + 24 pp.

UNEP, Nairobi Convention and International Maritime Organization 2020a. Regional oil spill preparedness in eastern African and the western Indian Ocean.Background Document. (*https://www.nairobiconvention.org/clearinghouse/sites/default/files/Regional%20Oil%20Spill%20Preparedness.pdf*)

UNEP, Nairobi Convention and International Maritime Organization.2020b. Regional oil spill preparedness in eastern African and the western Indian Ocean. Workshop Report – 3 to 5 March 2020. (*https://www.nairobiconvention.org/clearinghouse/node/476*)

UNEP/Nairobi Convention Secretariat and CSIR (2009b). Guidelines for the Establishment of Environmental Quality Objectives and Targets in the Coastal Zone of the Western Indian Ocean (WIO) Region, UNEP, Nairobi, Kenya, 169p

UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, (2009a). Regional Synthesis Report on the Status of Pollution in the Western Indian Ocean Region. UNEP, Nairobi, Kenya, 91 pp.

UNEP/OCHA Environment Unit. (2013). Environmental Emergencies. Comoros. Report of Scoping Mission (*https://www.eecentre.org/wp-content/uploads/2019/06/Report-EE-Mission-Comoros-FINAL- 2013.pdf*).

United Nations Environment Programme, Nairobi Convention Secretariat and Council for Scientific and Industrial Research. (2022). Western Indian Ocean: Guidelines for Setting Water and Sediment Quality Targets for Coastal and Marine areas. UNEP, Nairobi, Kenya. XXIV + 109 pp.

URT (2009). The United Republic of Tanzania. Development, 7(5,371,780,231.09), 2,274,923,575.00-29.08.

URT (2019). Tanzania Water Resources Atlas. Ministry of water, Water resources division. ISBN 9789976597134

URT (2020). Water sector status report of 2015-2020. UURT (2021). National Environmental Policy, 2021. The United Republic of Tanzania (URT), Vice President's Office. 62p.

Walmsley, B. and Patel, S. (2012). SADC Environmental Legislation Handbook 2012. Pretoria: Development Bank of Southern Africa in collaboration with the Southern African Institute for Environmental Assessment.

Williams, J. G., Moyle, P. B., Webb, J. A., and Kondolf, G. M. (2019). Environmental flow assessment: methods and applications. John Wiley & Sons.

WRA, (2019). Water Resources Authority Strategic Plan for the period 2018– 2022

This page is intentionally blank

Chapter 5: Planning for Constructed Wetlands

By Zai Mseli, Asumin Kantanga and Richard Kimwaga
University of Dodoma and University of Dar es Salaam, Tanzania

HIGHLIGHTS

For the effective and smooth implementation of the CW technology, planning plays a central and critical role. CW Planning refers to a well-organized and systematic manner of identifying and establishing the requirements and key issues to consider during design, construction as well as operation and maintenance of CW technology. Essentially, it entails an understanding and considering the preparatory and support factors. However, from the resource's scarcity perspectives, planning is about prioritizing interventions based on the available meagre resources. This chapter discusses the planning principles of the CW technology to ensure the successful operation while meeting the treatment objectives.

5.1 General CW Planning Considerations

A conceptual planning phase is essential (Davis 1995). CW can be designed in a variety of system types and configurations to meet specific wastewater treatment requirements, alternative sites are often available, and a variety of local, native plant species can be chosen (Davis, 1995). Every site is unique, and the design of a CW system will be site-specific (Davis, 1995).

The planning phase entails the following sets of activities and tasks (Davis, 1995);

- Characterizing the quantity and quality of the wastewater to be treated;
- Determining the discharge standards to be met;
- Selecting the appropriate construction site;
- Identifying and establishing the procurement plan for the CW construction materials (*e.g.* the source of CW substrate and vegetations);
- Selecting CW system type and configuration;
- Specifying the design criteria to be met by the detailed engineering plans;
- Anticipation and plan for the operation and maintenance including monitoring of CW; and
- Resources and capacity available to manage the CW in its entire life cycle.

Economic factors include the land area required the type of water containment, the control and transport of water through the system, and vegetation (Davis, 1995). Setting and prioritizing the objectives of the CW system is key to the creation of a successful system (Davis, 1995). The characteristics of a local natural wetland should be used as a model for the CW, modified to fit the needs of the project and the specifics of the CW site. Admittedly, throughout our CW implementation experience, no due considerations were adequately directed to the planning phase. The failures observed in previously constructed CW systems in our experience are partly attributed to the lack and inadequate of thorough planning. Because of this weakness, we thought it worthy to have a stand-alone book chapter which describes the CW planning.

A CW should be designed to entirely take advantage of the natural features of the site and to minimize its disturbance (Davis, 1995). CW shape is largely dictated by the existing topography, geology, and land availability. The number of cells depends on topography, hydrology, and water quality. On level sites, cells can be created with dikes. On sloping sites, cells can be terraced (Davis, 1995).

A site-sensitive design that incorporates existing features of the site reduces the amount of earthmoving required and increases the visual attractiveness of the site. Earth grading and shaping can blend newly created landforms into the existing landscape (Davis, 1995). Basins and channels can be curved to follow the natural contours of the site. Various types of vegetation can be planted in and around a constructed wetland to reduce erosion, screen views, define space, control microclimate, and control traffic patterns (Davis, 1995).

Planning should be oriented toward the creation of a biologically and hydrologically functional system (Davis, 1995). Plans should include clear goal statements and standards for success. The possible future expansion of the operation should be considered. The planning process should detail instructions for implementing a contingency plan in case the system does not achieve its expected performance within a specified time (Davis, 1995). Plans should be reviewed and approved by the appropriate regulatory agencies (Davis, 1995).

Key factors to be considered while planning for CW by (Davis, 1995) include;

- Design data and information collection and acquiring,
- Site Selection,
- Land use and access,
- Land availability,
- Topography,
- Environmental resources permit and regulations,
- Structures dictated by the design,
- Cells including liners,
- Flow control structures of inlet and outlets, and
- System lifetimes.

The listed factors above are comprehensively expounded in the proceeding sections.

5.2 Assessment of Current and Future Land Use Plan Through Master Plan

5.2.1 Land Use and Land Use Plan

Access to the land is an important factor for CW planning. Due to concerns about odours or insects and the economy, the wetland should be situated far from residential areas and the wastewater flow to the CW and throughout the entire process should utilize gravity. Personnel, delivery vehicles, and construction and maintenance equipment should all be able to get to the site. The CW may be constructed on private land in some instances. Thus, CW construction site must be selected with care. The landowner must cooperate with the development project and fully comprehend the limitations and uncertainties of the CW technology. The suitability of a location for a constructed wetland will also be affected by the values and uses of adjacent land now and in the future. Considerations are due to the viewpoints of environmental and public interest groups, as well as those of residents. The wetland and the property next to it should be separated by a large buffer zone. Therefore, assessment of current and future land use plan is important (Davis, 1995). Assessment of current and future land use plan is undertaken systematically in order to evaluate and select the best land for development and plan revision options.

The CW construction site can be objectively selected based on the established several criteria such as location, size, hydrology, geology, ecological condition, land ownership, land accessibility, mode of disposal of treated wastewater, use and values of the site and adjacent land, competing uses and regulatory consideration (environmental regulatory considerations); for selected changes to land use and where they should be applied or recommended. The evaluation aimed at a change in rights of land use, their restriction, or their improvement, involving investments (*e.g.* terraces, afforestation, etc.) can only be successful in a sustainable way when the land law creates the appropriate conditions. Therefore, during the implementation of the land use map, applicable land law is indispensable. In addition to consideration of physical factors, the suitability of areas for a protected land use is determined by unstable ecosystem (*e.g.* forests on steep slopes) or scarce and diversity of plant communities.

Land use planning can be applied at three broad levels: national, district and local. These levels correspond to the levels of government at which decisions about land use are taken. The process of allocating land to competing and sometimes conflicting uses to ensure the rational and orderly development of the land in an environmentally sound manner and the creation of sustainable human settlements is referred to as land use planning. Planning is for people, whose needs drive the planning process. This is useful in the following aspects (Community-planning-zoning, 2019):

- It allows the communities to plan the development in a way that protects valued resources. Planning can enable the identification of the environmental features like wetlands, agricultural lands, trees, and steep slopes and offer suggestions for preserving those resources from being destroyed or degraded by inappropriate development,

- It offers guidance for shaping the community's appearance. Policies that foster a distinct sense of place can be outlined in a plan,

- It promotes economic development**.** The plan has useful information that helps prospective businesses or firms decide where to locate,

- It gives justification for decisions. Plans give a real and objective premise to support zoning decisions and can be utilized by communities to protect their decisions whenever challenged in court.

The first step in the land use analysis process is to conduct an inventory of existing uses. The land use inventory classifies land uses into different categories. Land use maps can be developed and made available for review to aid this process. A well-proven method of recording the natural potential of the planning area is to work out land units, *i.e.* areas with homogeneous potentials in a map. The land units can have similar topographical features, edaphic/ soil features, vegetation cover and climate. This information can be given by the land users based on transect walks, aerial photographs and Satellite data. Each land unit presents similar problems and opportunities and will respond in similar ways to management.

However, before areas are subdivided into land units, the objective of the subdivision must be clarified: does it serve mainly for the land use analysis or also for land use planning? For example, the following units can be distinguished: planning units; land utilisation units; resources management units; units of rural development; units for protecting food sources; units for consolidating a social organization, etc. (Davis, 1995).

Land use mostly falls within the main categories such as residential, institutional, business/commercial, industrial, agricultural, forestry, recreational/park, transportation, and other relatively natural land uses. Each of these broader categories can be further subdivided, based on the nature and intensity of the activities that are undertaken.

Land use plans are essentially zoning plans, which outline the future location and type (residential, office, retail, industry) of development activity that is to be permitted and not permitted (*i.e.* green space, parks, etc.) within urban and regional areas over a set horizon period (normally 5–15 years). For comparison, the Integrated Water Resources Management and Developments (IWRMD) Plans at catchment and at basin level in Tanzania provide information on water availability, environmental flows, sectorial water demands and social economic status of each basin in the short- (5 years), medium- (10 years) and long- (20 years) terms.

The land use plan provides continuity across time and gives successive public bodies a common framework for addressing land-use issues. The land use plan may consists of the following headings: Title; summary highlighting problems and recommendations; introduction with long-term goals for the planning area, related legislation and other plans, description of the planning area; management problems and options; implementation aspects and workplan with details of projects, location, time, resources required and responsibility; monitoring procedure for reviewing progress and revising the plan; appendices with supporting information.

The map showing land-use allocations and recommendations is the focal point of the land-use plan. An important part of the land use plan is a description of the selected land-use types, including their management specifications and the land units for which they are recommended. The land use maps are assessed using the following criteria (FAO, 1993):

- The base-map details (roads, tracks, settlements, administrative boundaries) should be clear; users will constantly need to find where they are and what should be done.
- The features shown in the maps (*e.g.* land-use types, soils, water resources) should be easy to see; a good quality of cartography, normally using colour, is essential.
- The legend (key) must be an integral part of the maps, which among others indicate the land use types of the planning area.

Land use planning can be applied at three broad levels: national, district and local. These are not necessarily sequential but correspond to the levels of government at which decisions about land use are taken. Land evaluation is an integral part of land use planning. Various types of decisions are taken at each level, where the methods of planning and kinds of plan additionally vary. Nonetheless, at each level there is a need for a land-use strategy, policies that indicate planning priorities, projects that tackle these priorities and operational planning to get the work done. It is better to have more interaction between the three levels of planning. At the national level, planning is concerned with national goals and the allocation of resources; the district level refers not necessarily to administrative districts but also to land areas that fall between national and local levels; The local planning unit may be the village, a group of villages or a small river catchment (FAO, 1993).

Land use planning can be applied at three broad levels: national, district and local. These are not necessarily sequential but correspond to the levels of government at which decisions about land use are taken. Land evaluation is an integral part of land use planning. Various types of decisions are taken at each level, where the methods of planning and kinds of plan additionally vary. Nonetheless, at each level there is a need for a land-use strategy, policies that indicate planning priorities, projects that tackle these priorities and operational planning to get the work done. It is better to have more interaction between the three levels of planning. At the national level, planning is concerned with national goals and the allocation of resources; the district level refers not necessarily to administrative districts but also to land areas that fall between national and local levels; The local planning unit may be the village, a group of villages or a small river catchment (FAO, 1993).

A wide variety of methods are used in land-use planning. They come from the natural sciences (climatology, soil science, ecology), technology (agriculture, forestry, irrigation engineering) and the social sciences (economics, sociology). Some of the methods, notably used for land evaluation, are interdisciplinary. Generally, land evaluation is based on land characteristics and classification with units of similar proposals of use and management. Other major methods of land evaluation include mathematical methods of land evaluation, namely, fuzzy modelling. River basin planning is growing among communities and agencies so that biological, physical, and socio-economic components of the landscape system can be integrated into the land use planning framework (Sen and Chatterji, 2018).

Current land performance may be a focus of land evaluation. However, most of the time, it involves change and its consequences: with an alteration in land use and, in some instances, in the land itself. The evaluation process provides data that can be used to make such decisions, but it does not determine the land use changes that need to be made. The results of an evaluation typically provide information about two or more potential uses for each area of land, along with the benefits and drawbacks of each, in order to be effective in this role (FAO, 1976).

The process of planning for land use includes more than land evaluation. Depending on the situation, it plays a different specific role. The evaluation of land plays a significant role in these aspects (the recognition of the primary requirements of proposed alternative forms of land use; recognizing and mapping the various kinds of land in the area; comparison and evaluation of each type of land for various uses), and it provides data for the subsequent land use planning activities. Therefore, the necessity of altering the land use is recognized before land evaluation (FAO, 1976); this could be the creation of productive new uses that are or the provision of services, like the designation of a constructed wetland treatment plant or recreational area.

5.2.2 Land Use Master Plan

A master plan is a policy document that guides the physical development of a community. The zoning or land use plan can be a chapter in the master plan, a separate document of the master plan or integrated throughout the master plan. Typically, the zoning plan part of a master plan, in addition to the rest of the plan, will include (Garderner, 2019):

- A proposed schedule of regulation by district that includes at least building height, lot area, bulk, and setbacks,
- Standards or criteria to be used to consider rezoning consistent with the master plan,
- A description of each zoning district and proposed zoning map,
- An explanation of how the land use categories on the future land use map relate to the districts on the zoning map,
- A description of each zoning district, general purpose of each district and the general locations for those types of districts.

A master plan is a dynamic long-term planning document that provides a conceptual layout to guide future growth A master plan is a dynamic long-term planning document that provides a conceptual layout to guide future growth and development. Master planning is about making the connection between buildings, social settings, and their surrounding environments. A master plan includes analysis, recommendations, and proposals for a site's population, economy, housing, transportation, community facilities, and land use. It is based on public input, surveys, planning initiatives, existing development, physical characteristics, and social and economic conditions (The World Bank Group, 2015).

Master planning can assume some or all these roles:

- Develop a phasing and implementation schedule and identify priorities for action,
- Act as a framework for regeneration and attract private sector investment,
- Conceptualize and shape the three-dimensional urban environment,
- Define public, semiprivate, and private spaces and public amenities,
- Determine the mix of uses and their physical relationship,
- Engage the local community and act as builder of consensus.

5.2.3 Future Land Use Plan

Linking present and long-term (future) problems is part of the future land use plan. Land use planning is implemented to associate solutions for present problems (*e.g.* soil erosion, wastewater pollution, insufficient agricultural production and low income in rural households) with the planning towards long-term conservation and sustainable use of land resources. Therefore, such planning is based on precautions and is future-oriented based on the interests, viewpoints and problem-solving potential of the participants in the planning.

A link exists between regional or district-level land use planning and implementation and national strategic planning. The dissemination of information to the subordinate and superior planning levels, *i.e.*, the population as the decision-makers who use privately the areas and the state as trustee of public interests, is one of its primary responsibilities (Davis, 1995). At local level (village-level land use), the most important subject is the implementation of the land use plan. The plan at this level is very detailed, and all stakeholders can take part directly in the decision-making process.

The current land use map can constitute an initial, but a basis for future land use prediction. Additionally, the current land use types may include rainfed agriculture, irrigated agriculture, market gardening, plantations, pastureland, forest, orchards, uncultivated land, water bodies, residential areas, etc. The maps feature the land unit area as the actual land use or the potential land use, which can be analysed and manipulated digitally in Geographical Information System (GIS).

To assess the current land use situation and the possibility of modelling possible future changes associated with a complex of adopted measures, GIS and models are used. GIS allows the integration of diverse spatial data, for example, data about soils, climate, vegetation, and other and also to visualize available information in the form of maps, graphs or charts, 3D models. GIS allows the use of remote sensing data to monitor anthropogenic influence in a specific area and estimate the scales and rates of degradation of green cover, flora, and fauna for land use purposes.

Future land use may be predicted using modelling approaches and then used for assessment of future land use plan. For example, future prediction of land use and land cover change was done using Module for Land Use Change Evaluation (MOLUSCE) tool, a QGIS plug-in (Msovu *et al.*, 2019; Kumar *et al.* (2022) used Artificial Neural Network (ANN) based Cellular Automata (CA) model to simulate the future land use-land cover using land use maps of 2010 and 2020. For the future land use plan, a well-prepared simple preview of potential future developments may include the future visions of the different stakeholders.

There could be other models relevant to different aspects of land-use planning. For example, models for the prediction of net present return from data on inputs, production, costs, and prices (FAO, 1993). However, it should be borne in mind that models are only as reliable as the input data; where possible, models should be calibrated for the planning area, its climate, soil types, etc.; data should be entered, and the results compared with an independent measure for the model validation.

5.2.4 Reporting Assessment of Land Use Plan

With the plan at hand, for the implementation agencies to improve the way the plan is being applied and for the planning team to learn from experience and respond to changing conditions or requirements, information on the status, how well the plan is being implemented, and whether it is successful must be obtained. The following questions need to be answered:

- Are the land-use activities being carried out as planned?
- Are the effects as predicted?
- Are the costs as predicted?
- Are the assumptions on which the plan was based proved to be correct?
- Are the goals still valid?
- How far are the goals being achieved?

To answer all the above questions, monitoring or assessment data (*e.g.* physical, economic and social) are required. By analysis of the data collected, what has been achieved is compared with what was intended. Problems in the implementation of the plan are identified, or in the data or assumptions on which the plan is based. Successes are identified too. Also, the current status of the plan and the current or future development demands are reviewed and compared, to assess the viability of current or future planned development. An improved land-use plan can then be suggested for decision making.

The results of the land use plan assessment are presented in a report and maps, giving the types of information already described. This includes map legends and tables to convey the assessment results to the land users or developers or stakeholders in summary form. Also, supporting explanations are always required, to explain the procedures used, to give descriptions of the types of land use, their management and improvement specifications, and their economic and social consequences, as well as to record the data and assumptions on which the assessment was based.

5.3 Community Mobilization and Sensitization Campaigns

Community mobilization is the process by which people come together to identify common problems or goals, mobilize resources and in other ways develop and implement strategies to reaching the objective they want to accomplish. Community sensitization campaigns is defined as a two-way communication program that allow as campaign managers to share information as well as create opportunities for residents to become actively involved in the project (Atkin and Freimuth, 2013). The word campaign here emphasizes the strategies to facilitate communication and community engagement. These campaigns aim to create demand for constructed wetlands for sanitation service.

The main objective of the community mobilization and sensitization campaign is to raise awareness on the CWs technology and promote its adoption among various stakeholders, including the public, private sector, government agencies, NGOs, and other interested parties When preparing the sensitization campaign on CWs needs to be focused depending on the groups you intend to raise awareness on CW's techniques.

Target audiences: Information about the audience is most often utilized to identify specialized subgroups to be reached, to devise message appeals and presentation styles, and to select sources and channels. The community sensitization campaign must outline the target audiences with regards to the potential users of the CW technology. This will facilitate the communication with different demographic groups and improve overall CWs campaign efficiency. The community must be divided into different categories:

- Local sewerage authorities,
- Institutions,
- Community members.

Tools and Strategies: The sensitization campaign has different tools and strategies as follows:

- Preparation of plan for awareness rising on the use of constructed wetlands to encourage the choice of CWs technology,
- Select the group of people who understand well the CW's technology for dissemination of information,
- Develop the awareness material tools on Constructed Wetlands (eg.: brochures, leaflets, booklets, posters and banners),
- Identify existing users of the CWs technology and their major concerns in order to share their experiences,
- Prepare training workshops on the use of CW focusing on the target group such as local authorities, institutions and different private and public sectors,
- Use of communication platforms and disseminate information about CWs technology such as social media, videos, series of newspaper articles, community events, meetings and presentations..

Outputs: The main outputs of the community mobilization and sensitization campaign are the following:

- To introduce training materials on CWs for use,

- Increase awareness of the value of CWs and its services and functions in wastewater management,
- Introduce affordable and sustainable wastewater treatment technique as an option to improve the wastewater management issues,
- To encourage and initiate researchers on CW technology for wastewater treatment.

5.4 Definition of Treatment Objectives

The primary aim of wastewater treatment is to remove as much suspended solids as possible before the remaining water, called effluent, is discharged back into the environment. As solid material decays, it uses up oxygen, which is needed by the plants and animals living in the water. "Primary treatment" removes about 60 percent of suspended solids from wastewater (Kimwaga *et al*., 2004). This treatment also involves aerating (stirring up) the wastewater to put oxygen back in. Secondary treatment removes more than 90 percent of suspended solids (Senzia *et al*., 2003). There are three main stages of the wastewater treatment process known as primary, secondary and tertiary water treatment.

The primary treatment objective is the removal of settleable organic solids and floating organic material (called scum) to reduce the suspended solids load for downstream treatment processes (AECOM, 2014; Metcalf and Eddy, 2014). The secondary treatment is the further treatment of the effluent from the primary treatment tank to remove the residual organics and suspended solids. CW treatment systems use rooted wetland plants and shallow, flooded or saturated soil to provide secondary and tertiary wastewater treatment objectives. CWs are designed to take advantage of natural wetlands' chemical and biological processes to remove contaminants from the wastewater (Skousen *et al*., 2004). The main principle is to employ natural materials (gravel, sand, plants) and naturally occurring processes under controlled conditions for treatment.

5.5 Wastewater Characterization and Quantification

The design of any wastewater treatment plant is primarily governed by the quality and quantity of wastewater influent and the required quality parameters of the treated effluent. The major types of wastewaters that must be treated include domestic, municipal, industrial and stormwater runoffs (Sundaravadivel and Vigneswaran, 2001). Influent characteristics of wastewater can be defined based on physical, chemical, and microbiological properties (Table 5.1) (Arias and Brown, 2009; GoU, 2013).

Table 5.1: Wastewater properties and their necessity for identification

Wastewater Impurities	Necessity for identification
Physical Properties	
Total solid (TS)	To assess the reuse of wastewater and to determine the most suitable types of operation and processes for its treatment
Total volatile solids (TVS)	
Total suspended solids (TSS)	
Volatile suspended solids (VSS)	
Total dissolved solids (TDS)	To assess the condition of wastewater
Colour	To determine if odour will be a problem
Odour	For the design and operation of biological processes in treatment facilities
Temperature	To determine the amount of oxygen required to stabilize the wastewater completely
Chemical properties	
Chemical oxygen demand (COD)	To determine the amount of oxygen required to stabilize the waste biologically/chemically
Biological oxygen demand (BOD)	
Organic nitrogen (org. N), free ammonia ($NH4^{+}$), Nitrate (NO_3^-), Nitrites (NO_2^-)	To determine the presence of Nutrients and degree of decomposition in the wastewater
Total phosphorus, Organic phosphorus (org. P), inorganic phosphorus (in-org. P)	To assess the suitability of wastewater for agriculture
Chlorine	
Sulphate (SO_4^{2+})	To assess the treatability of sludge
Heavy metals	To assess the suitability of wastewater for reuse and the toxicity effects in the treatment
Biological properties	
Coliform organisms	To identify the presence of pathogens
Bacteria, protozoa and viruses	To identify the presence of specific organisms in connection with plant operation and effluent reuse.

The impurities in wastewater must be removed prior to disposal or reuse to protect receiving waters from faecal contamination; protect receiving waters from deleterious oxygen depletion and ecological damage (eutrophication); produce microbiologically safe effluent for agricultural reuse, and preferably, reduce methane and carbon dioxide from entering the atmosphere (Sundaravadivel and Vigneswaran., 2001). Effluent quality requirements are determined by the discharge limits or desired end user with each respective country having its own (Table 5.2) (RoK, 2008; Okeyo *et al*., 2018; URP, 2020). For example, if the water is to be reused, the effluent quality must match the end user's reuse quality requirements.

Table 5.2: Wastewater discharge standards (RoK, 2008; Okeyo et al., 2018; URP, 2020)

Parameters	Units	WIO regions			
		Tanzania	Kenya	South Africa	Mauritius
Temperature	°C		+3 of water body ambient temp		40
pH		6.5 - 8.5	6.5 - 8.5	5.5 - 9.5	5 - 9
BOD_5	mg/L	50	30		250
COD	mg/L	50 - 200	50	75	750
Oil and grease	mg/L	5	Nil		20
Dissolved solids (DS)	mg/L	3000	1200		
Suspended solids (SS)	mg/L	100	30	25	300
Total Nitrogen	mg/L	10	2	3	
Total Phosphorus	mg/L		2		
Total coliform	Count/100mL	1000	1000	1000	<400
Nitrate	mg/L		20	15	25
Phosphate	mg/L		30		
Sulphide	mg/L		0.1		1
Arsenic	µg/L		0.02	0.02	200
Cadmium	µg/L		0.01	0.005	20
Lead	µg/L		0.01	0.01	2
Chromium IV	µg/L		0.05	0.05	100

Estimates of domestic and commercial wastewater are based on the supplied water. Studies have shown that depending on the water consumption pattern, different portions of the supplied water are collected as wastewater (Mackenzie, 2002; URP, 2020). Like water supply design, wastewater quantification is a function of the wastewater flow rates, which depends on the design period, population, commercial and industrial growth, infiltration and inflow, and the variability of the wastewater flow rates (Metcal and Eddy, 2003).

Design Period: The design period (also called the design life) is a time beyond which the system cannot continue without major rehabilitation or new works. New systems are generally made large enough to meet the demand for the future. The number of years selected for the design period is based on the following: Regulatory constraints; the rate of population growth; the interest rate for bonds; the useful life of the structures and equipment; the ease or difficulty of expansion, and performance in early years of life under minimum hydraulic load (Mackenzie, 2002). For CW, the recommended design life is 10 to 15 years (MOW, 2020).

Wastewater Components

Domestic or sanitary wastewater: Wastewater is discharged from residences, commercial (*e.g.* banks, restaurants, retail stores), and institutional facilities (*e.g.* schools and hospitals). For design consideration, the value of 60 to 90% of the per capital withdrawal (consumption) of water becomes wastewater (Metcalf and Eddy, 2003). The lower value (< 60%) may be adopted for the semiarid region or where the water supply is insufficient (URT, 2020).

Industrial wastewater: Wastewater is discharged from industries (*e.g.* manufacturing, and chemical processing industries). Industrial water uses vary widely according to the nature of the manufacturing processes. In practice, design work is therefore desirable to inspect the plant (industry) concerned and make careful estimates of the quantities of wastewater produced (Mackenzie, 2002). Suppose the industry's water needs are known. In that case, estimates of wastewater flow can be made by assuming that 85 to 95 % of the water utilized ends up as wastewater without internal recycling (Metcalf and Eddy, 2003).

Infiltration and inflow (I/I): Water enters the sewer system from groundwater infiltration, and stormwater from roof drains, foundation drains and submerged manholes. The rate and quantity of infiltration depend on the length of the sewers, the area to be sewered, the soil, topographic condition, and characteristics and conditions of the sewer material (Mackenzie, 2002).

Stormwater: Runoff from rainfall and snow melt is considered as stormwater. Historically, many communities adopted collecting stormwater and wastewater in combined sewers and conveying the peak dry weather flow to the wastewater treatment plant. At the same time, large surges of stormwater were diverted directly to surface water bodies. The resulting mixture of sewage and stormwater significantly adversely impacts the receiving water bodies (Mackenzie, 2002).

Variation of wastewater flows. Water consumption and wastewater production change with the seasons, the days of the week, and the hours of the day. Wastewater flow rates vary over several time scales ranging from diurnal to the design period (Metcalf and Eddy, 2003). Fluctuations are more remarkable in small communities than in large communities and during short rather than long periods. The variation in wastewater flow rate is normally reported as a factor of the average day. Peak factor needs to be established to control the variation of wastewater flow rate (Metcalf and Eddy, 2003). The peak flow factor is the ratio of peak flow to average flow. It is established for each major establishment or each flow category in the system. The normal range of 1.5 to 4 is used where no actual measurements are available (Metcalf and Eddy, 2003).

5.6 Selection of the Type of CW System

The typical goals associated with the operation of a CW are effective pollutants removal, easy operation and maintenance (O&M), low-cost operation, aesthetic value, and economic benefits (Carty *et al.*, 2008). As with all types of CWs, maintenance is very important. Without maintenance, the wetland will fail before the end of its design life. Good system performance and ease of maintenance begin with a proper selection of type of CW. The types of CW are governed by flow control, inlet, and outlet structures. Flow type, continuous or intermittent, needs to be controlled so that the water level in a constructed wetland can be maintained (UN-HABITAT, 2008). In the free water surface (FWS) wetland, the water table is maintained above the soil surface, while in the subsurface flow (SSF) type, it is kept below the soil surface with typical water depths. The flow control system's inlet and outlet structures are essential in maintaining water levels. Therefore, the flow control mechanisms should be kept as simple as possible for routine operation and ease of maintenance.

Inlets for FWS and SSF wetlands should be simple structures comprising an open-end pipe, channel, or gated pipe, which releases water into the wetland. The gravel size placed at the SSF wetland's inlet should be graded from coarse to fine to reduce the risk of solids clogging the wetland bed (Carty *et al.*, 2008). Flow must be well distributed at the inlet region to ensure as much loading as possible and reduce the risk of clogging and channelling. Channelling often occurs when the length-width ratio of the channel is small; short-circuiting occurs. The availability of ample tropical sunlight and nutrients allows algae to grow profusely. Algal growths can affect the hydraulics at inlet areas when surface manifolds are used. Clogging by suspended solids in wastewater is also a significant issue with SSF. Therefore, influent suspended solids concentration must be appropriately controlled (Carty *et al.*, 2008). The hydraulic conductivity of beds can be improved by using gabion-type gravel-based inlets. In FWS wetlands, the water level is controlled by the outlet structure, which can be a weir or spillway. Water depths in the SSF wetlands are maintained with manifolds located just above the bottom at the outlet. Perforated subsurface manifolds are then connected to an adjustable outlet that offers better flexibility and reliability (Carty *et al.*, 2008).

5.7 Selection of the CW Construction Site

To achieve the best possible facility design, construction, and operation, it is necessary to evaluate the suitable location. The use and accessibility of the land, the availability of land in the event of subsequent expansion, the topography and soils of the site, the environmental resources at the site and in the adjacent area, and the impact on neighbours should all be considered when selecting a location.

For water to flow through the system by gravity and avoid the need for costly pumping, the site that is designated for a constructed wetland should not only be conveniently located close to the source of the wastewater but also have sufficient space and be gently sloping. Additionally, as stated by Tanaka *et al.*, (2011), the duration for which wastewater is held within a constructed wetland is related to its viability as a wastewater treatment facility. The chosen location ought to be sufficient to meet this current need and any anticipated future expansion. A passive treatment site must also be located above the water table, away from the floodplain, free of endangered or threatened species, and in compliance with local authority guidelines and regulations.

According to the DANRCS, (2016), CWs should be located outside of the boundary area of natural wetlands of any classification and where there is less risk of contamination of groundwater resources. The quantity of information that must be gathered and assessed for site selection should depend on the size of the wetland, the type of wastewater, location, and other factors (Brodie, 1990). Generally, the location that is ideal for CWs is the one that:

- is close to the wastewater source and conveniently located,
- easily accessible,
- provide a gently sloping area so that water can flow through the system by gravity,
- the area should also contain soils that can be sufficiently compacted to reduce seepage to groundwater,
- should be above the water table, not lying in a floodplain, and
- devoid of threatened or endangered species and archaeological or historic resources.

5.7.1 Land Use and Accessibility

The suitability of a site for a CW normally depends on current needs and any potential growth. It is important to consider locals' views as well as those of public interest and environmental organizations. The wetland and the property next to it should be separated by a substantial buffer zone. The wetland should not be next to the property's edge. It is necessary for the landowner to cooperate with the project and fully comprehend the limitations and risks associated with a new technology like constructed wetland treatment.

A significant consideration is accessibility. The wetland ought to be situated in a way that allows water to flow by gravity and as far away from dwellings as possible provided that the odours or insects could be a problem. The site should be accessible to personnel, delivery vehicles, and construction and maintenance equipment. When constructing a wetland on private land, careful consideration must be given to the landowner. The suitability of a site for a constructed wetland will also be affected by the values and uses of adjacent land at present and in the future.

5.7.2 Topography

When designing a landscape, shape, size, and orientation in relation to the wind's current are all aspects to consider. Even though it is possible to construct a constructed wetland almost anywhere, choosing a location with gradual slopes to collect and hold water simplifies design and construction, reduces operational and maintenance costs, and makes it easier to maintain (EPA, 1998). Because the topography typically favours gravity flow, previously drained wetland areas, such as previously converted agricultural sites, may be ideal for a constructed wetland. Since a low, flat area where water flows by gravity is ideal for a constructed wetland, it is essential to ensure that the area is not already a wetland as throughout the year, not all wetlands have standing water. If a site contains jurisdictional wetlands, state regulatory personnel should be contacted.

5.7.3 Hydrology

Hydrological conditions must be taken into account if one is interested in the richness of flora and fauna or utilizing wetlands for pollution control (Scholz and Lee, 2005). Hydrologic considerations when choosing a location for a wetland include identifying the patterns of surface and groundwater flow, their quantity and quality, the depth of the groundwater table, and existing and potential uses. The hydrology of the system and other factors influence the performance of any constructed wetland system. Not only can precipitation, infiltration, evapotranspiration (ET), hydraulic loading rate, and water depth have an impact on the removal of organics, nutrients, and trace elements, but they also have an impact on whether the wastewater is concentrated or diluted. In order to properly design a constructed wetland treatment system, a hydrologic budget must be prepared. The performance of the treatment can be significantly affected by adjustments to the detention time or water volume (EPA, 1998).

5.7.4 Geology

Geologic considerations encompass surface and sub-surface soil characteristics, bedrock depth, topography, and availability of construction materials within the area and neighbourhood.. Characterization of soil and surface materials should be carried out at the sites for the thickness and depth, classification, and composition, use as construction material, drainage characteristics, potential for erosion and variability. The depth of the bedrock frequently prevents a site from being considered for constructed wetlands. Sites with shallow bedrock necessitate ripping or blasting, as well as the import or removal of a significant amount of soil or rock. Cut and fill requirements are influenced by topography. The ideal condition for the site is level to slightly sloping. Steep slopes necessitate more earth-moving activities and raise the cost of the CW treatment system.

5.7.5 Permits and Regulations

To determine the regulatory requirements for a proposed constructed wetland and its discharge, the appropriate agency or agencies must be contacted. A permit is required for work in a natural wetland or waterway and discharge to natural waters (EPA, 1998). In cases where communities have been zoned, approval may be required. Prior to wetlands siting, environmental regulatory considerations are crucial for assessing general concerns regarding the treatment system's performance. This will reduce the number of interruptions or delays caused by public perceptions or unanticipated environmental issues.

5.8 Establishment of Vegetation and Substrate

5.8.1 Wetland Plants/ Vegetation

According to Wallace, (2004), the following conditions must be met for plant establishment to succeed in a constructed wetland;

- the plant species must be appropriate for the wetland's hydrology,
- the plant material (such as the seed, tuber, rhizome, and pot) must be viable at planting time,
- sufficient time for the establishment of CW plants,
- during the startup phase, water level management must be compatible with the needs of the newly established plants. The wetland will grow vegetation if the three above requirements are met.

The wetland will grow vegetation if the three above requirements are met. Although FWS wetlands depend on plants to a much greater degree than Vertical Flow Bed (VSB) wetlands, all wetland systems owe much of their public acceptance to the vegetative communities they support (Kadlec *et al.*, 2000; Wallace, 2004). Plants play an extremely important role in FWS wetlands. They shade the water column, provide surface area for biofilm growth, and aid in the cycling of nutrients and organic carbon (Liu *et al.*, 2009). Thousands of plant species are adapted to grow in wetlands. However, only a few plant species (*Typha latoflia*, *Phragmite mauritius*) have been widely used in CW in WIO region (Haule *et al.*, 2002). Ideally, plants in treatment wetlands should be tolerant of high nutrient levels and be able to propagate through rhizome spread (Wallace, 2004). They also must be tolerant of saturated soil conditions and be able to thrive in an anaerobic environment. In addition, wetland plants must be readily available from local plant nurseries (Wallace and Knight, 2006; Wallace, 2004).

5.8.1.1 Wetland Planting Stock

When considering wetlands as a treatment option, designers must take steps to ensure that planting stock will be available in the quantity and quality needed for the project at a cost-effective price. Options for plant materials according to Wallace and Knight, (2006)rather than being borderless by nature, the digital has to be understood as producing different kinds of borders, demanding different kinds of politics of location. New potentialities arise with the challenge of creating a politics fitting to the current mode in which locations become slippery. Discussing the emergence of cyberfeminism in the early 1990s and a more recent example of digital feminism - the #SolitarityIs-ForWhiteWomen hashtag - this article thinks through the following questions: what does the \"cyborg\" as a posthuman (and postgender include:

- Natural colonization/ regrowth (FWS wetlands). This option typically requires delaying the start-up of the treatment wetland for one or more growing seasons.
- Commercially available planting stock. This is the most common method of obtaining planting stock for small- to mid-size VSB and FWS projects; large projects may require contract growing with a commercial nursery.
- Donor plants from another treatment wetland. This option is often chosen for small projects when the plant species involved are very easy to propagate, *e.g.* common reed (*Phragmites australis*) or reed canary grass (*Phalaris arundinaceous*).
- Onsite wetland plant nursery. For large projects, a plant nursery can be created at the project site to provide the required planting materials. The nursery must be decided very early as matured 1 - 2 years old plants are preferred (Kadlec *et al.*, 2000)

Wetland vegetation can be established with seed, seedlings, whole plants, or parts of plants (rootstocks, rhizomes, tubers, or stem cuttings) (Vymazal, 1998). Since seeds generally do not sprout in water, vegetative propagation by runners and stolons is common in wetland plants, even though many of them produce seeds carried by the wind. Although they are primarily food storage organs, many emergent wetland vegetation species have rhizomes, rootstocks, or tubers that can produce new plants.

a) **Seeds**

Suitable seed stock, soil moisture, light, and temperature provided favourable conditions, for establishment of wetland plants directly from seeds (Kadlec *et al*., 2000). Seed germination is highly dependent on the soil/seed contact and the moisture regime of the soil as seeds are sown directly into the soil (Vymazal, 1998). For FWS systems that use a native soil rooting substrate or VSB technology variants that employ sand beds, it is typically simpler to establish wetland plants from seed (Gesellschaft zur Förderung der Abwassertechnik d.V (GFA, 1998).

Some species produce few seeds; others have seeds that can be harvested in large quantities from the ground. For instance, whereas mature bulrush culms may only contain 20 to 30 seeds each, a typical cattail seed head contains thousands of individual seeds. Additionally, seed viability varies greatly between plant species. Most wetland seeds can be applied with rotary seeders or manually and then lightly raked into the surface soil layer if sufficient quantities are available. A spartina salt marsh can be established with an estimated l.2 106 seeds per hectare (4.9 105 seeds per acre) (Broome *et al*., 1988).

b) **Bare-Root Plants**

Bare-root varieties of herbaceous and woody wetland plants are available. Hand-dug shallow holes are typically used to plant bare-root seedlings. Bare-root seedlings typically have a survival rate of 80 percent or better, which is significantly higher than the rate achieved by germination of seeds in the field. The bare-root plants' initial success is largely determined by their size; Most of the time, plants with small root stock don't have enough energy to make it through the transplanting process.

c) **Rhizomes**

Most plant stocks are rhizomes or tubers conveyed from a wetland plant nursery (Scott D. Wallace, 2004). Rhizomes or tubers are often provided by herbaceous wetland plants. Rhizomes that have at least one shoot or bud and are horizontal or vertical can be planted directly in the bed. According to Vymazal, (1998) the extent of damage done to the shoots during sapling and planting and their stage of development will determine whether or not this method is successful. Rhizomes that are still dormant can be shipped to the project site. The stems of plants that have broken dormancy are frequently clipped back to make shipping and planting easier. More stored energy is available to support plant establishment in larger rhizomes.

d) **Potted Plants**

Seedlings can be planted and grown in potting soil-filled containers to establish planting materials with developed root structures (Kadlec *et al*., 2000). When compared to seeds and bare-root seedlings, potted plants have a greater advantage for initial growth, primarily due to their larger stored energy reserves and minimal root structure damage during planting (if it is properly sized). However, potted plants are more expensive. As a result, these plants are typically used sparingly for ornamental purposes or specific planting objectives for wildlife habitat purposes.

e) **Field Harvested Plants**

Herbaceous wetland plants can, in certain cases, be employed for planting in newly constructed wetlands. Wetland plants like cattails and bulrush are common in roadside ditches, man-made ponds, and along canals in areas with abundant natural wetlands and high regional water tables (Kadlec *et al*., 2000). Depending on local regulations, a permit for the collection of plants may be required. Another possibility for stock planting is the treatment wetlands that are already in place. Field collection can happen by hand reaping or by utilizing an excavator to scoop wetland plants starting from the earliest stage spread them on an open, upland region where they are isolated by hand into reasonable units. Any of the plant stock sources tend to be the most labor-intensive for this method.

5.8.1.2 Condition of Planting Stock

The size and condition of the planting stock should be specified by the designer once a suitable source has been found. The majority of the planting material for small-scale wetland projects will come from rhizomes or tubers purchased from a wetland plant market. The rootstock's bodies and shoots ought to be rigid to the touch. Bodies and shoots that are mushy, soft, and appear to be decayed or rotten should not be accepted (Wallace, 2004). New roots on an established rootstock ought to be clean, white, and rigid to the touch. Figure 5.1 depicts a healthy Typha latifolia plant that was taken from a VSB system near Lutsen, Minnesota, in the United States. Take note of the rhizomes' and roots' firm, white conditions.

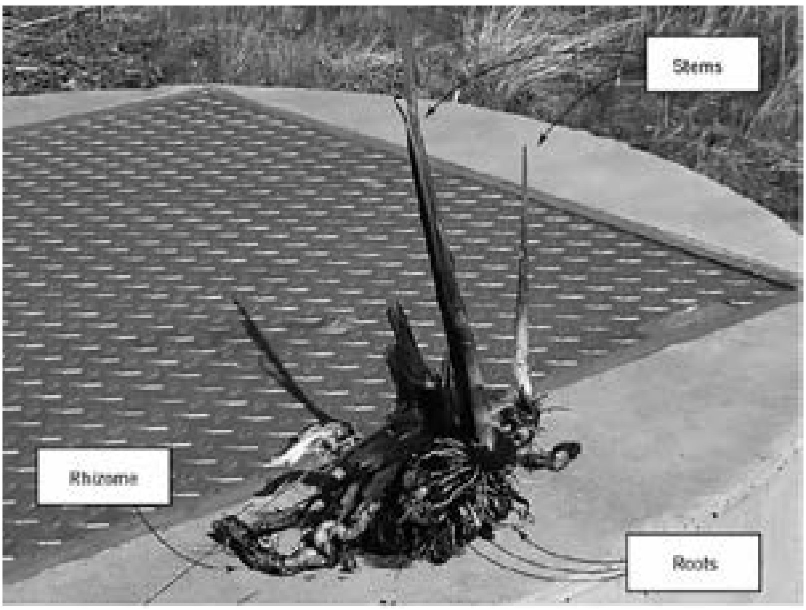


Figure 5.1: Example of healthy plant stock and root development. (Photo courtesy S. Wallace).

The rhizome stores the energy necessary to get the plant going; Compared to small stock, larger tubers or rhizomes offer a much better chance of success. The size of the tubers that make up the rootstock should be at least 1.5 cm (one inch.) in diameter (Vymazal *et al*., 1998; Haule *et al*., 2002; Kadelc and Wallace, 2006). The length of the rhizomes that make up the rootstock should be at least 5 cm (two inches.) long. Since each tuber may have multiple buds or shoots, the number of roots or tubers rather than the number of buds or shoots should be used to count the plant (Wallace, 2004).

If potted plants are used, they should be at least 10 cm (four inches) in pots (Wallace, 2004). If the bound soil/root mass is not the same size as the container, the result will be a plant that is 5 cm tall in a 10 cm pot (Wallace, 2004). The sides and bottom of the peat pot should be well-rooted and well-anchored for plants in them. The plants should appear healthy and free of leaf spots, insect damage, or wilting if they are growing at the time of installation. Plant material should be kept cool and under the shade after being delivered to the job site. Plant stock that is exposed to the sun can quickly dry out and become useless. The majority of wetland plant species are extremely susceptible to drought (Wallace, 2004).

5.8.1.3 Planting Wetland Vegetation

In wetland treatment systems, almost all planting is done by hand. In the FWS wetland, the rooting substrate remains saturated despite the lower water level. Scooping a shallow depression of about 6 cm or 3 inches is used to install plants (bare root, field-harvested, or potted) out of the substrate, into the depression with the plant's root mass, and back into the soil around the root mass. Figure 5.2 shows this process. For VSB wetlands, planting should likewise be possible the hard way. The VSB media is directly planted with rhizomes and rootstocks. In most cases, the level of the water is lowered to make planting easier. As depicted in Figure 5.3, the water level is immediately raised following planting to prevent the rhizomes from drying out.

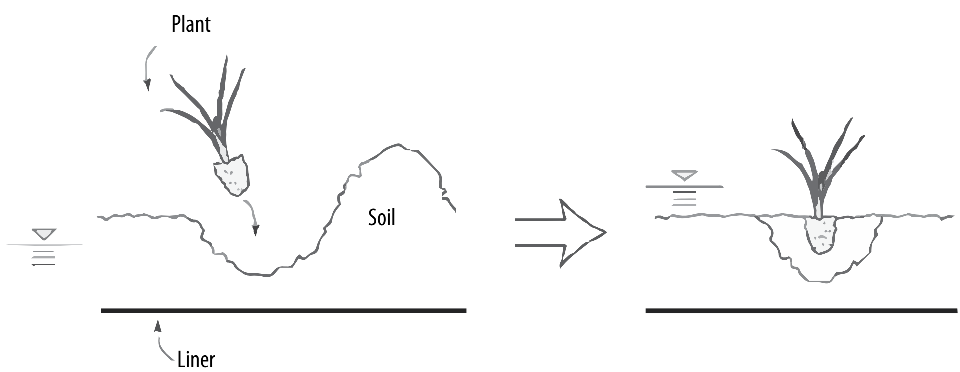


Figure 5.2: Procedures for installing potted plants in a standard FWS wetland (Wallace, 2004).

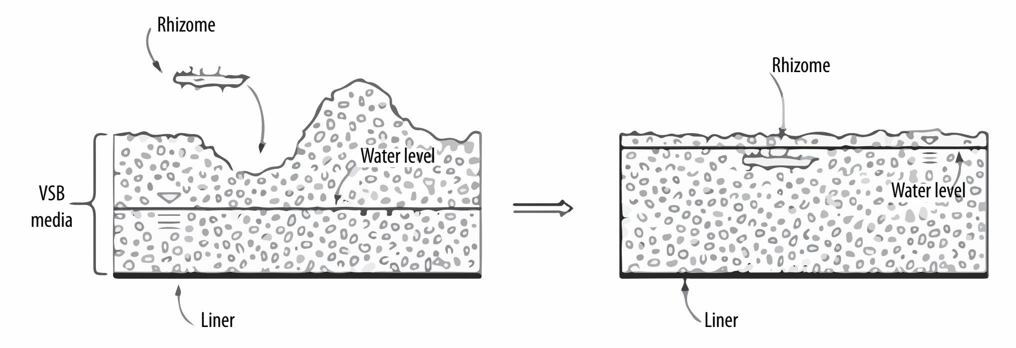


Figure 5.3: Procedure for planting rhizomes in a standard VSB wetland

For wetlands that are insulated with mulch, the procedure is slightly different. To sub-irrigate the mulch layer after planting, the water level is typically raised above the top of the VSB bed (Wallace, 2004). As depicted in Figure 5.4, if potted or bare-root plants are used, the mulch is tightly packed around the plant for stability, protection, and good water contact with the roots.

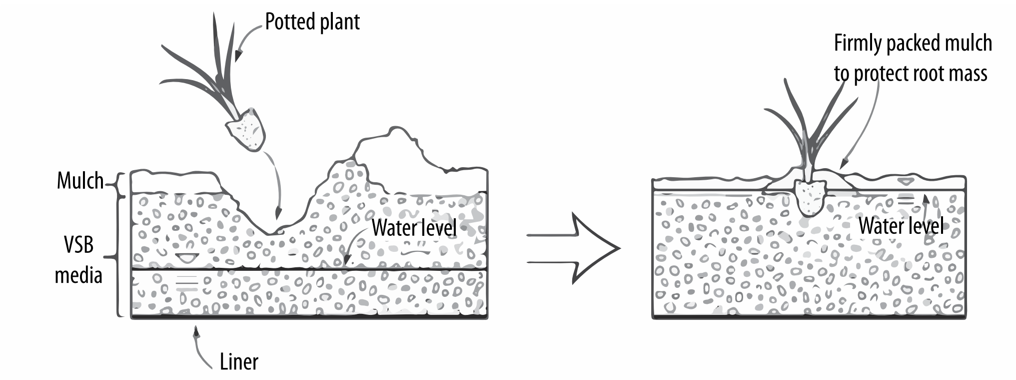


Figure 5.4: Procedure for installing potted plants in a mulch-insulated VSB wetland (Wallace, 2004).

To avoid soil compaction in soil based VSB systems, extreme caution is required; Workers typically use plywood to distribute their weight and minimize the impact on the media in these applications (Kickuth, 2002). Workers quickly adapt their tools to the task because of the repetitive nature of the work. A tool for entrenching is one of the most frequently used tools for planting. A skilled labourer can plant between 80 and 120 plants per person per hour in a VSB wetland and between 60 and 80 plants per person per hour in a FWS wetland.

5.8.1.4 Successful Plant Establishment

For plant establishment to be successful in a constructed wetland:

- The species of plants must be appropriate for the wetland's hydrologic conditions.
- The plant material (such as the seed, tuber, rhizome, and pot) must be viable at planting time.
- Water level management during the startup phase must accommodate the establishing plants' requirements..

Plants in wetlands are adapted to a hydric environment and are very resistant to drought. There may be widespread mortality if the plants are allowed to dry out during the establishment phase, when there is very little available water-drawing root system.

For non-mulched VSB wetlands, the water level should be raised to the bed level and for mulched systems approximately 3 cm above the gravel bed so that the mulch is sub-irrigated. During establishment, the objective is to supply the plant's root zone with continuous water (Wallace, 2004). The water level in FWS wetlands should just cover the top of the rooting substrate (a "mud flat") for planting. To get oxygen and sunlight, emerging plants need to be able to breathe, and if the new shoots are flooded for a long time, the plants will drown. The water level can be gradually raised to the design level as the plant shoots get taller, but it should always be below the plants' tops.

In constructed wetlands, design specifications for vegetation establishment should clearly delegate responsibility for plant maintenance from planting to establishment. To ensure that the plant survives and grows, regular inspections of the soil are necessary for successful establishment. The frequency of these inspections varies depending on the project, but should be sufficient enough to address potential issues in advance.

The viability of the planted propagules *i.e.* seeds, seedlings, or mature plants harvested in the field should be examined during the initial plant inspection. The estimated percentage of cover and average plant height are used to track subsequent plant growth. Before and during the operation of a wetland treatment system, non-destructive methods are utilized to determine the state of plant development.

An estimate of plant cover is how much of the ground is covered by stems and leaves. By walking through or next to a plant stand and visually identifying the plants' cover category, this parameter can be estimated. In a constructed wetland treatment system, cover estimates and plant health observations should be a regular part of operational monitoring. Problems must be anticipated and prevented before they become serious or have progressed too far due to the importance of plants for maintaining the performance of wetland treatment systems and their slow growth rate. When the plants have been permanently damaged by operator neglect or wildlife grazing, re-establishing a healthy plant community in a constructed wetland is a slow process.

5.8.1.5 Summary

The proper and effective functioning of CW systems are largely dependent on plants. All wetland systems owe much of their public acceptance to the vegetative communities they support, even though FWS systems rely significantly more on plants for treatment performance than VSB systems. Designers should take into account important factors like hydrology, climate and latitude, cost and availability of planting stock, plant size and propagation rate, water quality, maintenance requirements, and overall project objectives when selecting plants for treatment wetlands (Kadlec *et al.*, 2000).

The plant species must be able to tolerate the wetland's hydrologic environment for successful plant establishment. Additionally, it is essential that the planting stock be viable at the time of planting and that the treatment system's water level be managed to meet the plant's startup requirements. Wetland plants that are just starting to grow can be grazed by wildlife. To safeguard the plants, it may be necessary to employ animal control methods in some instances.

5.8.2 Substrate

Selecting suitable substrates for use in CWs for the treatment of municipal wastewater is an important issue. The substrate not only serves as a suitable growing medium for plants but also makes it possible for wastewater to move successfully (Zhang *et al.*, 2007). It offers locations for physical, chemical and biological transformations, as well as a place to store pollutants that have been removed (Zhang *et al.*, 2021) Substrate are mainly natural materials such as soil, sand, gravel, and organic materials (Zhang *et al.*, 2021). The choice of substrate is determined by the hydraulic permeability of the substrate and its capacity to absorb nutrients and pollutants (Vymazal *et al.*, 1998).

Hydraulic conductivity is very low for very small particles and very high for the large particles. Despite their high conductivity, very large particles only have a small amount of wetted surface area per unit volume of microbial habitat. Other factors to be considered during the selection of substrate materials include their cost and local availability, hydraulic and engineering viability, the ability to re-move contaminants, support for plant growth, microbe adhesion, safety, substrate plugging, substrate life, recycling, and disposal issues (Zhang *et al.*, 2021).

5.8.2.1 HF Wetland Substrate

Media used in HF wetlands are said to have diameters ranging from 0.2 mm to 30 mm (ONORM B 2505, 1997; Vymazal, 1997; GFA, 1998; EC/EWPCA, 1990; U.S. EPA, 1988; Steiner and Watson, 1993; U.S. EPA, 1993; Reed *et al.*, 1995; U.S. EPA, 2000). It is suggested that the media in the system's inlet and outlet zones have a diameter of between 40 and 80 mm to prevent clogging and extend from the system's top to bottom. According to the U.S. EPA, (2000), there does not appear to be any discernible advantage in the removal of pollutants from the treatment zone when using various sizes of media, ranging from 10 to 60 millimetres (mm). The recommended substrate sizes are shown in Figure 5.5, with media ranging from 40 to 80 mm at the inlet and outlet zones and 5 to 20 mm at the treatment zone (UN-HABITAT, 2008).

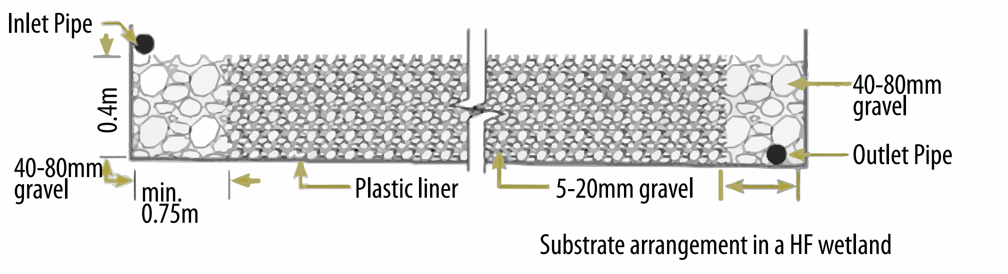


Figure 5.5: Substrate configurations in an HF wetland. (UN-HABITAT, 2008).

5.8.2.2 VF Wetland Substrate

When choosing a substrate, the important characteristics are d10 (effective grain size), d60 (the quotient between d60 and d10), and the uniformity coefficient. The construction of a VF wetland requires a variety of different substrate designs, not just one. Different research works report that the effective grain size ought to be 0.2 < d10 < 1.2 mm, consistency coefficient 3 < d60/d10 < 6 and water driven conductivity Kf 103 to 104 m/s (Reed *et al.*, 1990, Vymazal *et al.*, 1998, GFA, 1998, Lienard *et al.*, 1998, Brix, 2004, Korkusuz, 2005).

Porous media with smaller pore sizes show the fastest rate of decrease in permeability for SS influent characteristics. Because of sediment accumulation at the surface of the sands, the permeability of the sands decreases more rapidly than that of the gravel. However, larger particle sizes result in a deeper clogging depth (Walker, 2006). Sand with a d10 > 0.3 mm, d60/d10 < 4, and a permeability of 10-3 to 10-4 m/s is recommended as the primary substrate. The arrangement of the substrate should be as shown in Figure 5.6.

The available nation soils maps show the significant soil types present and their relationship to site geology and topography. Because soils are stratified and vary with depth, the soil maps provide a general description of the characteristics of the soil, but they cannot be relied upon for detailed, site-specific information. It is essential to know the characteristics of the soil at the depth of the excavation if the wetland is to be excavated.

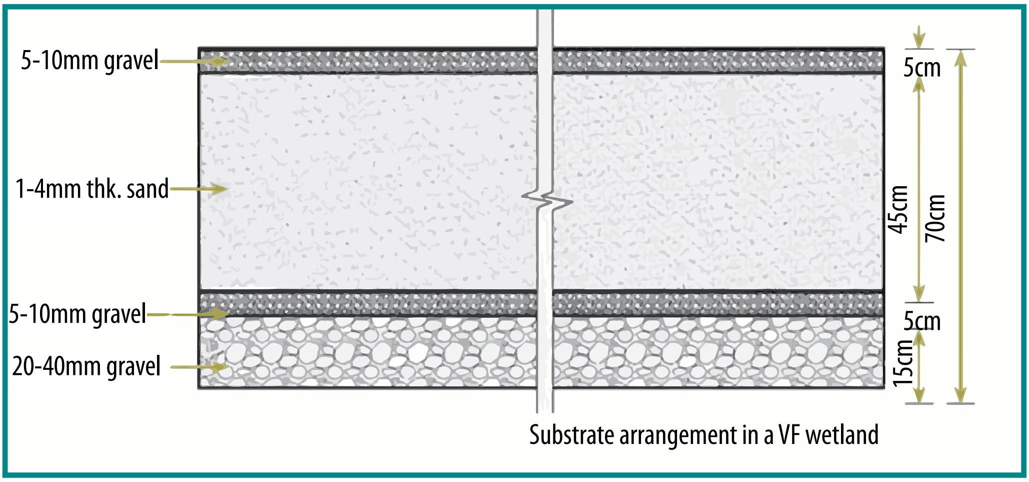


Figure 5.6: VF wetland substrate arrangement. (UN-HABITAT, 2008).

Before using soils in the wetland, they should be analysed. Field data collection is required to obtain site-specific information on the hydraulic conductivity and permeability of the soils. The percentage of organic matter, mineral content, and clay content of the soil should all be measured in laboratory analyses. The sand's properties should be examined in as accredited laboratory. The hydraulic conductivity of the grain should be measured and analyzed. Figure 5.7 depicts a typical sand grain size distribution suitable for VF CWs.

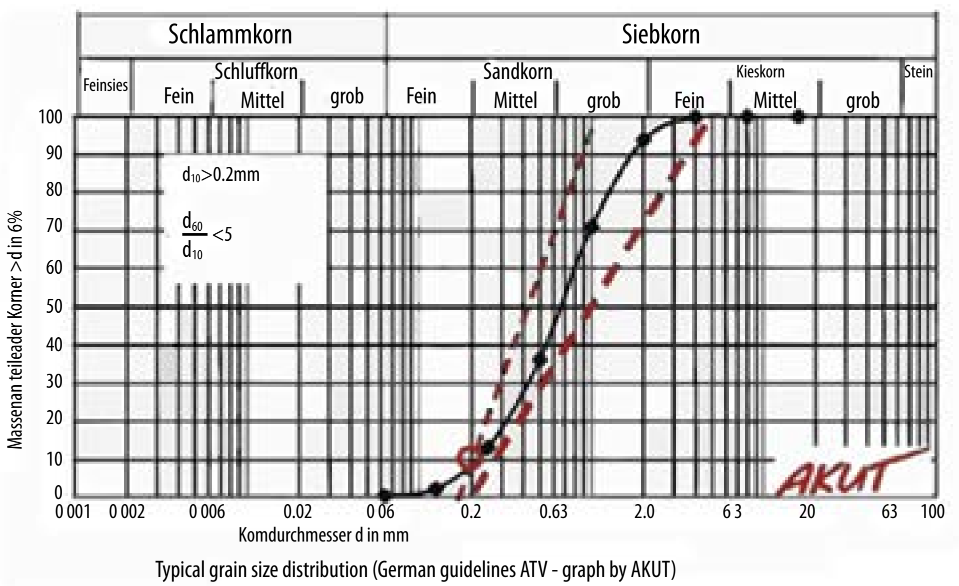


Figure 5.7: Typical distribution of grain sizes (AKUT graph based on German guidelines ATV) (UN-HABITAT, 2008).

5.9 Planning Examples

Depending on the location and the treatment objectives of CW, different countries in the WIO region have varied wastewater treatment goals and type of wastewater. Most of the implemented CWs in Tanzania have been designed to achieve the secondary and tertiary treatment objectives solely for domestic wastewater (Mbwette *et al*., 2002; Senzia *et al*., 2002; Kimwaga *et al*., 2003). While some CW were designed, constructed and operated as pilot system, others were put in place as the results of research. The CW at the University of Dar es Salaam and Ardhi University were designed for research objectives to upgrade effluents from waste stabilization ponds and to treat effluent from Upflow anaerobic sludge blanket reactor, respectively (Mashauri *et al*., 2000; Mashauri and Kayombo, 2002; Kaseva *et al*., 2002; Mwegoha *et al*., 2002; Senzia *et al*., 2003; Kimwaga *et al*., 2002a, b, 2004; Mbuligwe, 2004). For practical purposes, CW were installed at Water Supply and Sanitation/Sewerage Authorities, including Moruwasa (Morogoro), Iruwasa (Iringa), Mwauwasa (Mwanza), and Muwasa (Moshi), was meant to polish effluent from the Waste Stabilization Pond. Geita Water supply and sewerage authority and Mwanza Abattoir polish wastewater from biodigester, and the Banana breweries industry polish the brewing wastewater from the clarifier, in contrast to Kuwasa (Kigoma), which treats on-site faecal sludge from a sludge drying bed.

Additionally, CW were designed as a secondary treatment from septic tanks (Kaseva *et al*., 2002) in most schools, including St. Antony Secondary School, Kleruu Education College, Ruaha Secondary school, Iringa Girls Secondary school, and Waliuli Asri Islamic College. In the WIO region, the mostly widely used types of constructed wetlands are horizontal subsurface flow (HSSF) (Mashauri and Kayombo, 2002; Mashauri *et al*., 2000, Kaseva *et al*., 2002; Senzia *et al*., 2003; Kimwaga *et al*., 2002a,b, 2004; Mwegoha *et al*., 2002; Mbuligwe, 2004). For instance, in Tanzania, all the above-mentioned constructed wetlands are SSHF because of their performance effectiveness and environmental friend, *i.e.* subsurface flow avoids the creation of mosquito breeding sites.

Phragmites mauritianus is the plant species most commonly used in Tanzania (Haule *et al*., 2002; Kaseva, 2004, Senzia *et al*., 2003, Kimwaga *et al*., 2003). In Tanzania, all CW have been planted with PM, except for the Ardhi University CW, which were planted Typha latifolia (Mbuligwe, 2004). The preferred choice for the *Phragmites mauritianus* is based on its strong performance, productivity, tolerance to organic loadings, and adaptability to a specific environment (Haule *et al*., 2000; Vymazal *et al*., 1998). At Ardhi University, the *Typha latifolia* which was employed for the research purposes have presented encouragingly promising results (Mgana, 2000; Mbuligwe, 2004). Rhizomes have been employed to establish vegetation in every constructed wetland in Tanzania because they develop shoots and mature plants more quickly than seedlings. As a result, planted rhizomes produced many daughter plants within a few weeks. In Mauritius, CWs were piloted to treat greywater. Like in Tanzania, Madagascar CWs were piloted of the treatment of domestic wastewater.

5.10 References

AECOM, I. B. (2014). Water Reuse And Environmental Conservation Project.

Arias, M. E., and Brown, M. T. (2009). Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia. Ecological Engineering, 35(7), 1070-1078.

Atkin, C. K., and Freimuth, V. (2013). Guidelines for formative evaluation research in campaign design. Public communication campaigns, 4, 53-68.

Brix, H. and Johansen, N.H. (2004). Guidelines for vertical flow constructed wetland systems up to 30 PE. Økologisk Byfornyelse og Spildevandsrensning No. 52. Miljøstyrelsen, Miljøministeriet (in Danish).

Brodie, G. A. (1990). Constructed wetlands for treating acid drainage at Tennessee Valley Authority coal facilities. In Constructed wetlands in water pollution control (pp. 461-470). Pergamon.

Broome, S. W., Seneca, E. D., and Woodhouse Jr, W. W. (1988). Tidal salt marsh restoration. Aquatic Botany, 32(1-2), 1-22.

Carty, A., Scholz, M., Heal, K., Gouriveau, F., and Mustafa, A. (2008). The universal design, operation and maintenance guidelines for farm constructed wetlands (FCW) in temperate climates. Bioresource technology, 99(15), 6780-6792.

Davis, L. (1995). A handbook of constructed wetlands: A guide to creating wetlands for: agricultural wastewater, domestic wastewater, coal mine drainage, stormwater. In the Mid-Atlantic Region. Volume 2. Domestic wastewater. USDA-Natural Resources Conservation Service.

EC/EWPCA (1990) European design and operations guidelines for reed bed treatment systems. Presented to the Conference ``Constructed Wetlands in Water Pollution Control'', Cambridge, UK, September 1990. Also available as WRc Report UI 17, WRc Swindon, UK, December, 1990.

EPA. (1998). Design Manual - Constructed Wetlands and Aquatic Plant Systems for Municipal Water Treament. Wetlands, (September).

FAO, (Food and Agriculture Organisation). 1976. A framework for Land Evaluation. FAO Soils Bull. 32: FAO Rome. Pp. 87

Food and Agricultural Organization, FAO. (1993). Sustainable development of drylands and combating desertification. FAO position paper.Rome

Gesellschaft zur Förderung der Abwassertechnik d.V. (GFA). (1998). Arbeitsblatt ATV – A 262 Grundsätze für Bemessung, Bau und Betrieb von Pfl anzenbeetwn für kommunales Abwaser bei Ausbaugrößen bis 1000 Einwohnerwerte, St. Augustin, Germany.

Haule, K. S., Johnsen, F. H., and Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. Journal of environmental management, 66(1), 31-42.

Kadlec, R. H., Knight, R. L., Vymazal, J., Brix, H., Cooper, P., and Haberl, R. (2000). Knight, Cooper, Brix, Vymazal, Haberl, Kadlec. Constructed Wetlands for Pollution Control.pdf (p. 151). p. 151. Retrieved from *http://biblioteca.cehum.org/handle/CEHUM2018/1649*

Kaseva, M. E. (2004). Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater—a tropical case study. Water research, 38(3), 681-687.

Kaseva, M. E., Mbwette, T. S., and Katima, J. H. (2002). Domestic Sewage Treatment in a Pilot Plant Composed of Septic Tank and Constructed Wetlands-A Case Study in Dar es Salaam, Tanzania. In IWA Conference on Wetland Systems for Water Pollution Control, Arusha, Tanzania.

Kickuth, R. (2002). Personal Communication between Kickuth R. and Wallace S.D.

Kimwaga, R. J., Mashauri, D. A., Mbwette, T. S. A., Katima, J. H., and Jørgensen, S. E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. Physics and Chemistry of the Earth, Parts A/B/C, 29(15-18), 1243-1251.

Kimwaga, R., Mashauri, D., and Mbwette, T. (2003). Meeting health improvement indicators in waste stabilization ponds effluents by a coupled dynamic roughing filters and subsurface horizontal flow constructed wetland in Tanzania. Prospective College of Engineering and Technology, University of Dar es Salaam, Dar es Salaam, Tanzania

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E., 2002. Mathematical modelling of the TSS removal in a coupled dynamic roughing filter and subsurface horizontal flow constructed wetland system treating WSP effluent, in: Proc s. 8th Internat. Conf. Wetland Systems for Water Pollution Control, University of Dares- Salaam, Tanzania and IWA, pp. 843-857.

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E. (2002a). Modelling sludge accumulation in dynamic roughing filters coupled to a horizontal subsurface flow constructed wetland, in: Proc. 8 Internat. Conf. Wetland Systems for Water Pollution Control, University of Dar-es-Salaam, Tanzania and IWA, pp. 788-798.

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E. (2002b). Mathematical modeling of the TSS removal in a coupled dynamic roughing filter and subsurface horizontal flow constructed wetland system treating WSP effluents, in: Proc. 8th Internet Conf. Wetland Systems for Water Pollution Control, University of Dares-Salaam, Tanzania and IWA, pp. 843-857.

Korkusuz, E. A. (2005). Manual of practice on constructed wetlands for wastewater treatment and reuse in Mediterranean countries. Report AVKR, 5.

Kumar, R., Nadda, R., Kumar, S., Razak, A., Sharifpur, M., Aybar, H. S., ... and Afzal, A. (2022). Influence of artificial roughness parametric variation on thermal performance of solar thermal collector: An experimental study, response surface analysis and ANN modelling. Sustainable Energy Technologies and Assessments, 52, 102047.

Liénard, A., Boutin, C. and Esser, D. (1998). France. In : "Constructed wetlands for wastewater treatment in Europe.", Ed. Vymazal J., Brix H., Cooper P.F., Green M.B., Haberi R., 1998, Backhuys Publishers, Leiden, NETHERLANDS, pp.153-168

Liu, D., Ge, Y., Chang, J., Peng, C., Gu, B., Chan, G. Y. S., and Wu, X. (2009). Constructed wetlands in China: Recent developments and future challenges. Frontiers in Ecology and the Environment, 7(5), 261–268. https://doi.org/10.1890/070110

Mashauri, D. A., and Kayombo, S. (2002). Application of the two coupled models for water quality management: facultative pond cum constructed wetland models. Physics and Chemistry of the Earth, Parts A/B/C, 27(11-22), 773-781.

Mashauri, D. A., Mulungu, D. M., & Abdulhussein, B. S. (2000). Constructed wetland at the University of Dar es Salaam. Water research, 34(4), 1135-1144.

Mbuligwe, S. E. (2004). Comparative effectiveness of engineered wetland systems in the treatment of anaerobically pre-treated domestic wastewater. Ecological engineering, 23(4-5), 269-284.

Mbwette, T. S. A., Katima, J. H. Y., Pratap, H. B., and Kayombo, S. (2002, September). Wetland systems for water pollution control. In Proc. 8th Int. Conf. on Wetland Systems for Water Pollution Control (pp. 16-19).

Metcalf and Eddy / Aecom (2014) Wastewater Engineering: Treatment and Resource Recovery, 5th ed, McGraw-Hill Education, New York, NY

Metcalf and Eddy. (2003). Wastewater Engineering. International Edition: Treatment and Reuse, Fourth Edition. ISBN 978-0071122504, published by Mc Graw-Hill Higher Education, New York, USA.

MoW. (2020). Design, Conctruction Supervision, Operation & Maintenance (DCOM) Manual. Design of Sanitation Projects. In Mkuki na Nyota. The United Republic of Tanzania. Ministry of Water (MoW).

Msovu, U. E., Mulungu, D. M., Nobert, J. K., and Mahoo, H. (2019). Land use/cover change and their impacts on streamflow in Kikuletwa Catchment of Pangani River Basin, Tanzania. Tanzania Journal of Engineering and Technology, 38(2), 171-192.

Mwegoha, W., Katima, J. H. Y., Mbwette, T. S. A., Njau, K. N., Jorgensen, S. E., and Nielsen, S. N. (2002). Modeling the effects of suspended solids accumulation on the hydraulic conductivity of gravel packed horizontal subsurface flow constructed wetlands. University of Dar es Salaam, PO Box, 35131.

Okeyo, A. N., Nontongana, N., Fadare, T. O., and Okoh, A. I. (2018). Vibrio species in wastewater final effluents and receiving watershed in South Africa: implications for public health. International journal of environmental research and public health, 15(6), 1266.

ÖNORM B 2505 (1997). Bepfl anzte Bodenfi lter (Pfl anzenkläranlagen) – Anwendung, Bemessung, Bau und Betrieb (Subsurface flow constructed wetlands – Application, Dimensioning, Installation and Operation), Österreichisches Normungsinstitut: Vienna, Austria.

Reed S.C. *et al*., (1990). Natural systems for wastewater treatment – Manual of practice FD16. Water Pollution Control Federation, 601 Wyhe Stre*et al*exandria, Virginia. Cited by Grant, N. and Griggs J. (2001). Reed beds for the treatment of domestic wastewater, BRE.

Reed, S. C, Crites, R. W., and Middlebrooks, E. J. (1995) Natural Systems for Waste Management & Treatment, Second Edition, McGraw Hill, New York, N.Y.

RoK (Republic of Kenya). (2008). Ministry of Water and Irrigation Draft Practice Manual for Sewerage and Sanitation Services in Kenya

Scholz, M., and Lee, B. H. (2005). Constructed wetlands: A review. International Journal of Environmental Studies, 62(4), 421–447. *https://doi.org/10.1080/00207230500119783*

Scott D. Wallace, P. . (2004). University Curriculum Development for Decentralized Wastewater Treatment Constructed Wetlands : Design Approaches CIDWT / University Disclaimer. Design, (September).

Sen, T. K., and Chatterji, S. (2018). Land Use Planning: Basics and Approaches. Geospatial Technologies in Land Resources Mapping, Monitoring and Management, 471-488.

Senzia, M. A., Mashauri, D. A., and Mayo, A. W. (2003). Suitability of constructed wetlands and waste stabilisation ponds in wastewater treatment: nitrogen transformation and removal. Physics and Chemistry of the Earth, Parts A/B/C, 28(20-27), 1117-1124.

Senzia, M. A., Mashauri, D. A., Mayo, A. W., Mbwette, T. S., Katima, J. H., Pratap, H. B., and Nielsen, S. N. (2002, September). Performance of horizontal subsurface flow constructed wetlands located downstream of primary facultative and maturation ponds in Tanzania. In Int. Conf. on Wetlands Systems for water Pollution Control, Arusha, Tanzania.

Skousen, J., Rose, A., Geidel, G., Foreman, J., Evans, R., and Hellier, W. (1998). Handbook of technologies for avoidance and remediation of acid mine drainage. National Mine Land Reclamation Center, Morgantown, 131.

Steiner, G. and Watson, J. (1993) General Design, Construction and Operation Guidelines; Constructed Wetlands Wastewater Treatment Systems for Small Users Including Individual Residences, Second Edition. Tennessee Valley Authority Resource Group Water Management TVA/WM—93/10.

Sundaravadivel, M., and Vigneswaran, S. (2001). Constructed wetlands for wastewater treatment. Critical Reviews in Environmental Science and Technology, 31(4), 351–409. *https://doi.org/10.1080/20016491089253*

Tanaka, N., Ng, W. J., and Jinadasa, K. B. S. N. (2011). Wetlands for Tropical Applications. In Wetlands for Tropical Applications. *https://doi.org/10.1142/p599*

UN-HABITAT. (2008). Constructed Wetlands Manual.United Nations Human Settlements Programme for Asian Cities. Retrieved from www.unhabitat.org

URT (2020). Water sector status report of 2015-2020. URT.

U.S. EPA (1988). Design Manual. Constructed Wetlands and Aquatic Plant Systems for Municipal Water Treatment. EPA/625/1-88/022. U.S. Environmental Protection Agen- cy, Cincinnati, OH, US. Available at www.epa.gov

U.S. EPA (2000). Constructed Wetlands Treatment of Municipal Wastewaters. EPA/625/R-99/010. U.S. Environmental Protection Agency, Washington, D.C., US. Available at: www.epa.gov

U.S. EPA. (1993). Domestic septage regulatory guidance. EPA/832/B-92/005. Washington, DC.

Vymazal, J. (1998). Removal mechanisms and types of constructed wetlands. Constructed wetlands for wastewater treatment in Europe, 17-66.

Vymazal, J., (1997). Subsurface horizontal-flow constructed wet- lands for wastewater treatment: the Czech experience. Wetlands Ecol. Manage. 4, 199–206.

Walker, A. (2006). Predicting the clogging of saturated substrates used in the construction of vertical flow systems by suspended solids.

Wallace, S., and Knight, R. (2006). Small-Scale Constructed Wetland Treatment Systems: Feasibility, Design Criteria, and O&M Requirements. In Feasibility, Design Criteria, and O&M Requirements.

World Bank Group. (2014). The World Bank Group A to Z 2015. World Bank Publications.

Zhang, H., Tang, W., Wang, W., Yin, W., Liu, H., Ma, X., … Zha, J. (2021). A review on China's constructed wetlands in recent three decades: Application and practice. Journal of Environmental Sciences (China), 104(June), 53–68. *https://doi.org/10.1016/j.jes.2020.11.032*

Zhang, Z., Rengel, Z., and Meney, K. (2007a). Removal of nutrients from secondary-treated municipal wastewater in wetland microcosms using ornamental plant species

Chapter 6: Design of Constructed Wetlands

By Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

Design is one of the most critical steps in putting up a certain engineering structure in place including CW technology. Broadly, design is about the process of determining the size and site of the CW to accommodate a given amount of wastewater and faecal sludge for a particular type of CW to meet a pre-specified and pre-determined treatment objective in compliance with the standards. Two types of design exist. Firstly, process design which deals with the size determination of CW and secondly, the physical design which is about determining the construction site. This chapter focuses on the process design where various design approaches and equations have been presented based on their applicability in the WIO region. A brief description has been presented with the need for the preliminary and pre-treatment units before CW. The chapter concludes by giving the CW design examples to consolidate to the design theoretical part. The following sections discuss the CW design proceeded by preliminary or pre-treatment units.

6.1 Design of Pre-treatment Units

Before designing, it should be borne in mind that the CW substrate wetland can be rapidly filled up with debris, grit, and solids from raw wastewater if these materials are not removed prior to the CW (Sundaravadivel and Vigneswaran, 2001; Kimwaga *et al*., 2004). If unattended, the substrate filled up materials can easily result into clogging the CW system which if it were designed as sub-surface flow CW may result into ponding. Therefore, a minimum preliminary/primary treatment should be carefully provided to remove the settleable solids (Sundaravadivel and Vigneswaran 2001; Kimwaga *et al*., 2004). However, some systems in France have avoided the primary treatment units and used staged vertical flow constructed wetlands that are operated in parallel, instead (Molle *et al*., 2004).

Initially, it was perceived that CWs would not require pretreatment, and screened and unscreened wastewater could be applied to the system (Molle *et al*., 2004). However, experience over the last two decades has shown that appropriate pre-treatment could contribute to the simpler operation and maintenance of wetland systems (Kasseva *et al.*, 2000, Kasseva *et al.*, 2002, Senzia *et al.*, 2002; Kimwaga *et al.*, 2004). Therefore, current recommendations are to precede the constructed treatment wetlands with preliminary and primary treatment systems (Sundaravadivel and Vigneswaran, 2001). Preliminary treatment involves screening and/or comminution (where applicable) to remove coarse solids and organic loading rates (Sundaravadivel and Vigneswaran, 2001). It can be achieved by using Imhoff tanks, septic tanks, primary sedimentation tanks, dynamic roughing filters or stabilization ponds (Kasseva *et al.*, 2000, Kasseva *et al.*, 2002, Senzia *et al.*, 2002; Kimwaga *et al.*, 2004). While preliminary treatment is now considered as a minimum, often it may not be sufficient. Therefore, wherever possible, treatment wetlands should be preceded by both 'preliminary' and 'primary' treatment (Figure 6.1).

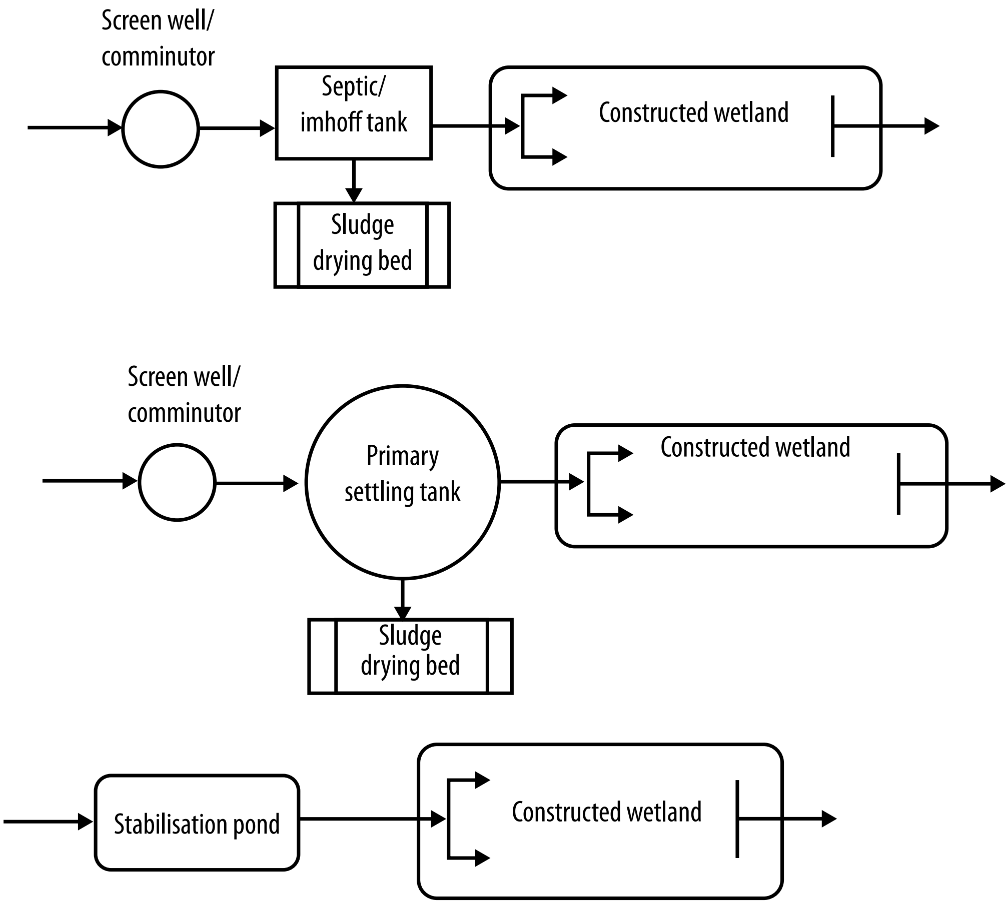


Figure 6.1: Various pre-treatment options with CW (Sundaravadivel and Vigneswaran, 2001)

For smaller systems, screening followed by a well-designed imhoff tank/ septic tank and dynamic roughing filters may be adequate (Sundaravadivel and Vigneswaran, 2001; Kimwaga *et al.*, 2004). For medium and large systems, stabilization ponds will be useful as pretreatment systems, if land is not a limitation (Sundaravadivel and Vigneswaran, 2001; Senzia *et al.*, 2003). Where land area is limited, primary settling tanks are recommended (Sundaravadivel and Vigneswaran, 2001).

Preliminary treatment mainly separates the coarsely dispersed solids out of the liquid phase. The preliminary treatment prepares wastewater influent for further treatment in the CW by reducing or removing problem wastewater characteristic such as total suspended solids (TSS) that could otherwise impede the operation of the CW by causing wear and tear in the mechanical equipment such as pumps or unduly increase maintenance of the CW (Kimwaga *et al.*, 2004; Sundaravadivel and Vigneswaran, 2001). The typical problem characteristics include large solids and rags; grit; odours etc. The preliminary treatment of wastewater comprises mainly the screen and grit chamber (Sundaravadivel and Vigneswaran, 2001). A screen is a device with openings, generally of uniform size, that is used to retain solids found in the influent wastewater to the treatment plant, which removes coarse materials from the wastewater (Sundaravadivel and Vigneswaran, 2001). Grit chamber remove grit, consisting of sand, gravel, or other heavy sold materials that have specific gravities much greater than those of the organic solids in the wastewater (Sundaravadivel and Vigneswaran, 2001).

6.2 Factors Affecting the Treatment Performance in Constructed Wetlands

An understanding of the factors affecting the CW treatment performance is the very first step to be considered in the design. The design of constructed treatment wetlands (CW) like any other wastewater treatment plant (WWTP) is largely governed by wastewater influent quality and quantity, and the required treated effluent quality parameters standards (Metcalf and Eddy., 1991). Other factors include; the type of vegetation and the environmental conditions such as water temperature which influences many of the biochemical reactions occurring in the CW (Vymazal *et al.*, 1998; Senzia *et al.*, 2003; Kadelc and Wallace, 2008; Kimwaga *et al.*, 2004). The design and implementation of a WWTP can have many constraints beyond these quality parameters (Sundaravadivel and Vigneswaran, 2001). These constraints include the issues concerning financing, the availability of space, the appropriateness of the technology for local application, the availability of an appropriately trained workforce, climatic conditions, site location and geology, and hydrological and hydrogeological factors (Sundaravadivel and Vigneswaran, 2001). All these constraints and requirements should be carefully and exhaustively considered during the planning stage of CW (please refer to Chapter five).

6.2.1 Influent Wastewater Characteristics and Effluent Water Quality Requirements

Experience has shown that the CW technology has been applied to treat various types of wastewaters majorly including domestic, municipal, industrial (*e.g.* from landfills, pulp and paper manufacturing, mine drainage, petroleum refining, electroplating, textile dyeing etc.), agricultural, agro-industrials, and stormwater runoffs (Vymazal *et al.*, 1998, Kadlec and Wallace, 2000). Influent characteristics of wastewater can be defined based on physical, chemical, and microbiological properties (Vymazal, 2001). The physical, chemical and biological characteristics considered for the CW design have been comprehensively discussed in Chapter 3 However; the focus of this book is domestic wastewater treatment. Effluent quality requirements and standards are generally determined by the discharge limits and/or possibly on the end user's requirements using various respective country's effluent standards (Vymazal *et al.*, 1998; Cooper *et al.*, 1999, Mbwette *et al.*, 2002). The influent and effluent wastewater characteristics together with the amount of the generated wastewater to be treated, the type of plant species and the substrate determine the size of CW (Vymazal *et al.*, 1998; Cooper *et al.*, 1999). During the design of CW, it is mandatory to determine the influent wastewater characteristics either by estimation or actual measurements through laboratory analysis (Sundaravadivel and Vigneswaran, 2001, Vymazal *et al.*, 1998).

6.2.2 Temperature

The rates of reaction of almost all biochemical processes are temperature dependent and increase with increasing temperatures (Cooper *et al.*, 1996). Therefore, the tropical environment will favour the biodegradation of organic matter, nitrification/denitrification, etc. (Mbwette *et al.*, 2002). The removal rates of BOD and nitrogen in FWS constructed wetlands can be estimated with Eq. (6.1) (Reed *et al.*, 1995). Table 6.1 shows similar results published by Sundaravadivel and Vigneswaran (2001).The removals of coliforms and phosphorus can be estimated with Eq. (6.1 and 6.2) (Kadlec and Knight, 1996; Economopoulou and Tsihrintzis, 2004).

$$\frac{Ce}{Ci} = e^{-K\frac{t}{T}} \text{ (for BOD and N).(6.1)}$$

$$K_{T=} k_{20} \, \Theta_{20}^{(T-20)}$$

For BOD, $K_T = 0.678 \ (1.06)^{T-20} (d^{-1})$

For nitrification, $K_T = 0.21870.678 \ (1.0684)^{T-20} d^{-1}$

For denitrification, $K_{T= \ 1.15^{T-20}(d^{-1})}$

$$\frac{Ce}{Ci} = e^{\frac{k1}{h1}} \text{ (for coliforms and P).} \quad (6.2)$$

For fecal coliforms, $K_1 = 0.3 \ (m d^{-1})$

For P, $K_1 = 0.0273 \ (m d^{-1})$

$$h_1 = \frac{Q}{A}$$

where:

C_e — Pollutant effluent concentration

C_i — Pollutant influent concentration ((mg/L for BOD, N, and P) and (coliform count/100mL for faecal coliform),

K_T — Reaction rate parameter (d^{-1}),

K_1 — Reaction rate constant (m d^{-1}),

h_1 — Hydraulic loading rate (m d^{-1}),

t— Hydraulic residence time (HRT) (d),

Q — Design flow rate ($m^3 d^{-1}$),

A — Mean surface area (m^2),

T — Water temperature or ambient temperature in °C

The HRT can, thereafter, be estimated based on the most critical case. For the effective removal of ammonium, it is recommended to have a minimum of 6 – 8 days of retention (Economopoulou and Tsihrintzis, 2004).

Table 6.1: Temperature coefficients and rate constants (Sundaravadivel and Vigneswaran, (2001))

Pollutant	Surface flow systems		Subsurface flow systems	
	θ_{20}	k_{20}	θ_{20}	k_{20}
BOD	1.060	0.678	1.060	1.104
Nitrification	1.048	0.218	1.048	0.411
Denitrification	1.150	1.000	1.150	1.000
Pathogen removal	1.190	2.600	1.190	2.600

6.2.3 CW Wetland Type

Different CW plant species have got different root penetration depth which in turn determines the depth of the CW (Brix 1996; Brix 1997; Haule *et al.*, 2002; Brix 2003;). Also, plant roots affect the hydraulic conductivity of the plant rooted gravel. Thus, plant type must be considered while conducting the CW design.

6.3 Sizing of Constructed Wetland (FWS and SSF)

Different CW plant species have got different root penetration depth which in turn determines the depth of the CW (Brix 1996; Brix 1997; Haule *et al.*, 2002; Brix 2003). Also, plant roots affect the hydraulic conductivity of the plant rooted gravel. Thus, plant type must be considered while conducting the CW design.

$$A = \frac{Q\ (lnCo - lnCc - 0.6539)}{65\ K_T d} \tag{6.3}$$

$K_T = K_{20}\ (1.1)^{T-20}$, d = bed slope,

Or else:

$$A = \frac{Q\ (lnCo - lnCc - 0.6539)}{301\ K_T S^{\frac{1}{3}}},\ \text{S = bed slope} \tag{6.4}$$

The following equation allows the estimation of the areal requirement for SSF wetland based on BOD.

$$A_s = \frac{Q\ (lnCo - lnCc)}{K_T d\eta}, \qquad K_T = K_{20}\ (1.06)^{T-20},\ \eta = \text{bed porosity.} \tag{6.5}$$

The following assumptions are typically made for wetlands design:

- The temperature of water is approximately equal to the mean ambient temperature. This is a reasonable assumption for tropical environments (Kadlec and Knight, 1996) and the shallow depths of CW.
- The removal rates for BOD and nitrogen in FWS constructed wetland systems can be based on first-order kinetics and plug flow models proposed by the US EPA., (1988) and Reed *et al.* (1995), which have been used in the design of most constructed wetland systems in the USA and Europe (Chen *et al.*, 1999; Economopoulou and Tsihrintzis, 2003; Economopoulou and Tsihrintzis, 2004). These can be applied in tropics but with suitable modifications to account for different climatic conditions.
- The hydraulic conductivity which is the function of the media type is presented in Table 6.2

Table 6.2: Media characteristics for SSF systems (US EPA, 1998)

Media type	Max. 10% grain size, mm	Porosity, η	Hydraulic conductivity (k) m^3/m^2d	K_{20}
Medium sand	1	0.42	420	1.84
Coarse sand	2	0.39	480	1.35
Gravelly sand	8	0.35	500	0.86

6.4 Determining the Design Approach

Various sets of CW design guidelines have been developed, published and used (Cooper 1990; Vymazal *et al.*, 1998; Cooper, 1999; Brix and Arias, 2005; Brix *et al.*, 2006; Vymazal and Lenka 2008; Kadlec and Wallace 2008). Kadlec and Knight (1996) pointed to the exponential growth of new information in the field of CW and warned against the blanket use of simplistic design guidelines for all situations. The approaches currently used to design CW are not significantly different from the approaches used in conventional biological treatment systems (Sundaravadivel and Vigneswaran, 2001). CW are commonly designed as attached growth biological reactors (Vymazal *et al.*, 1998; Cooper, 1999; Kadlec and Wallace 2008). In attached growth processes, sufficient contact with biofilms on substrates like gravel, plant stems, roots, and sediment layers is important, because much of the pollutant removal is mediated by microbial activity (Vymazal *et al.*, 1998; Cooper 1999; Kadlec and Wallace 2008).To maximize pollutant removal by this process, CW design aims to optimize the theoretical hydraulic retention time (HRT), and then ensure that the actual HRT is as close as practicable to the theoretical HRT. So to sum up, the CW design approach considers HRT as a critical design parameter.

6.5 Design Procedures

Increasingly, CWs are getting global widespread recognition as effective alternatives for wastewater treatment at reduced costs if one is looking from life cycle cost analysis perspective (Vymazal *et al.*, 1998; Mbwette *et al.*, 2002; Kadlec and Wallace 2008). The process of designing and predicting the performance of CW is improving rapidly, as more experience is gained with the operation of these systems (Kadlec and Wallace 2008; Vymazal and Lenka 2008). Designing CW entails the following key steps:

- Sizing for a particular wastewater flow rate, pollutant loading, and desired removal of a given pollutant;
- Inlet and outlet structures for water level control, recycling, flow splitting and distribution;
- Flow path configuration for cells in parallel and/or series;
- Depth variation within and between cells for habitat diversity (when required), better flow distribution, and pollutant removal;
- Planting details, including species selection, planting density, range of species; and
- An operation and maintenance plan.

6.6 Design Approaches for Sizing of Constructed Wetland.

Broadly, there are three main design approaches for sizing the CW, *i.e.*, The UK model for the Design of constructed wetlands, the first-order plug-flow Biokinetic Model and the Population Equivalent (PE) model. A brief description of these models is explained below:

6.6.1 The UK Model for the Design of Constructed Wetlands

The simplest model for the treatment of domestic wastewater is adopted in the UK, where the treatment wetlands are mostly designed as subsurface flow systems (Sundaravadivel and Vigneswaran, 2001). For horizontal flow systems, the surface area A_h is calculated using equation (6.6) (Brix *et al.*, 1998):

$$A_h = \frac{Q_d(\ln Co - \ln Ce)}{k_{BOD}} \tag{6.6}$$

where;

Q_d = average daily flow rate of wastewater, $m^3.day^{-1}$

C_o = average BOD of the influent, mg. L^{-1}

C_e= average design BOD of the effluent, mg. L^{-1}

k_{BOD} = reaction rate constant, $m.day^{-1}$

The rate constant kBOD has been measured as 0.06 for systems used for secondary treatment of wastewater, and 0.31 for tertiary treatment.

For secondary treatment of sewage, assuming 250 Lpcd (litres per capita per day) and BOD in the range of 150 to 300 mg. L^{-1}, the area is calculated as about 2.5 to 5.0 m^2 per person. For tertiary treatment, the area requirement is computed to be arrived as 0.5 to 1 m^2 per person. For systems treating combined sewer overflow is considered as equivalent to tertiary treatment.

This model for sizing the CW is only limited to BOD removal. It is assumed that BOD is a critical removal parameter in the sense that its removal implies that all other parameters will also be removed from wastewater.

6.6.2 The First-Order Plug-Flow Biokinetic Model

Organic degradation (BOD, COD and TOC), nitrification, adsorption, and disinfection (pathogen removal) in biologically driven processes generally follow first-order kinetics (Metcalf and Eddy., 1991). Accordingly, the performance of attached-growth biological reactors is described as a first-order kinetic reactions model assuming that plug-flow and steady state conditions prevail in the reactor. First-order reactions are said to occur when the rate of reaction is directly proportional to the first power of the concentration of the reactants (in case of treatment systems, the pollutants). Thus, pollutant removal in treatment wetland can be expressed as in Equation (6.7) to (6.13)

$$\frac{C_e}{C_o} = e^{-k_T t} \qquad (6.7)$$

where;

Co = average influent BOD concentration, mg.L^{-1}

Ce = average design effluent BOD concentration, mg.L^{-1}

k_T = temperature dependent first-order reaction rate constant, day^{-1}

t = hydraulic retention time, day.

Hydraulic retention time ***t*** is expressed as:

$$t = \frac{LWD\eta}{Q} \qquad (6.8)$$

where;

L = length of wetland, meter

W = width of the wetland, meter

D = depth of water column, meter

η = porosity of the substrate medium (percentage expressed as fraction)

Q = average flow rate, m^3.day^{-1}

Substituting the value expression for '***t***', the following expression is obtained.

Rearranging the terms to obtain the area (m^2) of subsurface flow wetland required.

$$\left(\ln C_e - \ln C_O\right) = -k_T \frac{LWD\eta}{Q} \qquad (6.9)$$

The value of the rate constant k_T is estimated using the following equation.

$$A_s = LW = \frac{Q\left(\ln C_o - \ln C_e\right)}{k_T D\eta} \qquad (6.10)$$

$$k_T = k_{20}\ \Theta_{20}^{(T-20)} \qquad (6.11)$$

Where θ_{20} is the temperature coefficient for rate constant. The values of θ_{20} and k_{20} depend on the type of pollutants encountered in surface and subsurface flow systems. Values for common pollutants are presented in Table 6.3.

Table 6.3: Temperature coefficients and rate constants (Source: Adapted from Reed et al., 1995

	Surface flow systems		Subsurface flow systems	
	θ_{20}	k_{20}	θ_{20}	k_{20}
BOD	1.060	0.678	1.060	1.104
Nitrification	1.048	0.2187	1.048	0.411
Denitrification	1.150	1.000	1.150	1.000
Pathogen removal	1.190	2.600	1.190	2.600

Assuming that laminar flow prevails, and that Darcy's law applies, the flow rate in a constructed wetland can be determined as:

$$Q = A_c k_s S \tag{6.12}$$

where:-

Ac = cross-sectional area of flow, m^2

ks = hydraulic conductivity of the substrate medium, m.day^{-1}

S = hydraulic gradient (dimensionless).

In turn, the width of the wetland is then determined as:

$$W = \frac{A_c}{D} = \frac{Q}{k_s SD} \tag{6.13}$$

Once the width is determined, the length of the constructed wetland can be obtained from the surface of the wetland obtained from equation 6.10

6.6.3 Sizing Based on Specific Area Requirement per Population Equivalent (PE)

The specific area requirement per PE holds true where there is uniformity in the specific wastewater quantity and quality. In general, the rules of thumb suggested by several authors can be served as a safe bed (depending on the climatic conditions) (UN-HABITAT, 2008). However, the investment costs tend to be higher due to the conservative aspects of this approach (UN-HABITAT, 2008). Specific area requirements for HF and VF constructed wetlands have been calculated for various specific wastewater discharges for certain population (UN-HABITAT, 2008). Conservatively, the BOD contribution has been taken as 40g BOD/pe.d, 30% BOD load is reduced in the primary treatment and the effluent concentration of BOD is taken as 30 mg/L (UN-HABITAT, 2008). The K_{BOD} for HF and VF wetlands are taken as 0.15 and 0.20 respectively (UN-HABITAT, 2008). A specific area requirement of 1 m^2/pe required for HF constructed wetlands whereas the specific area of 0.8 – 1.5 m^2/pe for the VF wetland.

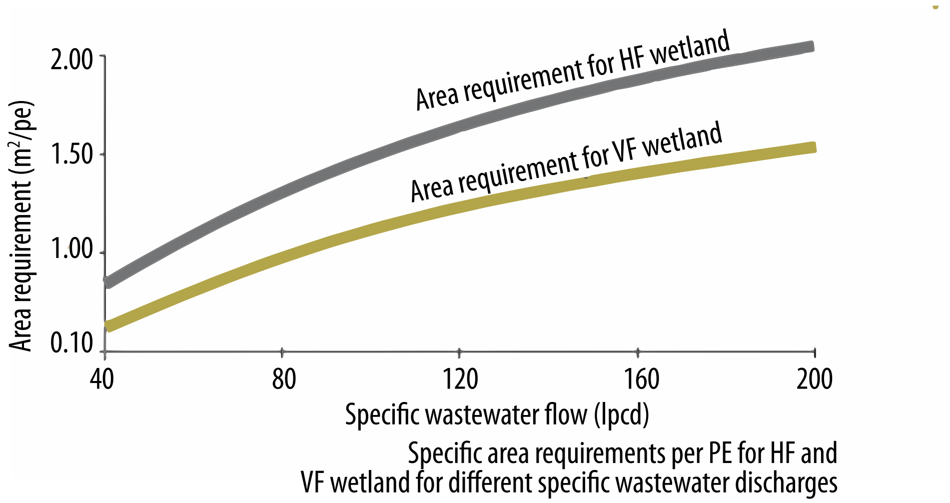


Figure 6.2: Specific area requirement per PE for HF and VF wetland for different specific wastewater discharges (UN-HABITAT, 2008)

Taking into considerations the cases in Nepal, it is to be noted that the specific area requirement presented in the graph is less than the specific area requirement given in various literatures because the K_{BOD} used in the literatures are lower and the specific wastewater discharges are high.

Based on the kinetic and hydraulic model outlined in the previous section, the currently summarized and recommended CW design procedure is.

- Determine wastewater characteristics and quantity. Determination of wastewater characteristics will entail laboratory analysis of selected wastewater parameters including BOD, Nitrogen, Phosphorus, Total Suspended solid, and temperature. The wastewater quantity to be estimated using the 80% rule, which means, 80% of water consumed turns into wastewater.
- Selection of plant species and determination of bed depth. Several authors suggest that bed depth must be used in calculating surface area requirement for both the surface flow and subsurface flow wetland (Cooper 1990; Cooper, 1999; Vymazal *et al.*, 1998; Brix and Arias, 2005; Brix *et al.*, 2006; Vymazal and Lenka 2008; Kadlec and Wallace, 2008). However, in the case of SF wetlands this means the depth of the water column. SSF wetlands are to be designed and operated in such a way that water level lies below the top surface of the bed. However, often it is experienced that surface flow occurs in SSF systems after a few months of operation. In all the SSF systems with BOD loading rate higher than 0.2 kg.m^{-2}.day^{-1} in UK and USA, surface flow was reported (Crites, 1994). For this reason, it is suggested that for the design,

the depth of the total water column both in and above the substrate (instead of only the depth of bed), is to be considered for the term 'D' in the model. That is, D = Db + Df, where Db is the depth of substrate media and Df is the depth of surface flow.

- Selection of the bed slope and defining hydraulic gradient will be the next step. A review by Conely *et al.*, (1991) indicates that slope varied from 0 to 10%, with most designs occurring within the 0 to 3% range. Only a minimum slope to pass the required flow rate is recommended, and in any case, it should not exceed 1% (Cooper, 1990).
- Selection of substrate media, in the case of subsurface flow wetlands, and defining hydraulic conductivity (ks) and porosity η.
- Determination of surface sectional area of flow (As) using the equation 6.10.
- Determination of bed width (W) and bed length (L) using the recommended L/W ratio
- Check for both hydraulic and organic loading rates.

6.7 Design of Inlet Structure, Feeding Arrangements, and Outlet Structures

6.7.1 Inlet Structures

Inlet structures play an important role in the constructed treatment wetlands by aiding the effectiveness and ensuring an even flow distribution across the full width of wetland cells. Somehow, the proper design of the inlet structure helps to avoid hydraulic short circuiting. A number of different inlet designs have been used (Sundaravadivel and Vigneswaran, 2001) (Figure 6.3).

Inlet and outlet structure for surface flow system is typically simple. Subsurface flow systems rely more on inlet and outlet structures for uniform flow distribution, particularly if the L/W ratio is smaller. Inlet and outlet structures help to maintain the subsurface flow mode of CW.

Inlets above the bed allow adjustment of flow distribution and maintenance, preclude clogging and back-pressure problems, and aerate the wastewater.

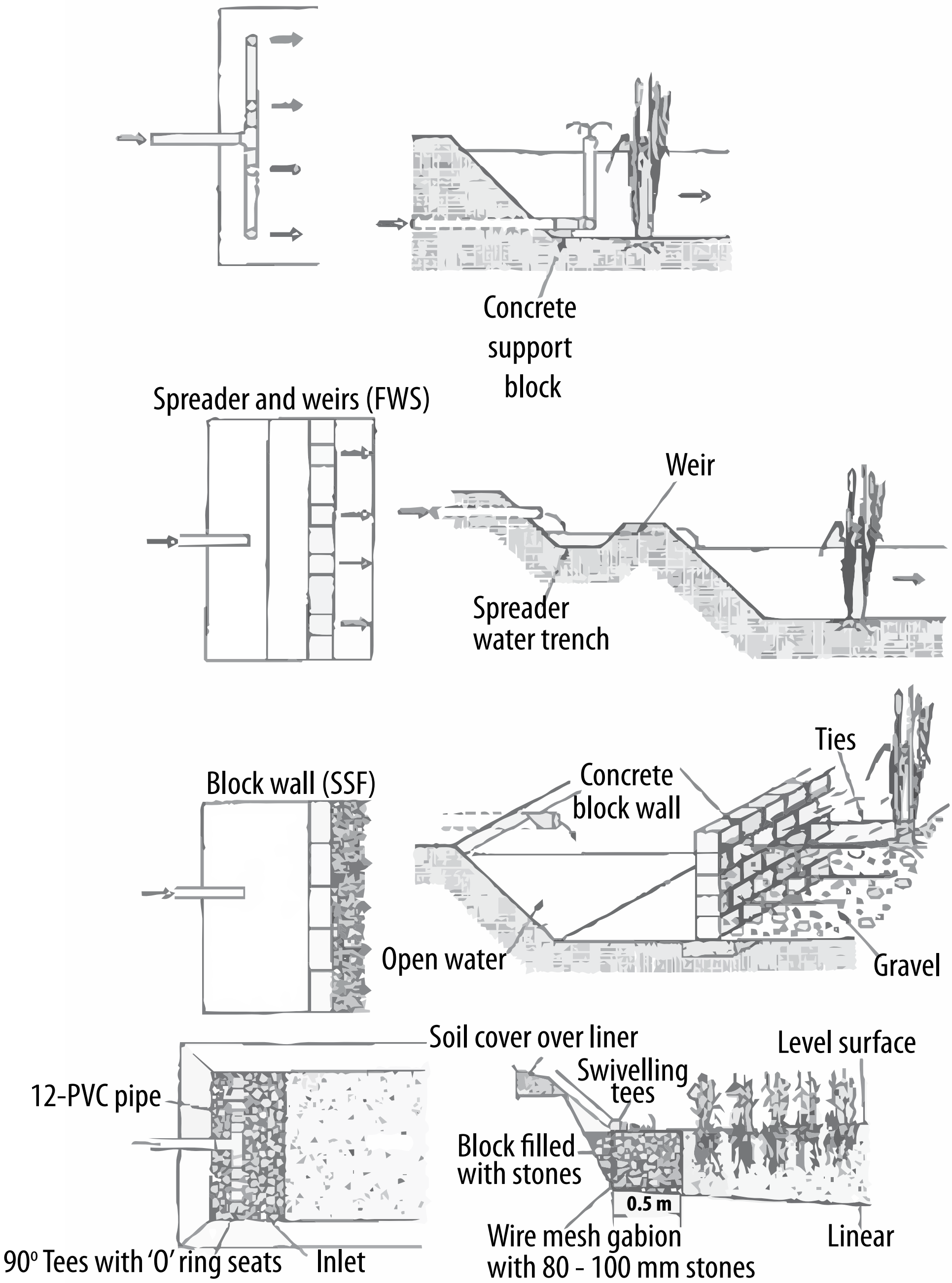


Figure 6.3: Inlet designs (Sundaravadivel and Vigneswaran, 2001)

The simplest methods for distribution of flow into the wetland include sawtooth weirs (Figure 6.4).

However, the weir system is often not recommended for flow distribution since they are expensive to construct, and the maldistribution of flow is often caused by screenable material collected on the edges (Cooper, 1993). Also, the channel tends to act as a sedimentation tank and collects sludge and grit. Some of the recommended feed arrangements to effectively utilize the wetland area in serpentine systems and those with large L/W ratio are presented in Figure 6.5.

The minimum recommended interval between two feed streams along the width is 3 to 5 m (Sundaravadivel and Vigneswaran, 2001). Smaller intervals are better for flow distribution. With large L/W ratio, piping is less, and inlet construction is simplified. However, to distribute solids in the influent across a greater portion of the wetland, the influent may need to be fed at different lengths of the cell or the effluent may be recirculated to dilute the influent pollutant solids concentration (Sundaravadivel and Vigneswaran, 2001).

Figure 6.4: Image of sawtooth weir (Credit: Getty Images)

6.7.2 Outlet Structures

In general, outlet collectors are similar in construction to the inlet structures (Sundara-vadivel and Vigneswaran, 2001). The functions of outlet structures are to (Kadlec and Wallace, 1996; Vymazal *et al*., 1998):

- Collect the effluent water without creating new dead zones in the wetland.
- Control the depth of water in the wetland.
- Assist in theprevention of clogging; and
- Provide access for sampling and flow monitoring.

Constructed wetlands using soil as substrate will require a stone collector with an open-jointed pipe running across the width of the cell at the base (Figure 6.6).

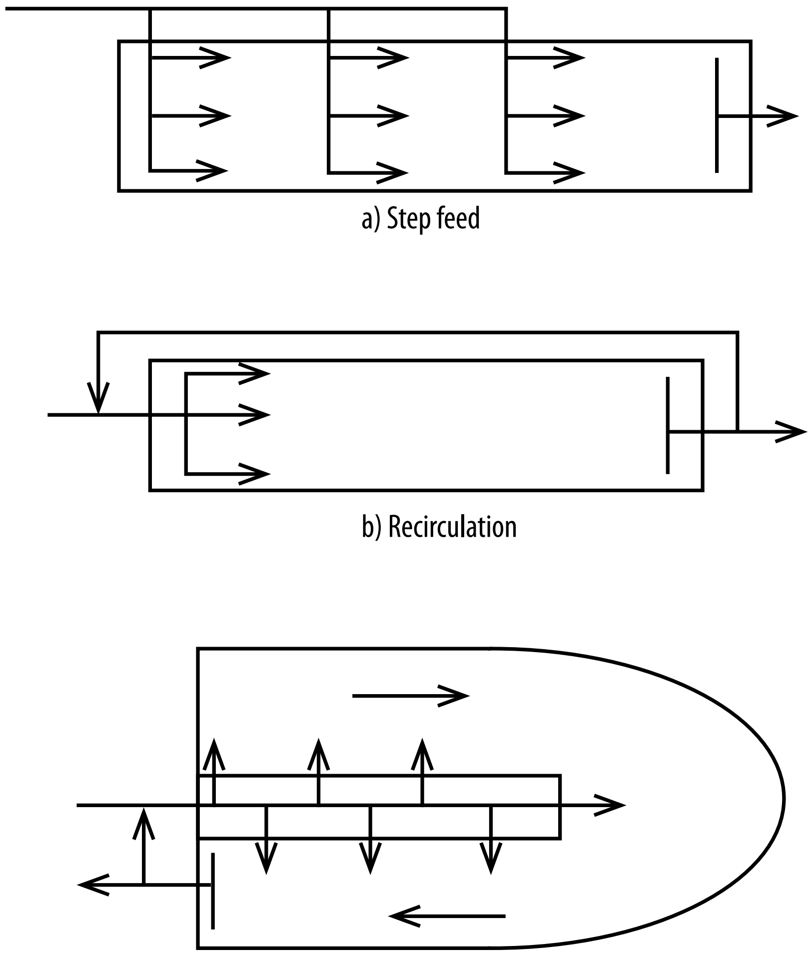


Figure 6.5: Feeding arrangements for CTWs (Adapted from Steiner and Freeman Jr, 1990)

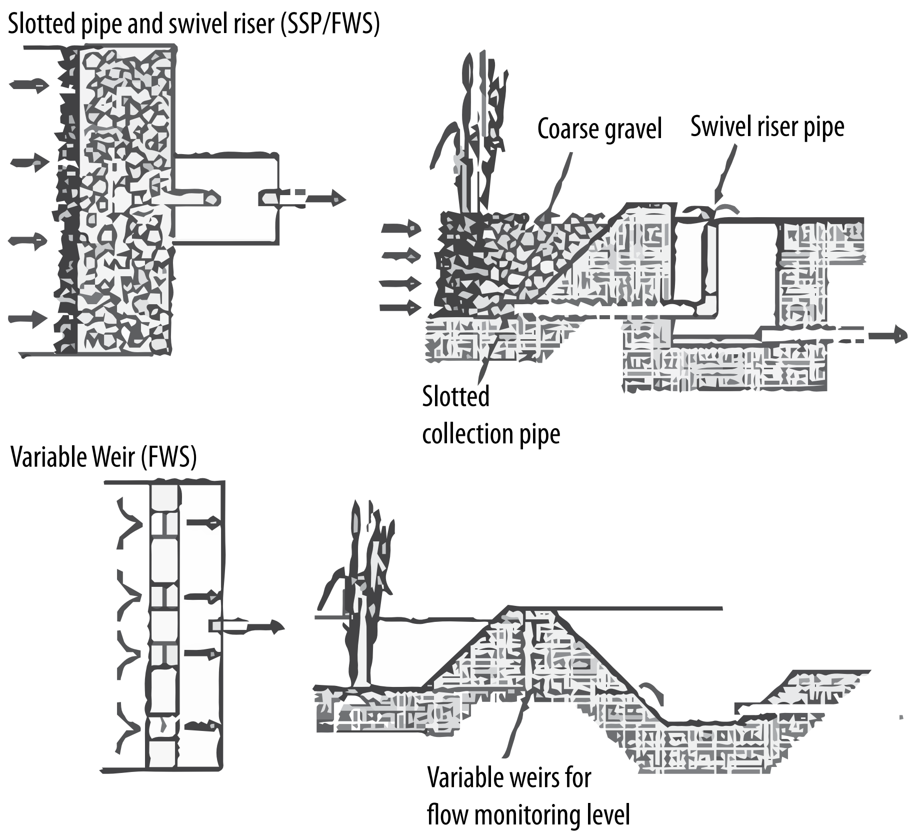


Figure 6.6: Outlet structures (Source: Adapted from DLWC, 1998)

It is essential to provide outlet structures in such a way as to adjust the depth of the water column in the bed (Vymazal *et al.*, 1998). The water level control helps to maximize the flow path of wastewater through the reed bed. A broad range of outlet structures are available to achieve this requirement:

- The simplest and the cheapest method is to use a 90°elbow with O-ring seals which allow the end of the pipe to be raised or lowered by twisting the elbow (DLWC, 1998).
- The vertical outlet pipe can comprise a series of socket sections or telescopic sections which can be adjusted to increase or drop the water level (DLWC, 1998).
- Drop board structure (Figure 6.7) that consists of several boards, usually100 mm in height, can be set into the embankment. By adding or removing the drop boards, the water level can be varied. Although constructed on-site, it can also be pre-cast and fixed at the site. Wooden drop boards are prone to shrinking and swelling due to soaking and drying, hence may pose difficulties while removing or replacing (DLWC, 1998).

Boards made of HDPE may help to overcome such problems. Boards need to be stored safely when removed (The drop board structure is expensive compared to other arrangements (DLWC, 1998). Nutrient-rich algal growth can develop in open water areas of the CW and can be expected to flush during high flow conditions A final filtering using fine screens to remove such biomass is desirable (DLWC, 1998). It is an important requirement for systems designed for phosphorus removal to reduce the export of phosphorus through biomass (White *et al.*, 1996). Two types of outlet screens can be considered. The first is a mesh-type screen on an orifice water level control structure to reduce the incidence of blockage by plants, debris, or other materials (The screen may house the entire outlet structure. The second type is a solid screen for weir-type outlet structures. This type can prevent floatable matters such as algae (DLWC, 1998).

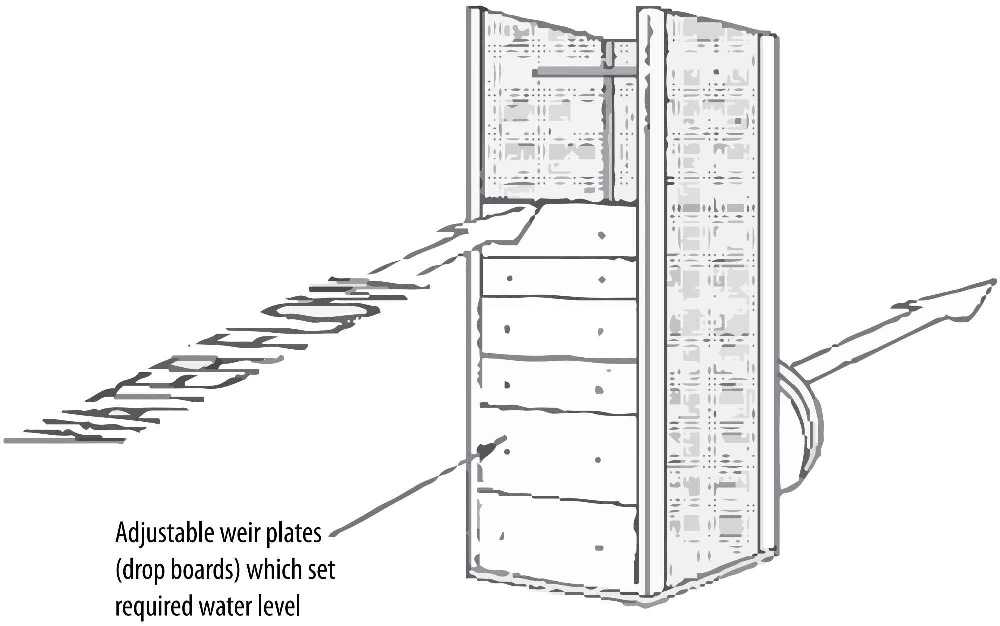


Figure 6.7: Outlet Screens (Drop board for water level control) (Source: Adapted from DLWC, 1998))

The proper function mode of CW solely depends on the outlet structure particularly for the sub-surface CW. As such the wastewater level is maintained by the outlet structures (Kadlec and Wallace, 1996; Vymazal *et al.*, 1998). A similar scenario has been adapted to maintain the sub-surface flow CW in the WIO region especially the Tanzanian experience. Figure 6.8 below demonstrate the wastewater level maintenance using the outlet structure.

Figure 6.8: Wastewater level maintenance. Left: Outflow pipes hanging on a chain at CW Waikeria, New Zealand. Right: Swiveling elbow at CW Bouvron, France (Photo: Jan Vymazal).

6.8 Worked Examples

Design Example **1: Determining Dimensions of the CW**

A CW is to be designed to treat domestic wastewater from a small town of 6000 population. Wastewater generation is estimated at 160 L per capita per day. The initial BOD of the primary treated wastewater is 180 mg/L and the treated wastewater needs to conform to a BOD standard of 30 mg/L. Fine and medium-sized gravel are as substrate material for wetland beds of depth 0.6 m. Further assumptions are porosity of 40% and hydraulic conductivity of 10.2 $\times 10^{-2}$ m/sec. The annual average temperature of the water is 27^{o}C. Determine the dimensions of the constructed wetland.

6.9 Solution

Average wastewater flow rate = 6,000 x160 = 960,000 L = 960 m^3/day

Influent BOD concentration Co = 180 mg/L

Design effluent BOD concentration Ce = 30 mg/L

Depth of bed (Db) is given (0.6 m), which is the average depth of rizhosphere (root zone) for common reed (Phragmites australis) and most other commonly used aquatic macrophytes. Assume the depth of surface flow (Df) as not more than 0.15 m, when the system is under stabilized operational conditions. Hence, the total depth of the water column (D) will be 0.6 + 0.15 = 0.75 m. Let the slope of the bed be 0.5%, Porosity (Hydraulic conductivity (ks) = 10.2×10^{-2} m.sec−1 = 8812.8 $m.day^{-1}$

Cross-sectional area of flow (using Equation 6.12)

$$A_c = \frac{Q}{k_s S} = \frac{960}{8812.8 \ * 0.005} = 21.8 \ m^2$$

where;

Q = average wastewater flow rate (m3/day)

ks = hydraulic conductivity (m/day)

S = slope.

Width of wetland bed (W) = Ac / D = 21.8 / 0.75 = 29 m, say 30 m. The reaction rate constant k27 can be calculated using values given in Table 4 for subsurface flow wetlands and Equation 6.11. Then, the area requirement for the SSF wetland is estimated.

$$K_{27} = 1.104 * (1.06)^{27-20} = 1.66 \ day^{-1}$$

$$A_s = \frac{960 \ [\ln(180) - \ln(30)]}{1.66 * 0.75 * 0.4} = 3454 \ m^2$$

Therefore, the length of the bed = 3454/30 = 115 m

Design Example 2: FWS System

Design an FWS wetland to produce secondary treated effluent quality in a warm climate with a mean annual temperature of 25°C. The design flow is 800 m^3 d^{-1}, influent wastewater is from a facultative lagoon with a BOD_5 concentration of 150 mg L^{-1}, and the treated effluent BOD_5 required is 15 mg L^{-1}. Assume the slope of the wetland will be 1% to allow drainage by gravity. Estimate required detention time at 25°C:

Solution:

$$K_T = K_{20}\ (1.1)^{T-20} = 0.0057\ (1.1)^{(25-20)} = 0.0092\, d^{-1}$$

$$t = \frac{(lnCo - lnCc) - 0.6539}{65\ K_T}$$

$$t = \frac{(\ln 150 - \ln 15) - 0.6539}{(65)\ (0.0092)} = 2.75\ \ d$$

For a warm climate site, use a 10 cm water depth on a year-round basis. If cattail plants are to be grown, the bed depth should be30 cm, the total bed depth, or ***d*** is 40 cm. Use the following equation to find the surface area required.

Use an aspect ratio (***L***/***W***) of 10:1 and determine dimensions for the wetland channels, assuming a square plot is available.

A = L/W =(10 W)W =550 m^2.

$$A = \frac{Q\ (lnCo - lnCc - 0.6539)}{65\ K_T d}$$

$$A = \frac{(800\, m^3)\ (\ln 150 - \ln 15 - 0.6539)}{(65)\ (0.0092)(0.4\ \ m)}$$

Thus, W = 23.48 m, L =234.8 m.

Design Example 3: SSF System

Calculate the required area and bed depth for an SSF system where influent wastewater is from a facultative lagoon. Assumed influent BOD_5 to the wetlands will be 150 mg L^{-1}. The desired effluent BOD_5 is 15 mg L^{-1}. The predominant wetland plant type in surrounding marshes is cattail. The water temperature is 25°C.

Solution:

Choose cattail for this SSF since it is successfully growing in the locality. The cattails penetrate approximately 0.3 m into the medium. The bed media depth (***d***) should, therefore, be 0.3 m. The bed slope is based on the site topography. Most systems will be designed with a slope of 1% or slightly higher. For this design, choose a slope of 1% for the ease of construction (s = 0.01). Reed *et al.* (1995) have indicated the need to check the value ***Ks S*** =8.60. Choose a media of coarse sand and from Table 6.2,

0.39, K_s=480 and K_{20}=1.35. $K_s S=(480)(0.01)=4.8$

$K_T = K_{20}(1.1)\ T^{T-20} = 1.35(1.1)^{25-20} = 2.17\ d^{-1}$.

Determine the cross-sectional area by using the following equation:

$$Ac = Q/(KsS) = 800/\ (480)(0.01) = 167\ m^2.$$

Determine the bed width:

$$W = Ac/d = 167/0.3 = 557\ m.$$

Determine the surface area required:

$$A_s = \frac{Q\ (lnCo - lnCc)}{K_T d\eta} = \ A_s = \frac{800(\ln 150 - \ln 15)}{(2.17)(0.3)(0.39)} = 7255\ m^2$$

Determine the bed length (L) and detention time (t):

$$L = A_s\ /\ W = 7255/557 = 13\ \text{m}$$

$$T = \frac{V_V}{Q} = \frac{LWD\eta}{Q} = \frac{(13)(557)(0.3)(0.39)}{800} = 1.06\ d$$

The example presented here is a general case. The local circumstances and standards should be considered by the designer. Let us calculate the sizing of a constructed wetland for a population of 400 with a specific wastewater flow of 80 litres per person per day.

- Average volume of wastewater (Q) = 400 x 80/1000 = 32 m^3/d
- To determine the influent BOD5 concentration, the wastewater sample should be analysed in an accredited laboratory. In the absence of a laboratory, the concentration can be calculated as below:
- BOD_5 contribution = 40 g BOD_5/pe.d
- BOD_5 concentration = 40 x 1000/80 = 500 mg/L
- Let us assume that 30% BOD_5 is removed by the primary treatment unit, then the influent BOD_5 concentration to the wetland (Ci) = 350 mg/L
- Effluent BOD_5 concentration (Ce) = 30 mg/Ll
- KBOD = 0.15 m/d for HF wetland and 0.2 m/d for VF wetland Substituting the values in the equation below.

6.10 References

Brix, H., (1996). Role of macrophytes in constructed treatments wetlands, in: Proc. 5th Internat.

Brix, H., (1997). Do macrophytes play a role in constructed treatment wetlands? Wat. Sci. Tech. 35(5): 11-17.

Brix, H., (2003). Plants used in constructed wetlands and their functions, in: Proc. Conf. The Use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands, V. Dias and J. Vymazal, eds., ICN and INAG, Lisbon, Portugal, pp. 81-109

Brix, H., and Arias, C.A., (2005). Danish guidelines for small-scale constructed wetland systems for onsite treatment of domestic sewage, Wat. Sci. Tech. 51(9): 1-9.

Brix, H., Cooper, P. F., Green, M. B., and Haberl, R. (1998). Constructed wetlands for wastewater treatment in Europe.

Brix, H., Schierup, H.-H., and Arias, C.A., (2006). Twenty years experience with constructed wetland systems in Denmark – what did we learn? in: Proc. 10th Internat. Conf. Wetland Systems for Water Pollution Control, MAOTDR 2006, Lisbon, Portugal, pp. 1633-1641

Conely L M, Dick R I, and Lion L W. (1991). An assessment of the root zone method of wastewater treatment Research Journal WPCF 63(6):239–247.

Cooper P. F. (1990) European design and operations guidelines for reed bed treatment systems, Paper presented in the conference on Use of constructed wetlands in water pollution control, 28

Cooper P.F., Job G.D., Green B., and Shutes R.B.E. (1996). Reed beds and constructed wetlands for wastewater treatment. WRc Publications. 184 pp. plus data diskette: Swindon, United Kingdom

Cooper, P. (1999). A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. Water Science and Technology, 40(3), 1-9.

Cooper, P., Griffin, P., Humphries, S., Pound, A., (1999). Design of a hybrid reed bed system to achieve complete nitrification and denitrification of domestic sewage. Water Sci. Technol. 40 (3), 283–289.

Crites, R. W. (1994). Design criteria and practice for constructed wetlands. Water Science and Technology, 29(4), 1-6.

DLWC (Department of Land and Water Conservation) (1998). The constructed wetland manualvol.1 DLWC, New South Wales Earth 27: 773-781.

Economopoulou, M. A., and Tsihrintzis, V. A. (2003). Design methodology and area sensitivity analysis of horizontal subsurface flow constructed wetlands. Water resources management, 17, 147-174.

Economopoulou, M. A., and Tsihrintzis, V. A. (2004). Design methodology of free water surface constructed wetlands. Water resources management, 18, 541-565.

Haule, K. S., Johnsen, F. H., and Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. Journal of environmental management, 66(1), 31-42.

Kadlec, R. H., and Wallace, S. (2008). Treatment wetlands. CRC press.

Kadlec, R.H., and Knight, R.L. (1996). Treatment Wetlands, CRC Press, Boca Raton, Florida

Kaseva, M.E., Mbwette, T.S., Katima, J.H., and Mashauri, D.A. (2000). Performance of a subsurface horizontal flow constructed wetland in polishing upward flow anaerobic sludge blanket pre-treated domestic wastewater under tropical conditions- a case study in Dar es Salaam, Tamzania, in: Proc. 7th Internat. Conf. on Wetland Systems for Water Pollution Control, Lake Buena Vista, Florida. University of Florida, Gainesville and Int. Water Association., pp. 1051-1059.

Kaseva, M.E., Mbwette, T.S.A., and Katima, J.H.Y. (2002). Domestic sewage treatment in a pilot plant composed of septic tank and a constructed wetland system – a case study in Dar es Salaam, Tanzania, in: Proc. 8th Internat. Conf. on Wetland Systems for Water Pollution Control, Arusha, Tanzania, University of Dar es Salaam and IWA, pp. 367-379.

Kimwaga, R.J., Mashauri, D.A., Mbwette, T.S.A., Katima, J.H.Y., and Jørgensen, S.E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilization ponds effluents in Tanzania, Physics and Chemistry of the Earth 29: 1243-1251.

Mbwette, T. S. A., Katima, J. H. Y., Pratap, H. B., and Kayombo, S. (2002, September). Wetland systems for water pollution control. In Proc. 8th Int. Conf. on Wetland Systems for Water Pollution Control (pp. 16-19).

Metcalf and Eddy Inc. (1991) Wastewater engineering: collection, treatment, and disposal, 3rdedition, McGraw, New York.

Molle P., Liénard A., Boutin C., Merlin G., Iwema A. (2004) How to treat raw sewage with constructed wetlands: an overview of the French systems. Liénard A., Burnett H. (eds.) Proceedings of the 9th International Conference on Wetland Systems for Water Pollution Control, 26–30 September 2004; Association Scientifique et Technique pour l'Eau et l'Environnement (ASTEE), Cemagref, and IWA: Avignon, France, pp. 11–18.

Reed, S.C., Middlebrooks, E.J., and Crites, R.W. (1995). Natural Systems for Waste Management and Treatment, 2nd ed., McGraw-Hill Book Company, New York

Senzia, A.M., Mashauri, D.A., and Mayo, A.W. (2003). Suitability of constructed wetlands and waste stabilisation ponds in wastewater treatment: nitrogen transformation and removal, Phys. Chem. Earth 28: 1117-1124

Senzia, M. A., Mashauri, D. A., Mayo, A. W., Mbwette, T. S., Katima, J. H., Pratap, H. B., and Nielsen, S. N. (2002, September). Performance of horizontal subsurface flow constructed wetlands located downstream of primary facultative and maturation ponds in Tanzania. In Int. Conf. on Wetlands Systems for water Pollution Control, Arusha, Tanzania.

Steiner G R and Freeman R J, Jr. (1990) Configuration and substrate design considerations for constructed wetlands wastewater treatment, in Constructed wetlands for wastewater treat- ment, 2nd ed. D A Hammer, Lewis Publishers, Chelsea, Michigan, pp. 363–377.

Sundaravadivel, M., and Vigneswaran, S. (2001). Constructed wetlands for wastewater treatment. Critical reviews in environmental science and technology, 31(4), 351-409.

U.S. EPA (1988) Design manual: Constructed wetlands and aquatic plant systems for municipal wastewater treatment, EPA 625/1-88/022, U.S. EPA Office of Water: Cincinnati, Ohio.

UN-HABITAT, (2008). Constructed Wetlands Manual. UN-HABITAT Water for Asian Cities Programme Nepal, Kathmandu

Vymazal J., Brix H., Cooper P.F., Green M.B., and Haberl R. (1998) Constructed Wetlands for Wastewater Treatment in Europe. Backhuys Publishers: Leiden, The Netherlands.

Vymazal, J. (2001). Types of constructed wetlands for wastewater treatment: their potential for nutrient removal, in: Transformations of Nutrients in Natural and Constructed Wetlands, J. Vymazal, ed., Backhuys Publishers, Leiden, The Netherlands, pp. 1-93.

Vymazal, J., and Kröpfelová, L. (2008). Wastewater treatment in constructed wetlands with horizontal sub-surface flow (Vol. 14). Springer science & business media.

White G, Kuginis L, Beharrel M and Young C. (1996).Urban stormwater management Journal Water July/August, pp. 48–52.

Chapter 7: Construction of Constructed Wetlands

By Leah Marwa and Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

In the WIO region, implementation experience has shown that the construction of CWs plays a critical and significant role in the successful treatment performance of this nature-based solution. No matter how good the design could be, if the CW is poorly constructed, it will not achieve the desired results. The construction of CWs is undertaken like any other civil engineering project and this necessitates that we present the knowledge and skills from our long-term experience with the construction of CWs. This chapter discusses the construction techniques and methods of CWs. It was thought necessary to make a clear distinction between CW design as one thing and its construction as completely different thing altogether that needs careful and thorough understanding.

7.1 Mobilization and Safety Precautions

Like any civil engineering project, the CW project should begin with resources mobilization and take the necessary precautionary tale.

7.1.1 Mobilization

Mobilization commences immediately after contract signing, and includes ***inter alia*** (Njau *et al.*, 2010):

- Preparing general arrangement and construction for necessary temporary works.
- Securing site storage for equipment, plants, and other project materials at a strategic location to facilitate easy deployment to various locations when needed.
- Acquiring plants and equipment necessary for transportation to the site and execution of works
- Finding accommodation for the site workers, both skilled and unskilled.
- Acquiring all necessary construction materials (according to the specifications given by the consultant) and ensuring their timely delivery.

7.1.2 Safety Precautions

Safety precautions and controls must be ensured for work persons, the public and properties. Key safety measures required include (Njau *et al.*, 2010):

- Appropriate, adequate, and easily accessible first aid kits are available at the work site.
- Training about safety controls and measures must be undertaken prior to commencement of work.
- Necessary safety gears such as helmets, gloves, dust masks, ear plugs/defenders etc., are provided and effectively used by all workers.
- Care should be taken when working with machinery in the vicinity of underground cables or piping systems.
- Dust control measures must be taken while undertaking clearance works and all other activities.

7.2 Site Preparation

During the construction of CWs, due considerations should be given to adequate and careful site preparation. All the implemented CWs generally investigated the importance of site preparation (Senzia, *et al.*, 2002; Kimwaga *et al.*, 2003; Njau *et al.*, 2010). The step that ought to be followed for the CW construction site preparation includes.

- Establish site boundaries and identify areas to be protected.
- Peg out the excavation area.
- Manually or mechanically excavate the site. In the process care should be observed not to disturb the stability of surrounding areas. In case of mechanical excavation, choose a machine that has a long reach, essentially able to cover your liner in soil without driving on it. Hire your machine from a contractor with an operator experienced in building wetlands.
- Ensure that the excavated basin is levelled (flat). This should be done by using a level instrument.

Figure 7.1 shows good and bad practices for leveling, guiding guidance on how it should be done.

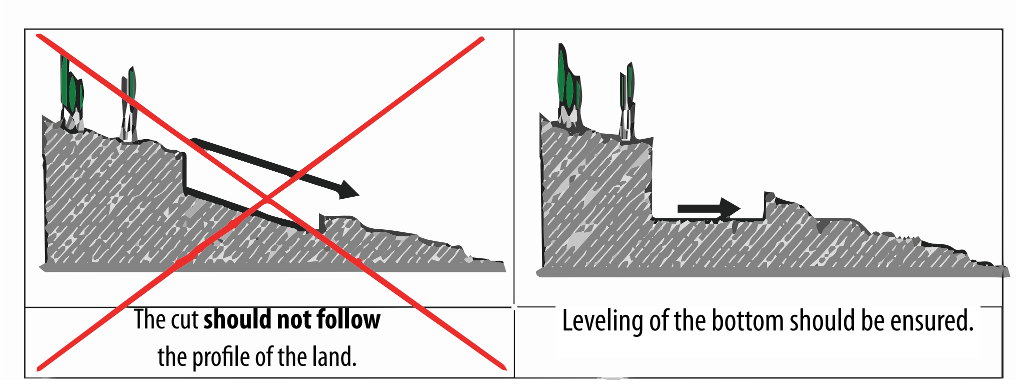


Figure 7.1: Site preparation of CW on sloped terrain (Njau et al., 2010)

7.3 Excavation works

Equally important is the methods for exaction for CW. A contractor or an individual undertaking the CW construction should be mindful of understanding the site from the onset that a CW is a shallow pond (about 1 meter in depth) (Senzia *et al*., 2002, Kimwaga *et al*., 2003; Njau *et al*., 2010). When deciding the excavation methods, especially if the CW is to be connected to other systems, the contractor must be aware that over-excavation elevates costs associated with resource use and backfilling requirements (Njau *et al*., 2020). Backfilling of some areas may also result in unstable soils. Do not disturb the soil unnecessarily since it may eventually lead into the loose soil requiring further stabilization and hence raising the construction costs (Njau *et al*., 2010). Figure 7.2 below provides some of the excavation methods which have been employed in Tanzania.

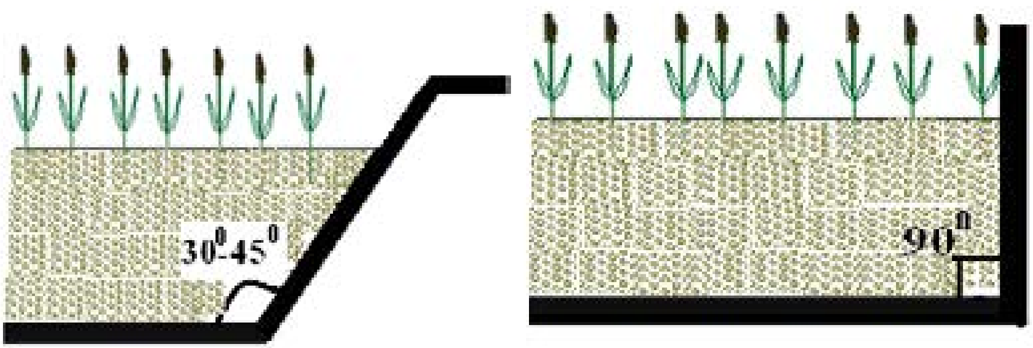
Manual excavation *Mechanical excavation*

Figure 7.2: Excavation of constructed wetlands (Credit: Njau et al., 2010)

NOTE. The depth of the CW at the lowest end after excavation and compaction of the bottom should not exceed 1.0 meter (Njau *et al*., 2010).

7.4 Construction of CW Walls

The next construction step is putting up the CW walls and beds. CW walls and beds have an important role to play in providing in a sealing and containing features such that the wastewater or faecal sludge won't find their way into the environment (Copper *et al*.,1996; Vymazal *et al*., 1998). As such walls must be built considering the stability of the surrounding ground. The wall should be preferably inclined at an angle between 30°C to 45°C from the bottom of the wetland (Figure 7.3) (Njau *et al*., 2010). If a vertical wall is chosen it must be structurally stable to retain the surrounding soil in order to eliminate the risk of collapsing due to soil movement (Figure 7.4).



(a)Recommended angle (b)Ensure structural stability

Figure 7.3: Recommended angle for CWs walls (Njau et al., 2010).

Figure 7.4: Collapsed embankment due to structural instability (Credit: Njau et al., 2010)

7.5 Lining of CW Bottom and Embankments

The bottom of the CW must be lined to prevent seepage of wastewater into the ground water (Mashauri *et al.*, 2000; Kimwaga *et al.*, 2002; Senzia *et al.*, 2002; Njau *et al.*, 2010). Clay soil or synthetic liners may be used for this purpose (Njau *et al.*, 2010). Engineering drawings must specify the type of lining materials to be used. If lining the bottom of the wetland with clay, there is a need to import a considerable amount of it to hold water and not break-up over time. This means that unless there is a source of a substantial amount of clay nearby, it can become costly. To prevent breakup, the clay must be applied in 15-centimeter layers and compacted after each layer is applied.

Embankments should be made of clay soil to prevent surface run-off and loose soil from gaining access to the CW cell; otherwise, the embankment should be compacted at 95% of the soil's maximum density (Njau *et al.*, 2010).

- Compact the bottom to get an even level (Figure 7.5).
- Compact (or fill) material with proper equipment.

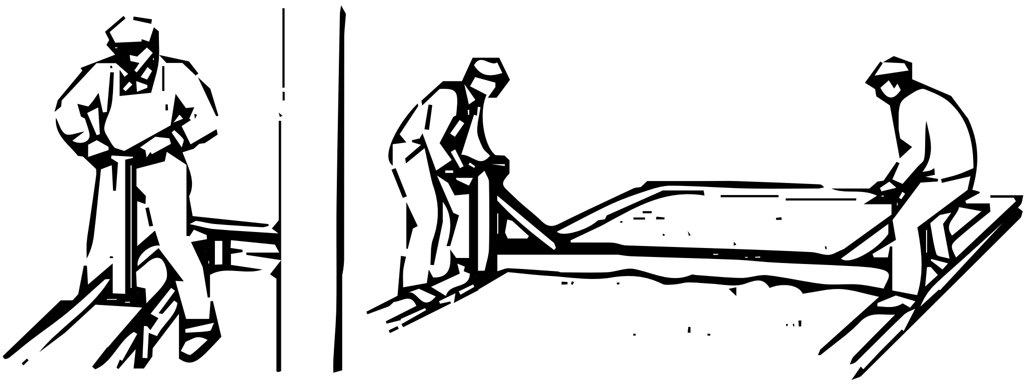


Figure 7.5: Compaction or lining the bottom of wetland to avoid seepage (Njau et al., 2010).

It is also possible to usea synthetic liner when constructing a CW in permeable soils. The synthetic liner must be aquatic safe, fish-grade. This means that the liner will not have been treated with any algaecides, pesticides or fungicides that may harm wildlife in the wetland ecosystem. The best quality liners are EPDM (45 millimetre or thicker) and PVC (30 millimetre or thicker). Synthetic liners can be purchased from pool supply and industrial liner companies. If using a synthetic liner, geo-textile padding to protect it is also needed. Make sure that the geo-textile material is aquatic safe and fish grade. Two pieces of geo-textile equal to the size of the liner (one underneath the liner and the second piece on top) are needed. Geo-textile often comes in a roll of a certain width, and it may be cut to the desired length of the wetland. Twelve inch (12") long twist galvanized landscape spikes and washers are needed to hold the liner and geo-textile in place. For a 232 square meter wetland, there will be need for 100 of each of the twelve inch (12") long twist galvanized landscape spikes and washers (Njau *et al.*, 2010).

7.6 Installation of the Inlet and Outlet System

Inlet and outlet structures are vital since they help to evenly distribute the inlet and collection of the treated wastewater (Vymazal *et al.*, 1998). The inlet and outlet part of the CW should be filled with stones between the sizes of 50 and 100 mm (Figures 7.6 and 7.7.) (Njau *et al.*, 2010).

Figure 7.6: Typical clean stones used for inlet and outlet zones (50 – 100 mm) (Credit: Njau et al., 2010)

7.6.1 Inlet/Outlet Stonework

The even distribution of wastewater in the inlet and outlet structure involves stones between sizes 50 and100 mm (Vymazal *et al.*, 1998; Njau *et al.*, 2010). These stones are either carefully placed without additional support or placed in a galvanized or pre-coated wire gabion box, 0.5 - 1 meter long, across the width of the CW (Vymazal *et al.*, 1998;Njau *et al.*, 2010).

(a) The recommended arrangement. (b) Too fine materials used at the inlet/outlet.

Figure 7.7: Recommended arrangement and size of inlet and outlet stonework (Credit: Njau et al., 2010)

7.6.2 Inlet and Outlet Piping

Piping materials should be PVC of Class A (Njau *et al.*, 2010). The inlet should be a distribution weir, trough or an open-ended pipe placed across the width (Njau *et al.*, 2010). The inlet distribution should be placed at the top of the wetland and covered by inlet stones. The outlet should be an open-ended pipe placed at the bottom of the wetland across the width. The outlet pipe should be connected as shown in Figure 7.8. (Avoid using closed ended perforated pipes because they cause immense resistance to flow and are subject to frequent clogging) (Njau *et al.*, 2010).

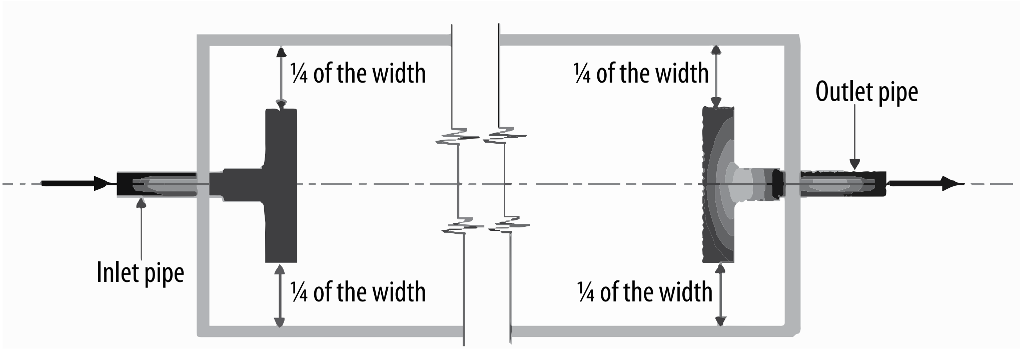


Figure 7.8: Plan view to show the layout of the inlet and outlet piping Njau et al., 2010).

The arrangement of the outlet pipe should be as shown in Figures 7.9, 7.10 and 7.11. The end of the outlet pipe should be raised to reach the level of 10 cm below the design substrate surface (Njau *et al.*, 2010). Remember to provide a washout line to drain the wetland in case of maintenance as shown in Figure 7.9.

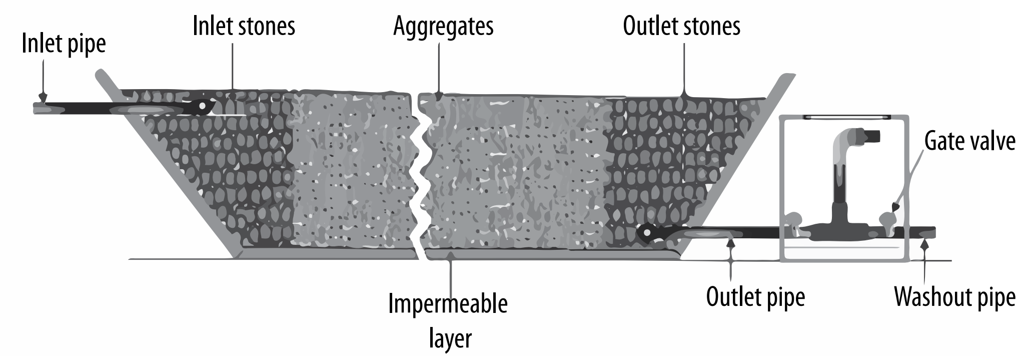


Figure 7.9: Position of inlet and outlet structures (Njau et al., 2010)

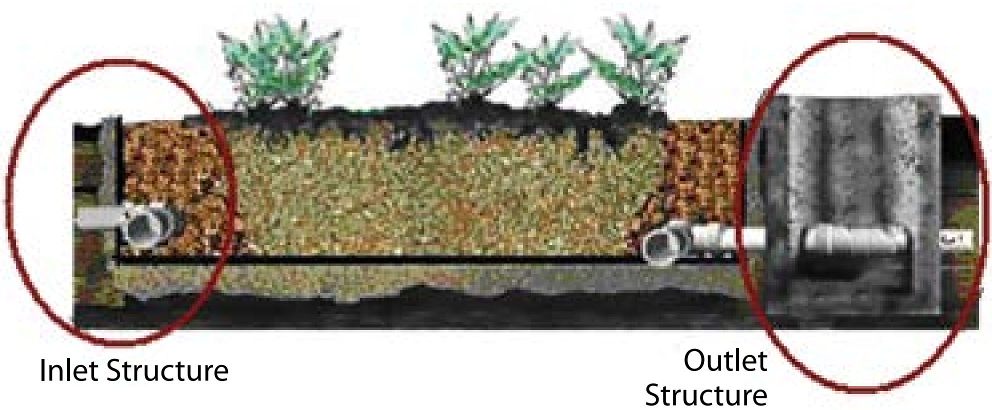


Figure 7.10: Incorrect positioning of the inlet and outlet pipes (Njau et al., 2010)

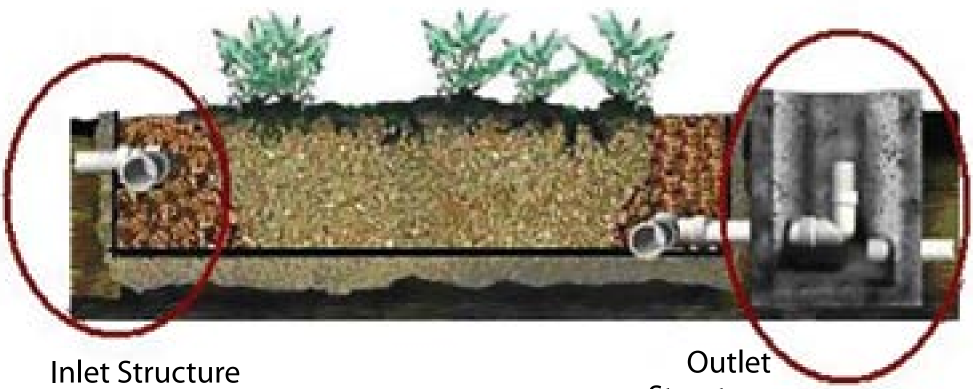


Figure 7.11: Correct positioning of the inlet and outlet pipes (Njau et al., 2010)

7.7 Substrate Packing and Filling

7.7.1 General

The role of the substrate (growth medium) in wetlands is to support vegetation and provide sites for biogeochemical reactions. Wetland substrate can consist of soil, sand, gravel, and organic materials. The substrate plays a significant role in removing pollutants by ion exchange/nonspecific adsorption and specific adsorption/precipitation in wetlands and this is complemented by the vegetation (Jinadasa *et al.*, 2006). The substrate must provide a suitable medium for successful plant growth and allow even infiltration and movement of wastewater. The choice of substrate is determined in terms of its hydraulic permeability and capacity to absorb nutrients and pollutants. Poor hydraulic conductivity in sub-surface normally results in CW surface flow and ponding which eventually and severely reduces the system's effectiveness (Vymazal *et al.*, 1998; Mwegoha *et al.*, 2002; Kimwaga *et al.*, 2004). The best combination of hydraulic conductivity and void ratio can be found with media in the size range of 12–25 mm, where larger-sized (37–75 mm) gravel media should be used near the inlet region (Vymazal *et al.*, 1998; Campbell and Ogden, 1999; Mwegoha *et al.*, 2002).

A successful operation requires a hydraulic conductance of approximately 10^{-3} to 10^{-4} $m^{-1}s^{-1}$ (Mwegoha *et al.*, 2002). The chemical composition of the substrate will also affect the system's efficiency, and soils with low nutrient content encourage direct uptake of nutrients from the wastewater by plants. Gravels should be washed to reduce clogging (increasing void spaces) for better filtration (Markantonatos *et al.*, 1996).

A mixture of organic clay soils, sand, gravel, and crushed stones could be used to provide support for plant growth (Haule *et al.*, 2000; Mwegoha *et al.*, 2002). These substrates are ideal reactive surfaces for ion exchange and microbial attachment and provide a sufficiently high hydraulic conductivity to avoid short-circuiting in the system (Hua, S. C, 2003).

7.7.2 Quality and size of substrate materials requirements

The required size of the aggregate should be in a range of 12-20 mm (Figure 7.12) (Vymazal *et al.*, 1998, Mwegoha *et al.*, 2002; Njau *et al.*, 2010).

- Make sure that the substrate is clean and free from dust and soil.
- If not, sieve the aggregate to ensure the recommended size.
- Wash with a lot of water to remove dirt and attached dust if necessary.

NOTE: All these activities should be done before filling the aggregate to CW (Njau *et al.*, 2010).

Clean and correct size of substrate materials should always be used.

Small size (below 12 mm) and dirty substrate materials should never be used

Figure 7.12: Construction of Constructed Wetlands-48: The required size and quality of wetland substrate material (Credit: Njau et al., 2010)

Note. Fill the right size of aggregate between the inlet structure and the outlet structure (This area is the treatment zone).

7.7.3 Size and Quality of Substrate Materials

Contractors must note that the size of the aggregates to be used as substrate is very strict (12-20mm) (Njau *et al.*, 2010). Moreover, undersize or fines are not allowed in the substrate materials. If the substrate is dusty or contains soil it must be cleaned with water before it is introduced into the wetland (Njau *et al.*, 2010). This type and quality of material can only be obtained as a special order from quarry operators because normally civil constructions do not need these strict specifications. The price is also higher than materials purchased for normal civil construction purposes (Njau *et al.*, 2010).

7.8 Planting

The planting of wetland vegetation is the last activity to be done before starting to operate of the wetland. Planting of the wetland is done using either plant cuttings (*Phragmites mauritianus*) or seedling (*Typha latifolia*). The plants to be planted should be viable. It should be noted that young macrophytes need acclimatization to high strength wastewater; therefore, freshwater or diluted wastewater can be used to propagate the wetland plants. The contractor must be aware that one of his/her activities is to plant the wetland with appropriate macrophytes as specified by the designer. This activity may involve someone conversant with plants in order to properly propagate the wetland plants.

The planting of vegetation is another significant factor in the construction of CWs, because the wetlands may not reach peak performance until the vegetation is well established (Vymazal *et al.*, 1998; Haule *et al.*, 2002). The selection of plant species depends on the source and characteristics of the wastewater to be treated. It is desirable to select plants with a high growth rate that would grow year around. Ideally, the chosen plant should grow densely, spread rapidly, and have an extensive horizontal and vertical root system. Roots must always be kept moist at all times before and after planting. Plants should be inserted into the media bed to a depth of 5–10 cm, with the shoots slightly exposed (Tanaka *et al.*, 2011).

Planting should be done at least six weeks prior to flooding the wetland with wastewater to reduce stress on the newly planted vegetation (Haule *et al.*, 2002). The planting period should avoid the rainy season. If the plants do not hold and grow afterwards, replanting between the original plants must be considered. If wastewater is not yet available after planting, the wetland shall be flooded with water. Failure to do so results in substantial plant death. It is also essential to ensure that the selected plants are free of disease and mould. The plant propagates used to treat wetlands can be seeds, rhizomes, seedlings, or field-harvested stocks.

7.8.1 Use of Seeds

Plants in the wetland can be established directly from seeds. Many wetland plants have seeds that can be field harvested in large numbers, whereas some species have few. For example, cattails (*Typha sp.*) carry thousands of individual seeds, while bulrushes (*Scirpus* sp.) contain only 20 to 30 seeds each. Seeds can be obtained from existing natural or constructed wetlands. Using seeds may be an economical option for planting. However, using seeds may take quite a long period to establish a feasible plant cover in the bed. Also, before maturation, weed plants that are difficult to control may overtake the wetland (Chambers and McComb, 1994). Another challenge of using seeds is the development of bed areas that do not have any plants. The use of seeds, therefore, is recommended only in conditions where other methods are not possible.

7.8.2 Use of Propagated Seedlings

Propagated seedlings have often been preferred as the most practical and cost-effective means of establishing plants in CWs (Parr, 1990; Surrency, 1993). Seedlings are early nursery plants. However, propagation of seedlings is required in regions where wetland plant nurseries are not present and where it is not possible to acquire in required numbers from existing/natural beds. Seedlings are easily planted using hand, and the survival rate of seedlings is significantly higher than for field germinated plants using seeds (Kadlec and Knight, 1996). Therefore, seedlings make arriving at a healthy plant cover with appropriate density easier. This, in turn, will be helpful in substantially reducing the system startup time for water quality control.

7.8.3 Use of Transplantation

Transplantation is an alternative to vegetate CW in the region where wetland plants are plentiful (Kadec and Wallace 1996; Vyamazal *et al.*, 1998; Haule *et al.*, 2002). Field harvesting of the transplants requires digging to scoop the plants from the ground and spread them in the open. Due to its size, transplanting mature plants may be more complex than planting seedlings. Larger and deeper holes must be made on the bed to allow the rhizome or root material to be completely buried. A major advantage of this method is that the plant cover is readily established once the planting is completed requiring very little or no startup period (Cooper, 1993).

7.8.4 Use of Rhizomes

Another method of employing plants from the field is using rhizomes to create new plants in treatment wetlands. Only the rhizome portion of the plant is placed in the bed rather than the entire plant. This technique produces shoots and mature plants more quickly than seedlings because herbaceous wetland plants store most of their growth reserves in their roots and rhizomes

(Grace, 1993). Within a few weeks, a correctly planted rhizome can yield many daughter plants (Kadlec and Knight, 1996). Rhizome segments with at least two nodes are better and must be planted 45° off the ground, with some protruding above the water (Haule *et al*., 2002).

7.8.5 Before Planting

- Landscape all disturbed areas. (During the landscaping of the disturbed areas make sure no soil will accidentally enter the wetland)
- Plant or seed grass around the constructed wetlands to prevent soil erosion.

Note. Once the cells are constructed, preliminary flooding of the cells is necessary. Flooding is necessary for checking leaks, and substrate levelling to prevent cracks in the liner (in the case of clay). The cells should be kept flooded until planting.

7.9 Construction of Spillway

This structure provides a controlled release of flows from a Constructed Wetland cell into a downstream area as shown in Figure 7.13**.**

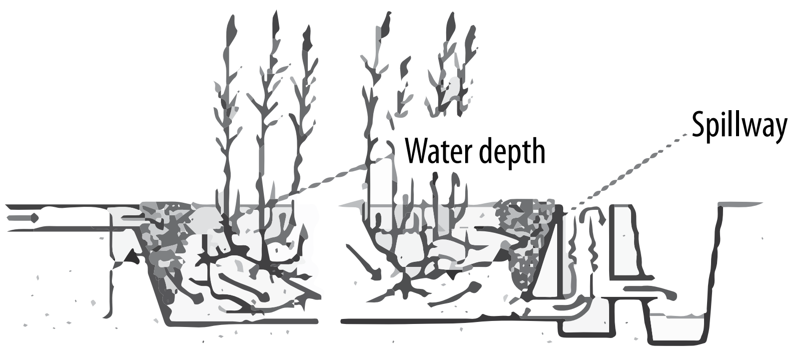


Figure 7.13: Subsurface flow constructed wetland showing spillway (Njau et al., 2010 adapted from Kadlec and Wallance, 2006).

The spillway should be constructed as specified in the design drawings. The invert levels specified by designers should be strictly observed (Njau *et al*., 2010).

7.10 Constructed Wetland Commissioning

7.10.1 Before Planting

Successful planting of CW should be done during warm seasons. Defer planting during the coldest months (*e.g.* May-August in Tanzania) (Njau *et al.*, 2010). If necessary, it is possible for a CW system's microorganisms can be used, without plants for up to six months, while waiting for appropriate time for planting.

7.10.2 Leveling of Gravel

The final levelling of gravel against the free water surface should be done by using secondary effluent for filling the system. Water levels should be dropped to approximately 50–100 mm. below the gravel surface for planting as shown in Figure 7.14 (Njau *et al.*, 2010).

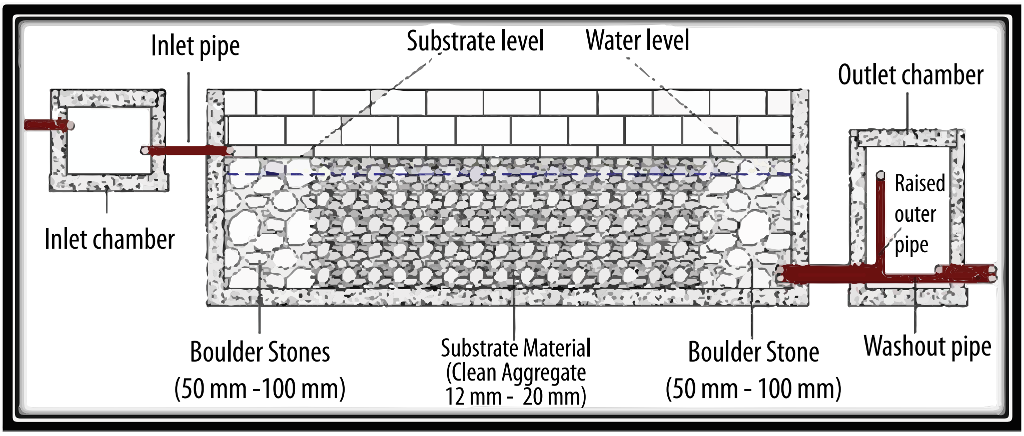


Figure 7.14: Arrangement of different components of a constructed wetland (Njau et al., 2010).

7.10.3 Water Level Control

Water level control and adjustment is critical to the establishment and survival of the plants and also to maintain subsurface flow. Roots of emergent plants must be kept wet as the plants will not survive if they are completely covered with water for extended periods. The water level should be dropped to 50–100 mm. below the gravel surface for planting and when in continuous use, normally, levels should be set at 100 mm. below the surface of the gravel at the outlet.

7.10.4 Weed Control

The control of weeds is necessary in order to avoid introduction of vegetation other than the planting stock. Weeds are controlled by uprooting them by hand. Spraying with herbicides should be avoided.

7.10.5 Check-up of Wetland Structures

Check the inlet and outlet structures and spillway to ensure the correct hydraulic functioning of the wetland. The inspection should consider ***inter alia***:

- Settlement of side slopes, pipe work and any surface blocking;
- Blockages, erosion, and scour of inlet/outlet structures;
- Any scouring of the spillway base;
- Any cracking, movement, or failure of spillway;
- Wastewater leakage.

7.11 Fencing and Protection

Plants introduced to wetlands may be vulnerable to physical damage from grazing, wind, waves, or sediment. Fences, sleeves, tree guards, fine-mesh silt screens, sticky oils or resins painted on planted vegetation, offshore walls or breakwaters, and other barriers could also be utilized to protect grown plants from such physical harm. Drought, excessive wind, and rain can all harm wetland systems. To reduce wind speed and improve aesthetics, trees can be planted all around a marsh (Tanaka, 2011).

7.12 General CW Construction Approval Tips/Steps

The following are the main tips to consider for a successful and effective construction of the CW facility to meet the intended treatment objectives (Njau *et al.*, 2010). Crucially, after site preparation, the contractor shall consult with the consultant for construction approval (Njau *et al.*, 2010).

- After setting out, the contractor shall check with the consultant for approval.
- After excavation, levelling and sloping, the contractor shall check with the consultant for control points, levelling and sloping inspection.
- After construction of bottom linings, side linings and embankment the contractor shall check with the consultant for control points, levelling and sloping inspection.
- Before after placing and mounting of inlet and outlet structures, the contractor shall check with the consultant for level and central lines inspection.
- Before filling aggregates or substrates, the contractor shall check with the consultant for grade, cleanliness, and leakage inspection.

- Aggregates at inlet and outlet zones should be large compared to others (as per specifications).
- Before planting wetland vegetation, the contractor shall check with the consultant for final approval.

7.13 Bidding for Constructed Wetland Works

In cases where the local capacity for CW construction supervision is not in place, there is need to seek the service of an individual/firm with skills, capacity, competencies, and experience through the bidding process. The bidding process for CW works is similar to that of other civil engineering works. However, the contractors must be aware that the following could reflect in the costs and they must quote properly for:

7.14 Concluding Remarks

This Chapter is a guide for Constructed Wetland contractors to be used during the bidding process and execution of the actual building of these systems.

7.15 References

Chambers, J. M., and McComb, A. J. (1994). Establishing wetland plants in artificial systems. *Water Science and Technology*, 29(4), 79-84.

Cooper P.F., Job G.D., Green B., and Shutes R.B.E. (1996). Reed beds and constructed wetlands for wastewater treatment. WRc Publications. 184 pp. plus data diskette: Swindon, United Kingdom

Cooper, P. F. (1993). The use of reed bed systems to treat domestic sewage: the European design and operations guidelines for reed bed treatment systems in Constructed wetlands for water quality improvement ed Moshiri G A, CRC Press/ Lewis Publishers, Boca Raton, Florida, pp. 203–217.

Grace, J. B. (1993). The adaptive significance of clonal reproduction in angiosperms: an aquatic perspective. *Aquatic botany*, 44(2-3), 159-180.

Haule, K. S., Johnsen, F. H., and Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. *Journal of environmental management*, 66(1), 31-42.

Hua, S. C. (2003). The use of constructed wetlands for wastewater treatment. Wetlands International—Asia Pacific: Selangor, Malaysia.

Jinadasa, K. B. S. N., Tanaka, N., Mowjood, M. I. M., and Werellagama, D. R. I. B. (2006). Effectiveness of Scirpus grossus in treatment of domestic wastes in a constructed wetland. *Journal of Freshwater Ecology*, 21(4), 603-612.

Kadlec, R. H. and Knight, R. L. (1996). Treatment wetlands CRC Press/ Lewis Publishers, Boca Raton, Florida.

Kimwaga, R., Mashauri, D., and Mbwette, T. (2003). Meeting health improvement indicators in waste stabilization ponds effluents by a coupled dynamic roughing filters and subsurface horizontal flow constructed wetland in Tanzania. Prospective College of Engineering and Technology, University of Dar es Salaam, Dar es Salaam, Tanzania.

Kimwaga, R.J., Mashauri, D.A., Mbwette, T.S.A., Katima, J.H.Y., and Jørgensen, S.E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilization ponds effluents in Tanzania, *Physics and Chemistry of the Earth* 29: 1243-1251.

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E., 2002. Mathematical modelling of the TSS removal in a coupled dynamic roughing filter and subsurface horizontal flow constructed wetland system treating WSP effluent, in: Proc s. 8th Internat. Conf. Wetland Systems for Water Pollution Control, University of Dares- Salaam, Tanzania and IWA, pp. 843-857.

Markantonatos, P. G., Bacalis, N. C., Lazaras, G., and Angelidis, M. O. (1996). Nutrient removal using reed bed systems in Greece. *Journal of Environmental Science & Health* Part A, 31(6), 1423-1434.

Mashauri, D. A., Mulungu, D. M., and Abdulhussein, B. S. (2000). Constructed wetland at the University of Dar es Salaam. *Water research*, 34(4), 1135-1144.

Mwegoha, W., Katima, J.H.Y., Mbwette, T.S.A., Njau, K.N., Jørgensen, S.E., and Nielsen, S.N., 2002. Modelling the effect of suspended solids accumulation on hydraulic conductivity of gravel packed horizontal sub-surface flow constructed wetland, in: Proc. 8th Internat. Conf. Wetland Systems for Water Pollution Control, University of Dar-es- Salaam, Tanzania and IWA, pp. 799-812.

Njau, K. N. and Renalda, M. (2010). Performance of horizontal subsurface flow constructed wetland in the removal of tannins. *Canadian Journal of Civil Engineering* 37(3), 496–501. https://doi.org/10.1139/l09-161.

Parr, T. W. (1990). Factors affecting reed (Phragmites australis) growth in UK reed bed treatment systems. In Constructed Wetlands in Water Pollution Control (pp. 67-76). Pergamon.

Senzia, M. A., Mashauri, D. A., Mayo, A. W., Mbwette, T. S., Katima, J. H., Pratap, H. B., and Nielsen, S. N. (2002, September). Performance of horizontal subsurface flow constructed wetlands located downstream of primary facultative and maturation ponds in Tanzania. In Int. Conf. on Wetlands Systems for water Pollution Control, Arusha, Tanzania.

Surrency, D. (1993). Evaluation of Plants for Coastal Dune Stabilization. In Coastal Zone'93 (pp. 2324-2331). ASCE.

Tanaka, N., Ng, W. J., and Jinadasa, K. S. N. (2011). Wetlands for tropical applications: wastewater treatment by constructed wetlands. World Scientific.

Vymazal, J. (1998). Removal mechanisms and types of constructed wetlands. Constructed wetlands for wastewater treatment in Europe, 17-66.

This page is intentionally blank

Chapter 8: Operation and Maintenance Requirements for Constructed Wetlands

By Leah Marwa and Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

Constructed Wetlands (CW) must be managed if they are to perform effectively and efficiently in the objective they have been designed for. These systems are regarded as low cost and simple in operation and maintenance. However, this by no means implies that CWs do not have any operation and maintenance needs. CWs need simple attendance such as checking for blockage in pipes, controlling vegetation growth, litter, and debris. If not cared for, they show poor treatment performance, become clogged and as a result, an eyesore. CWs require regular inspection and maintenance to ensure that they remain healthy, functional, and attractive. This chapter discusses the operational and maintenance requirements based on the experience gathered by the WSP and CW research group of the University of Dar es Salaam.

8.1 General Requirements and Considerations

Constructed wetlands unlike other conventional wastewater treatment technologies are simple in construction, have higher treatment efficiency, and are made to primarily rely on passive treatment mechanisms with a little need for continual maintenance as occurrences of problems within the wetland are very minimal (Sundaravadivel and Vigneswaran, 2001; Kayombo *et al*., 2005; Liu *et al*., 2009;; Mghaoui, 2015;)

However, because they are dynamic ecosystems with many variables, complications may arise during their operation (Kayombo, 2005; Sundaravadivel and Vigneswaran, 2001). Experience has shown that early failure is likely to occur on many sites if no maintenance plan is implemented. Blockages of inlets and outlets, flow-regulating devices, storage area siltation, algae growth, and plant dieback are the most common issues (Ellis *et al*., 2003; Lee *et al*., 2009costs, construction, operation and maintenance of constructed wetlands used for the treatment of highway runoff. Information is provided on the different types of wetlands and their mode of operation, the design and planting of a wetland system and the retrofitting of treatment structures, the performance and costs of wetlands and their operation and maintenance requirements. The benefits of wetlands in encouraging wildlife and improving the landscape are discussed. The implementation of Sustainable Drainage systems (SuDS). Forming an operation and maintenance plan during the design of the constructed wetland system is the best way to guarantee its economical operation and maintenance (Shutes, 2001; ; Tanaka *et al*., 2011; Njau *et al*., 2020). According to Kayombo *et al*., (2005), the requirements for operation and maintenance are typically site specific, so they must be tailored to a specific CW and reflect desired goals.

Sundaravadivel and Vigneswaran (2001) described the main goals for operating and maintaining CW systems to be:

- Ensure that the operation of the wetland adheres to the design objectives in all scenarios;
- Maximize treatment efficiency and capacity;
- Reduce costs by providing early warning mechanisms by detecting issues early on; and;
- Increase the system's lifespan, delaying major retrofitting and thus the system's long-term viability.

The effective macrophytes growth, the proper CW design and construction, as well as their operation and upkeep, are the primary factors that determine how well CW performs (Njau *et al*., 2010; Kimwaga *et al*., 2012). CW will last longer if they are operated and maintained properly (Njau *et al*., 2010). Water level and flow rate are the most important operational variables that can be used to affect treatment by constructed wetlands (Lee *et al*., 2009). At the DANRCS, (2016), functional necessities for CWs incorporate maintenance of water level in wetland cells appropriate for vegetation, control flow to wetland as per water budget, observing wetland performance, sampling effluent for nutrients before usage, inspection of inlet and outlet structures for damage. Repairing embankments, controlling desirable vegetation density, getting rid of invasive and/or non-native species that could be a problem in native habitats, getting rid of debris and sediment, fixing fences or other ancillary features, replacing wetland plants, fixing pipelines and spillways, and controlling undesirable rodents or vectors (such as mosquitoes) are all examples of maintenance requirements for CWs. The commissioning of CW facility at Ihelele water treatment plant in Misungwi Mwanza Tanzania involved hand over of the operational and maintenance manual to aid the crew who perform the O& M functions (Kimwaga *et al*., 2012).

The developed operation and maintenance plan which must be contained in O&M manuals should reflect the operational and maintenance requirements (Njau *et al*., 2010). The plan ought to be made and looked over with the operator in charge (Njau *et al*., 2010). Specific system characteristics that were discovered during actual operation can be incorporated into the updated plan (Njau *et al*., 2010). Maintenance of inlet and outlet structures, embankments, and vegetation, control measures for vectors and pests, and containment of potential pollutants during maintenance operations should all be included in the plan (Rousseau *et al*., 2008; DANRCS, 2016;).

8.2 Start-up Considerations

The start-up of a new wetland is a crucial time that includes filling and planting of the wetland as well as a period during which the medium or soil, plants, and microbes adjust to the wetland's hydrological conditions (Njau *et al*., 2010; Kadlec *et al*., 2000). If the changes in a newly constructed wetland are given time to stabilize, it should be fairly obvious that they can be tolerated. Because wetland biology can take a long time to develop, start-up transients may not always be brief (Reddy, 1997). It is best not to add wastewater to the plants until the new growth indicates that the roots have recovered from being transplanted, allowing a system to adjust to the new water chemistry by gradually increasing wastewater flow after stabilization is preferable to operating at the ultimate flow immediately. When compared to less concentrated water like stormwater or pretreated sewage effluent, highly concentrated wastewaters like agricultural waste require a more gradual introduction.

According to UN-HABITAT, (2008), the duration of the start-up period varies based on the type of design, the characteristics of the influent wastewater, and the time of year. During the start-up, several important processes take place, including (Njau *et al*., 2010):

- The density and area coverage of the plants increase.
- A litter layer is made up of old plant parts.
- If initially loaded, newly placed soils either release constituents or absorb them until they are fully loaded.

During the start-up, CW basin water tightness testing, antecedent conditions, and the ecological transition are all important factors to consider as discussed below (Njau *et al*., 2010);

8.2.1 CW Basin Weather Tightness Testing

The basin should be flooded to the design depth before accepting the final construction to ensure that the water levels and flow distributions meet expectations. To ensure that they are working properly, all components, including pumps and water control structures, should be tested thoroughly.

A water tightness test ought to be carried out if the CW basin is adequately and properly lined. After the basin has been sealed but the rooting soil has not yet been placed, this test is carried out. If excessive leakage has been discovered, repairs must be made. Raking the substrate and manually filling should be used to remove any erosion and channelling that occur during the initial operation. Filling and compacting thoroughly should be done to the spillways and rills on the slopes of the embankment. As needed, these areas should be resown and fertilized. An engineer should be consulted to determine the best course of action if seepage occurs beneath or through a dike.

8.2.2 Antecedent Conditions

Small treatment wetlands are frequently constructed using imported rooting soils or media with established characteristics (Mwegoha *et al.*, 2000; Njau *et al.*, 2010). It has been specified and emphasized that none of these contain contamination sources that could compromise the CW performance (Njau *et al.*, 2010). The type and density of the selected plants, as well as the fact that they only compete with algae for available system space during the growth-in period, are all known in this instance (Haule *et al.*, 2000; Njau *et al.*, 2010). The antecedent condition of the wetland soils is also known.

It is possible to construct CW without altering the original upland soils. Depending on the previous uses of the land, the soils may contain a significant number of pollutants; therefore, care must be taken to prevent pollution of the CW through proper and adequate cleaning using jetted water via spraying (Njau *et al.*, 2010). The process of adapting an ecosystem to the flows and pollutants that need to be treated occurs at several distinct points. However, before stable operation can be achieved in any given instance, there will be a period of adaptation. The repercussions of start-up phenomena require the attention of regulators and operators alike.

8.2.3 Ecological Transition

In CW, the development of the litter compartment typically takes between one to two years, while vegetation and biofilm typically take a few months to establish in CW (Kadlec and Wallace, 1996; Vymazal *et al.*, 1998; Haule *et al.*, 2002;;). If a SSF medium has been chosen for its sorption capacity, leaching or sorption of some constituents can take up to a year.

8.3 Operation and Maintenance (O&M) of CWs

For any system or procedure, achieving efficacy is extremely important. As a result, proper care and maintenance procedures are required (David *et al.*, 2022). Successful wetland performance is primarily dependent on operation and maintenance, even though the wetlands are intended to require minimal operational control or maintenance (Reddy, 1997). Constructed wetlands will last longer if they are operated and maintained properly. The most significant operational variables that can be used to influence the treatment performance of constructed wetlands are limited to hydraulic control processes like water level control and flow rate control because the wetland system rarely requires any mechanical equipment in the treatment process (Wallace and Knight, 2006; Lee *et al*., 2009; Tanaka *et al*., 2011;). According to Reddy, (1997), the primary day-to-day activities required for wetlands to successfully perform include adjustments of flow rates, water levels, water quality, and biological parameters. For sustainable plant operation, the utilization of local resources, knowledge, and workforce, various operation and maintenance options will need to be taken into consideration (Tanaka *et al*., 2011). Maintaining HRT should ensure that contaminants have sufficient contact with the microbial flora and bed for improved CW performance. In addition, the wetland should maintain a constant effluent flow to prevent gradient formation and preserve a healthy bed environment. In order to achieve the intended level of pollutant removal efficiency, wetland microflora must be provided with favourable conditions and unimpeded plant growth (David *et al*., 2022).

There are three types of operation and maintenance phases: start-up, routine, and long-term which significantly vary between them (UN-HABITAT, 2008; David *et al*., 2022). According to UN-HABITAT, (2008) and David *et al*., (2022), start-up requirements exhibit greater site-to-site variability, routine operations may be more influenced by design details, and long-term operations will reflect loading. Rousseau *et al*., 2008 and Reddy, (1997) mentioned CWs' operations and maintenance tasks, such as pump and control structure repairs; gestation of the vegetation; bother control and expulsion of amassed mineral solids which should be completed at significantly less regular stretches. The WIO region experience drawn from Tanzania shows that O&M was not given much attention (Njau *et al*., 2011). Through ten years' experience of this engineered system, apparently it came out clearly that most of the CWs had become malfunctioned largely due to lack of O&M, an element which called for the need to institutionalize the O&M manual.

8.3.1 Operation of CWs

A CW's functionality and thus its management, relies heavily on routine operations including flow rate/discharge and wastewater analysis (Njau *et al*., 2011). Water levels should be regularly monitored and evaluated in addition to regulatory requirements, inflow and outflow rates, wastewater quality, and other factors. According to UN-HABITAT, (2008), these data aid the operator in anticipating potential issues and selecting appropriate corrective actions over time.

The wetlands' pore space will gradually be reduced by solids from previous treatment units and decaying vegetation litter. Most of the solids will accumulate at the HF beds' inlet ends, where the pore space may significantly shrink in a few years (*e.g.* 5 years).

As a result of this reduction in the pore space, surface flow through the CW occurs. Hence, it is necessary to periodically remove the solid accumulation estimated by the loading. Periodically, the wetland's performance should be evaluated, and its operational conditions should be modified to increase treatment efficiency (Vergeles *et al*., 2015). To determine the efficacy of the treatment, samples need to be taken and analyzed. Finally, the following parameters must be examined:

- Total Suspended Solids (TSS);
- Biochemical Oxygen Demand (BOD5);
- Chemical Oxygen Demand (COD);
- Ammonia;
- Nitrate;
- Phosphorus;
- Faecal Coliforms.

8.3.2 Maintenance of CWs

According to Vymazal, (2002)but the first full-scale constructed wetland (CW, inadequate maintenance frequently decreases the treatment system's effectiveness. He differentiated between operational issues brought about by inadequate maintenance and those brought about by system components that were not constructed or designed appropriately.

Long-term upkeep should be taken into account in constructed wetland planning (Jones, 1995). The wetland's treatment effectiveness and ecological benefits diminish over time if maintenance is neglected. In order to maintain the constructed wetland's functionality, wetland vegetation, water control structures, and pipes must all be maintained (Mackenzie and Mcilwraith, 2015).

Some of the points to consider while performing the CW maintenance are;

- In order to speed up plant coverage, replace damaged plants, or try out more suitable varieties, additional vegetation planting may be required.
- If it is anticipated that livestock grazing will be a problem, perimeter fencing may be required. Controlling the spread of undesirable plant species like purple loosestrife may require maintenance.
- Debris can become clogged in outlets and inlets, necessitating regular cleaning.

- Weekly inspections of inlet and outlet structures are recommended, with a focus on major storm events.
- Most importantly, the wetland may eventually require dredging to remove accumulated materials if it works well as a sediment and nutrient trap.
- Therefore, maintenance vehicles and possibly dredging equipment will require vehicular access to the site (Jones, 1995).

8.4 Management of the System

Staff with training and experience is required for the constructed wetland systems' maintenance. An integrated comprehension of these systems' biological, chemical, and hydrological processes is crucial to their long-term efficiency and sustainability. At the design stage, management plans and budgets must be prepared, and provisions must be made for resolving unanticipated operational issues (Shutes, 2001).

8.4.1 Monitoring and Evaluation (M&E)

To guarantee a successful operational performance, monitoring is of the utmost importance (Kayombo *et al*.,, 2005). Accurate data collection and analysis are necessary for early detection of changes in the performance of wetlands (Reddy, 1997; Ellis *et al*., 2003)which gives a state-of-the-art presentation of the science and technology of sewage treatment. The major variants of wetland systems are covered in this volume, namely: (i. Wetland monitoring is necessary to obtain sufficient data to determine the wetland's performance in meeting the objectives. The data must be collected accurately and consistently, and a knowledgeable operator should review it frequently to anticipate the need for operational changes. The level of detail of the monitoring will be determined by the size and complexity of the wetland system and may alter as the system matures and its performance becomes more well-known.

Inadequate operational control decisions and design flaws can result in significant ecological shifts in natural wetlands and prolonged periods of poor operational performance for constructed wetlands. Data collection and frequent data analysis are necessary for the early detection of subtle changes in the biological resources and water quality of a treatment wetland (Kadlec *et al*., 2000). If continuity is to be maintained throughout the project's many-decade lifespan, a well written monitoring plan is necessary. The monitoring plan should include clearly stated project goals, specific monitoring objectives, organizational and technical responsibilities, tasks, and methods, data analysis and quality assurance procedures, schedules, reporting requirements, resource requirements, and a budget (Njau *et al*., 2010).

According to Sundaravadivel and Vigneswaran, (2001) sampling of influent and effluent samples for characterization is one method of monitoring the CW system. It is recommended to start monitoring only the conventional wastewater parameters including DO, pH, TSS, BOD, COD, Nutrients (N and P) and coliforms (E coli, Faecal coliform). Reddy, (1997) reported additional parameters that should be monitored in a CW treatment system that include water levels and indicators of biological condition. System control will not be successful without these parameters. Other monitoring requirements may also be imposed by regulatory requirements. The size and capacity of the system, the expertise of the owner's staff and sampling equipment, as well as site-specific factors related to influent quality variability and climatic factors, determine the frequency of operational monitoring for system control.

Kadlec and Knight (1996) discussed the possible monitoring and program for the operation of a wetland treatment system, which is summarized in Table 8.1. The program includes measuring the water quality of wetlands' inflow and outflow water. The term "inflow" refers to both the natural inflow streams that may have an impact on the water quality or hydrological budget of the natural wetland treatment system and the sources of pretreated wastewater that enter the wetland.

Table 8.1: Typical minimum monitoring requirements for successful operation of wetland treatment systems (Kadlec and Knight, 1996)

Recommended parameters	Recommended sampling locations	Minimum sampling frequency
Inflow and outflow water quality		
All systems: Temperature, dissolved oxygen, pH, conductivity	Inflow(s) and outflow(s)	Weekly
Municipal systems: BOD_5, TSS, Cl-, as an inert tracer	Inflow(s) and outflow(s)	Monthly
Industrial systems: COD, TSS	Inflow(s) and outflow(s)	Monthly
Stormwater systems: TSS	Inflow(s) and outflow(s)	One storm event per month
Permit parameters as required: NO_2+NO_3-N, NH_4-N, TKN, TP Metals, organics, toxicity	Inflow(s) and outflow(s) Inflow(s) and outflow(s)	Monthly Quarterly
Flow	Inflow(s) and outflow(s)	Daily
Rainfall	Adjacent to wetland	Daily
Water stage	Within wetland	Daily
Plant cover for dominant species	Near inflow, near wetland centre, near outflow	Annually

A comprehensive monitoring survey would include measurement of: pH; dissolved oxygen; total suspended solids (TSS).; Biochemical and Chemical Oxygen Demands (BOD and COD).; nitrates and phosphates; heavy metals; and hydrocarbons that must be tested at all major inflows and outflows at least monthly (Shutes *et al.*, 1999; Kayombo *et al.*,, 2005).

Additionally, inflow and outflow stations can be monitored less frequently for organics or heavy metals in the wastewater. If the characteristics of the water at the inflow and outflow locations are highly variable, sampling should occur more frequently than monthly or quarterly (Njau *et al.*, 2010). For a visual analysis of trends and variability, it is necessary to properly record these water quality data in a computerized spread sheet. Operational control should be put into action whenever there is a possibility of a permit violation in the future.

The inflow and outflow locations should be used to estimate the daily flow rate. In some locations, the data can be obtained by installing flow meters (*e.g.* V-notch weir), and in non-instrumented locations, the stage data can be obtained by utilizing the stage discharge relationship. Likewise, a proper weir at the power source gives a basic method for estimating stream and gathering water tests (Harmel *et al.*, 2006). Quantifying the mass balance of the constituents in wetland treatment systems requires accurate flow estimation.

At a location close to the wetland system, rainfall should be monitored. Estimating the wetland water balance and anticipating elevated wetland conditions at the outflow location rely heavily on rainfall data. Pan evaporation data from a nearby regional weather station can be used to estimate evapotranspiration. As a result, measurements of rainfall, evapotranspiration, and inflow or outflow can be used to keep the wetland's water balance constant and to find groundwater exchanges that could be caused by leaks in the liner, if they are present.

Every day, the wetland's water stage—also known as its elevation or level—should be measured close to any outflow locations. A quantitative tool for interpreting hydraulic residence time in a wetland is created when stage measurements are combined with a topographical survey of the wetland. The operator receives information about the structural health of the fauna and vegetation through biological monitoring. The wetland's biota's operational performance is controlled by biological integrity, which is important from an environmental habitat perspective.

In every CW treatment system, the proportion of dominant plant species covered should be recorded quarterly to annually (Kadlec *et al.*, 2000; Njau *et al.*, 2010). When necessary, surveys of endangered or rare plant species may also be carried out for their proper protection (Kadlec *et al.*, 2000). As a result of the altered hydrological regime brought about by the prolonged discharge of pretreated wastewater, this monitoring provides a record of the biological changes that take place (Kadlec *et al.*, 2000).

A crucial aspect of maintaining the functioning of wetland areas is monitoring and evaluation. Accurate pretreatment, conservative constituent and hydraulic loading rates, the collection of monitoring data to evaluate system performance, and knowledge of successful operation strategies are all necessary for effective wetland performance. Despite its relatively straightforward design and construction, the CW system requires constant monitoring and maintenance.

8.4.2 Documentation and Recordkeeping

For CW O&M programs to be successful, accurate records must be kept of all O&M activities and malfunctions Hicks and Stober, (2020). According to Strande *et al.*, (2014) operators frequently refer to records in order to optimize O&M procedures, identify previous fluctuations in the facility's operation, and identify operational issues that may recur periodically, evaluate the efficacy of possible mitigation measures, and identify operational issues. As a result, CW operators should have easy access to these records.

The following are some examples of recordkeeping that are helpful for CWs:

- Information on the operation of the CWs including operating records, the operators logbook, evident reports, the treatment unit operating data sheet, and other records related to WW deliveries to the plant;
- Disaster response and emergency recovery records.
- Preventative and corrective maintenance records including the equipment maintenance logbooks and store room supply reports;
- Compliance reports including field and analytical data, and correspondence from regulatory officials; and
- Employee records, such as employee schedules, time sheets and injury reports

The type of records and the length of time for which they will be retained for a particular facility will be determined by the regulatory requirements and the technologies that are used. Since these records are tools that can be used by employees to assist in the day-to-day operation of the facility, a summary of the information should be used to optimize the O&M plan, as well as in the planning of any expansion to a CWs or in the design of new CWs.

8.4.3 Plant Security and Safety

CWs like any other treatment technologies are critical infrastructures and must therefore be secured from unauthorized entry and vandalism by fencing off of facilities and engaging security employees (Strande *et al.*, (2014). Managers can also create a culture of security by enacting the following guidelines:

- Including security as a topic in employee's meetings and discussions.
- Appointing a Plant Security Officer or assigning the duties to a responsible employee member.
- Enforcing security policies and procedures consistently and equitably; and
- Providing security training for all employees.

Introduced plants may be susceptible to physical harm from grazing, waves, sediment, or wind. To protect grown plants from such physical harm, other barriers, such as sleeves, tree guards, fine-mesh silt screens, sticky oils or resins painted on planted vegetation, offshore walls or breakwaters, can also be used as well as fencing off the planed beds (Vymazal, 2006). Wetland systems can be damaged by drought, excessive wind, and rain. Trees can be planted all around a marsh to reduce wind speed and improve aesthetics (Tanaka, 2011).

8.4.3.1 Health and Safety

The typical tasks required to operate and maintain CWs pose numerous risks to health and safety (Strande *et al.*, (2014)).Wellbeing and security viewpoints ought to hence frame an indispensable piece of the O&M plan, however, are frequently not offered satisfactory consideration.

The "Health and Safety Plan" outlines the procedures, practices, and tools that employees should use to carry out activities safely. Each wetland's health and safety plans are unique, but they also include aspects that are common to all CWs. Through the preparation of the safety plan and the placement of posters and signs in risk areas (such as beds and manholes), management strictly enforces health and safety procedures.

Figure 8.1 provides a safety notice illustration. The following topics ought to be included in the health and safety plans based on the authors' experience:

- Safety measures for O&M activities and personal protective equipment (PPE);
- Measures for hygiene and infection control;
- Emergency contact procedures;
- Safeguards against dangers of falling;
- Use of a buddy system, where plant staff work in pairs;
- Ensuring that at least 30 minutes aeration time is allowed between opening manholes and entering them to do repairs;

- Putting in place a system of written procedures, for instance for entrance to work in confined spaces;
- Electrical safety, *e.g.* lock-out/ tag-out (LOTO) where electrically powered equipment is in place Electrical safety, *e.g.* lock-out/ tag-out (LOTO) where electrically powered equipment is in place

Figure 8.1: Safety posters and signs are good reminders to follow proper procedures (Photo: David M. Robbins)

8.4.3.2 Personal Protective Equipment

Personal protective equipment (PPE) consists of the following items, which are worn to reduce exposure to hazardous conditions:

- eye protection against chemical or dust exposure, such as safety glasses, goggles, or face shields;
- gloves made of rubber latex or other materials, depending on the danger, to protect hands from chemicals or abrasion;
- safety equipment for breathing, such as dust masks and respirators if necessary for certain tasks;
- additional protective clothing, such as coveralls and footwear protection; and
- any additional equipment necessary for task-specific safety.

Even though the PPE that is required for each task is specified in the health and safety plan, it is the management's responsibility to ensure that the right PPE is provided, employees receive training on how to use PPE, and employees are adhere to the PPE usage guidelines. All O&M and monitoring activities at the wetland, including WW discharge, equipment O&M, effluent use, storage, and disposal, sample collection, processing, and end-product removal, require clearly defined safety procedures.

8.4.3.3 Infection Control

WW is infectious by nature. It frequently carries bacteria, viruses, or other pathogens that can cause disease (Metcalf and Eddy, 2004). When handling equipment that might have come into contact with WW, workers should always follow hygienic procedures and have the appropriate immunizations, such as tetanus and hepatitis A (Metcal and Eddy, 2004). Workers should have access to restrooms and areas where they can wash their hands. Infection control measures include:

- Making use of the appropriate PPE to shield the skin from coming into contact with waste/ faeces;
- Washing one's hands after coming into contact with WW or before eating;
- Immediately notify plant supervisors of illness.

8.4.3.4 Emergency Contact Procedures

Employees can access up-to-date telephone numbers and contact information in the event of an emergency thanks to emergency contact procedures. The contact list ought to be displayed in a common area that all employees can access and have access to a working telephone. First aid materials, supplies, and equipment must be provided for all wetlands, but especially those in remote locations. The actions that make up a typical emergency procedure are as follows (Njau *et al.*, 2010):

- Getting in touch with the right emergency personnel;
- Evacuating employees based on the situation (such as a fire or overflow);
- If the plant manager is not already present, call him or her;
- Assisting the affected personnel until emergency responders arrive and take charge of the situation; and
- Emergencies should be archived on an emergency report form which is then shared with administration for investigation. The operators' logbook must also contain full details about all emergencies.

8.4.4 Asset Management

As in any treatment facility, asset management is a comprehensive approach to constructed wetlands maintenance in order to maximize the facility's long-term effectiveness at the lowest possible cost. The following costs are included in an asset's total lifecycle costs:

- Capital expense of buying and establishment;
- Work expected for activity and support;
- Repairs-related spare parts;
- Essential consumables like chemicals or grease; and
- The costs of replacing the component when its useful life is up.

The stocks of tools and supplies that are required for long-term operational needs are integral to the costs of the entire lifecycle. Each CWs site ought to ideally have access to these (Lüthi *et al.*, 2011). It is possible to organize centralized stocks if numerous CWs utilize the same technology or equipment. The following elements ought to be incorporated into the maintenance plan for large treatment plants (USEPA, 2002):

- The present status of the resources;
- The required level of service that is "sustainable";
- The assets that are necessary for consistent performance;
- The lowest possible life-cycle costs; and
- The plan for funding over the long term.

The cost of the equipment and the significance of the asset cannot be compared without an asset inventory. It is important to highlight components that are necessary for the operation of the CWs and to immediately replenish them after they have been used. As a result, choosing a reputable provider and drafting agreements to guarantee prompt service are essential in these situations.

8.4.5 Management of Clogging

According to Brix, (1994), insufficient mechanical pretreatment of the wastewater is the primary cause of gravel media clogging. This is a major issue with HF CWs that can be solved by selecting coarse filtration materials and effectively removing suspended solids from pretreatment units (Vymazal, 2011). In VF CWs, Wallace and Knight, (2006)rather than being borderless by nature, the digital has to be understood as producing different kinds of borders, demanding different kinds of politics of location. New potentialities arise with the challenge of creating a politics fitting to the current mode in which locations become slippery. Discussing the emergence of cyberfeminism in the early 1990s and a more recent example of digital feminism - the #SolitarityIsForWhiteWomen hashtag - this article thinks through the following questions: what does the \"cyborg\" as a posthuman (and postgender found that the intermittent loading regime and the presence of macrophytes assist in preventing medium clogging. The growth of roots within the filter medium helps to decompose organic matter and prevents clogging, and the movements of the plants caused by the wind keep the surface open (Brix, 2003). Vymazal, (2011) suggested that, for the VF CW's to function effectively, it is necessary to carefully select the filtration material, distribute the wastewater evenly across the surface of the wetland, and select the optimal hydraulic loading rate.

8.4.6 Management of Vegetation

Vegetation management is very important in both the FWS and VSB wetland systems, especially in the first year of plant growth. Invasive vegetation (*e.g.* water hyacinth) has the potential to colonize and take over the wetland if it is not maintained, making it difficult, if not impossible, for the desired wetland vegetation to establish itself (Wallace and Knight, 2006)rather than being borderless by nature, the digital has to be understood as producing different kinds of borders, demanding different kinds of politics of location. New potentialities arise with the challenge of creating a politics fitting to the current mode in which locations become slippery. Discussing the emergence of cyberfeminism in the early 1990s and a more recent example of digital feminism - the #SolitarityIsForWhiteWomen hashtag - this article thinks through the following questions: what does the \"cyborg\" as a posthuman (and postgender.

In CWs, vegetation management is necessary for two reasons. It helps keep unwanted plant species under control and gets rid of excess plant debris. FWS wetlands can accumulate an excessive amount of plant biomass in particularly hot and dry climates, which frequently results in a mosquito problem. According to Wallace and Knight, (2006)rather than being borderless by nature, the digital has to be understood as producing different kinds of borders, demanding different kinds of politics of location. New potentialities arise with the challenge of creating a politics fitting to the current mode in which locations become slippery. Discussing the emergence of cyberfeminism in the early 1990s and a more recent example of digital feminism - the #SolitarityIsForWhiteWomen hashtag - this article thinks through the following questions: what does the \"cyborg\" as a posthuman (and postgender, a variety of vegetation management strategies are being considered, including mechanical harvesting and burning. Plant harvesting can effectively reduce the number of adult mosquitoes (Williams *et al.*, 1996); nonetheless, mechanical reaping is very troublesome to wetland tasks, and the removal of gathered plant material (which is generally water) is risky (Knight *et al.*, 2004). Since amassed plant biomass can recover, the advantage may just be transitory (Thullen *et al.*, 2002).

Even though the ash produced by burning will once more introduce nutrients into the water column, controlled burning is one of the alternatives that can be used to get rid of excess plant biomass in wetland treatment systems. According to Kadlec and Knight (1996), this might result in a short-term decrease in the effectiveness of the treatment. Knight *et al.*, (2004) observed that the most effective management strategy for CW is probably controlled burning on a schedule of two to five years with the ability to avoid the burned cell for at least one month.

In order to maintain the desired plant communities, FWS wetlands typically require some level of management. Purple loosestrife (*Lythrum salicaria*), one of the extraordinary plants, may invade wetland systems and require management or removal (see section species of invasive plants).

The growth of trees in wetland embarkations, particularly cottonwood (*Populus deltoides*) and willow (*Salix spp.*), is a problem that occurs more frequently. Mowing is the method that is easiest to control these. This necessitates the creation of berms with sufficient side slopes for mowing equipment. Burning can also be used to control trees (as part of a larger plan to manage plant biomass). When tree colonization continues to be a problem, periodic mowing will likely still be required, even if burning only occurs every two to five years (Njau *et al.*, 2010).

There is always the possibility that an undesirable plant will emerge, regardless of where the wetland is situated. As a result, the management and removal of undesirable plant species should be included in any wetland treatment system's operations and maintenance plan.

Table 8.2: Invasive plant species in WIOMSA Region Constructed Wetlands (Njau et al., 2010)

Scientific Name	Common Name	Problem	Management
Lythrum salicaria	Purple loosestrife	Exotic; loss of habitat in FWS wetlands	Biological control (beetle); herbicide
Populus deltoids	Cottonwood	Berm damage in FWS wetlands; wind-throw in VSB wetlands	Burn to kill seedlings; pull seedlings
Salix *spp.*	Willows	Berm damage in FWS wetlands; wind-throw in VSB wetlands	Burn to kill seedlings; pull seedlings
Urtica dioca	Stinging nettle	Nuisance plant in VSB	Pull plants (wearing gloves)

8.5 Reuse and Recycling of CW End Products

In addition to being used to improve the quality of usable water and the environment, the products and effluents of wetlands offer excellent opportunities for exploitation in developing countries (Aalbers, 1999).In CW systems, wastewater recycling or reuse must be addressed. A desirable recycling application is the irrigation of crops with treated effluent (Shutes, 2001). According to Rousseau *et al.*, (2008)depending on its quality, treated effluent can be reused for restricted or unrestricted irrigation of agricultural crops. Watering public parks, gardens, and other locations are additional uses. Effluent can also be used to clean, flush toilets and provide reliable water for natural wetlands or nature reserves. CWs can also be used as infiltration zones to replenish groundwater.

Since SF CW effluent already supports a basic food chain of Phyto- and zooplankton, it has more ecological value than effluent from conventional technologies. As a result, it has less of an impact on discharge in surface water. In the CWs some plant species have commercial value. Composting and mulching harvested plants, for instance, can produce soil additives; plant pulping produces fibres; and livestock feed is produced through silaging. Since the plants store carbon during their growth, they could be used to produce energy after harvesting, increasing the likelihood of obtaining carbon credits. Typically, the harvested plants are dried and dumped on the ground. Significant odors could be brought on by the drying process. Ground duckweed can be used as animal feed without being air-dried, and the hyacinths as vermicompost (Wallace and Knight, 2006)

The nutrients in the wastewater are transformed into biomass by algae or plants, which are then transported up the food chain to fish or even ducks, which can then be harvested for human consumption. Nutrient reuse is more prevalent in developing nations (Rousseau *et al.*, 2008)

Constructed wetlands can produce effluent that is suitable for reuse at a relatively low cost, provide opportunities for the recycling of nutrients, and accommodate wildlife when designed and maintained with care.

8.6 Basic Troubleshooting

By examining the effluent of the CW for both its visual appearance and its odour, one can get a sense of how well the filter bed is working:

A lack of oxygen in CW like any other WWTP is indicated by turbidity and/or greyish color (Metcalf and Eddy, 2004). The response ought to be::

- A uniform distribution of Vertical Flow Beds (VFBs) ought to be ensured. There may be insufficient time between the influent pumping events. As a result, the surface cannot dry out, which could result in clogging (Langergraber *et al.*, 2002).

In the case of Horizontal Flow Beds (HFBs), the effluent drainage needs to be reduced to make room for more oxygen to enter the filter bed (Kimwaga *et al.*, 2004).

- Anaerobic conditions in the filter bed are indicated by a foul-smelling odour similar to that of eggs. This is a very important circumstance. The filter bed should be rested, and the load placed on the filter bed should be decreased to increase the oxygen supply.
- Clear effluent with a slightly yellowish or brownish colour due to humic acids is typical in biological treatment systems, particularly CWs (Figure 8.2).

Figure 8.2: Effluent of the constructed wetland for visual appearance (Credit: Leah Marwa, 2023)

8.7 References

Aalbers, H. (1999). Resource Recovery from Faecal Sludge using Constructed Wetlands. (February).

Brix, H. (1994). Use of constructed wetlands in water pollution control: historical development, present status, and future perspectives [Uso de humedales construidos en el control de agua contaminada: Desarrollo histórico, estatus presente y futuras perspectivas]. *Water Science and Technology*, 30(8), 209–223.

Brix, Hans. (2003). Plants used in constructed wetlands and their functions. 1 St. International Seminar on the Use of Aquatic Macrophites for Wastewater Treatment in Constructed Wetlands, (December), 30.

David, G., Rana, M. S., Saxena, S., Sharma, S., Pant, D., and Prajapati, S. K. (2022). A review on design , operation , and maintenance of constructed wetlands for removal of nutrients and emerging contaminants. International Journal of Environmental Science and Technology, (August). *https://doi.org/10.1007/s13762-022-04442-y*

Department of Agriculture Natural Resources Conservation Service, U. (2016). Conservation Practice Standard Constructed Wetland (Code 656).

Ellis, J. B., Shutes, R. B. E., and Revitt, D. M. (2003). Guidance Manual for Constructed Wetlands. 112.

Harmel, R. D., King, K. W., Haggard, B. E., Wren, D. G., and Sheridan, J. M. (2006). Practical guidance for discharge and water quality data collection on small watersheds. Transactions of the ASABE, 49(4), 937-948.

Haule, K. S., Johnsen, F. H., and Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. *Journal of environmental management*, 66(1), 31-42.

Hicks, D. B., and Stober, Q. J. (2020). Monitoring of constructed wetlands for wastewater. In Constructed Wetlands for Wastewater Treatment (pp. 447-455). CRC Press.

Jones, W. W. (1995). Design Features of Constructed Wetlands for Nonpoint Source Treatment. *Environmental Protection*, (September), 1–6.

Kadlec, R.H., and Knight, R.L. (1996). Treatment wetlands. USA: Lewis, 1996. p. 950.

Kadlec, R. H., Knight, R. L., Vymazal, J., Brix, H., Cooper, P., and Haberl, R. (2000). Knight, Cooper, Brix, Vymazal, Haberl, Kadlec. Constructed Wetlands for Pollution Control.pdf (p. 151). p. 151. Retrieved from *http://biblioteca.cehum.org/handle/CEHUM2018/1649*

Kayombo, S. T. S. A., Mbwette, T. S. A., Katima, J. H. Y., Ladegaard, N., and Jørgensen, S. E. (2005). Waste stabilization ponds and constructed wetlands design manual. UNEP-IETC with the Danish International Development Agency (Danida), 1-59.

Kimwaga, R. J., Mashauri, D. A., Mbwette, T. S. A., Katima, J. H., and Jørgensen, S. E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. Physics and Chemistry of the Earth, Parts A/B/C, 29(15-18), 1243-1251.

Knight, R.L., Walton, W.E., O'Meara, G., Reisen, W.K and Wass, R.D. (2004). Strategies for effective mosquito control in constructed treatment wetlands. *Ecological Engineering*, 21, 211- 232.

Langergraber, G., Haberl, L., Laber, J., and Pressl, A. (2002). Evaluation of substrate clogging processes in vertical flow constructed wet- lands. In: Proceedings of the 8th International Conference on Wetland Systems forWater Pollution Control, 16–19 September, Arusha, Tanzania, pp. 214–228

Lee, C. G., Fletcher, T. D., and Sun, G. (2009). Nitrogen removal in constructed wetland systems. Engineering in Life Sciences, 9(1), 11–22. *https://doi.org/10.1002/elsc.200800049*

Liu, D., Ge, Y., Chang, J., Peng, C., Gu, B., Chan, G. Y. S., and Wu, X. (2009). Constructed wetlands in China: Recent developments and future challenges. *Frontiers in Ecology and the Environment*, 7(5), 261–268. *https://doi.org/10.1890/070110*

Lüthi, C., Panesar, A., Schütze, T., Norström, A., McConville, J., Parkinson, J., Saywell, D., Ingle, R. (2011). Sustainable Sanitation in Cities: A Framework for Action. Sustainable Sanitation Alliance (SuSanA), International Forum on Urbanism (IFoU), Papiroz Publishing House, Rijswijk, The Netherlands.

Mackenzie, S. M., and Mcilwraith C I. (2015). Produced by the Wildfowl and Wetlands Trust A guide for farmers and farm advisers in England Produced by the Wildfowl and Wetlands Trust Constructed Farm Wetlands Treating agricultural water pollution and enhancing biodiversity. Retrieved from www.wwt.org.uk/farmwetlands/

Metcalf L, and Eddy HP (2004). Wastewater engineering, treatment and reuse. McGraw-Hill, New York

Mghaoui, M. El. (2015). School of Science and Engineering Design of a Constructed Wetland for Trout Wastewater Treatment Egr 4402-Capstone Design.

Njau, K. N., Gastory, L., Eshton, B., Katima, J. H., Minja, R. J., Kimwaga, R., and Shaaban, M. (2011). Effect of diffusional mass transfer on the performance of horizontal subsurface flow constructed wetlands in tropical climate conditions. *Water Science and Technology*, 63(12), 3039-3045.

Reddy, K. R. (1997). Treatment Wetlands. *Soil Science*, 162(6), 454. https://doi.org/10.1097/00010694-199706000-00008

Rousseau, D. P. L., Lesage, E., Story, A., Vanrolleghem, P. A., and De Pauw, N. (2008). Constructed wetlands for water reclamation. *Desalination*, 218(1–3), 181–189. https://doi.org/10.1016/j.desal.2006.09.034

Shutes, R. B. E. (2001). Artificial wetlands and water quality improvement. 26, 441–447.

Shutes, R. B. E., Revitt, D. M., Lagerberg, I. M., and Barraud, V. C. E. (1999). The design of vegetative constructed wetlands for the treatment of highway runoff. 189–197.

Strande, L., Ronteltap, M., and Brdjanovic, D. (2014). Faecal sludge management: Systems approach for implementation and operation. In Faecal Sludge Management: Systems Approach for Implementation and Operation. Retrieved from http://www.eawag.ch/forschung/sandec/publikationen/ewm/dl/fsm_book.pdf

Sundaravadivel, M., and Vigneswaran, S. (2001). Constructed wetlands for wastewater treatment. *Critical Reviews in Environmental Science and Technology*, 31(4), 351–409. https://doi.org/10.1080/20016491089253

Tanaka, N., Ng, W. J., and Jinadasa, K. B. S. N. (2011). Wetlands for Tropical Applications. In Wetlands for Tropical Applications. https://doi.org/10.1142/p599

Thullen, J., Sartoris, J., and Walton, W.E. (2002). Effects of vegetation management in constructed wetland treatment cells on water quality and mosquito production. Ecological Engineering 18(4), 441-457.

UN-HABITAT. (2008). Constructed Wetlands Manual.United Nations Human Settlements Programme for Asian Cities. Retrieved from www.unhabitat.org

URT. (2009). The United Republic of Tanzania. *Development*, 7(5,371,780,231.09), 2,274,923,575.00-29.08.

USEPA (US Environmental Protection Agency). (2002). Onsite wastewater treatment systems manual. E.P.a./625/R-00/008. Office of Water and Office of Research and Development, Washington, DC

Vergeles, Y., Vystavna, Y., Ishchenko, A., Rybalka, I., Marchand, L., and Stolberg, F. (2015). Assessment of treatment efficiency of constructed wetlands in East Ukraine. Ecological Engineering, 83, 159–168. https://doi.org/10.1016/j.ecoleng.2015.06.020

Vymazal, J. (1998). Removal mechanisms and types of constructed wetlands. Constructed wetlands for wastewater treatment in Europe, 17-66.

Vymazal, Jan, H. B. (2006). Removal mechanisms and types of constructed wetlands. (January).

Vymazal, J. (2002). The use of sub-surface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. *Ecological Engineering*, 18(5), 633–646. https://doi.org/10.1016/S0925-8574(02)00025-3

Vymazal, J. A. N. (2011). Constructed Wetlands for Wastewater Treatment : Five Decades of Experience †. 45(1), 61–69.

Wallace, S., and Knight, R. (2006). Small-Scale Constructed Wetland Treatment Systems: Feasibility, Design Criteria, and O&M Requirements. In Feasibility, Design Criteria, and O&M Requirements.

Williams, C.R., Jones, R.D., and Wright, S.A. (1996). Mosquito control in constructed wetlands; Proceedings of WEFTEC '96, 69th Annual Conference and Exposition in Dallas, Texas; Water Environment Federation: Alexandria, VA, United States, pp. 333-344.

Chapter 9: Economics and Financing Options of Constructed Wetlands

By Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

The experience gathered in working with the CW technology demonstrates that despite the technical capability of this system as a nature-based solution for wastewater and faecal sludge management in the WIO region, the successful implementation and adaptation of CW technology in the region is still hindered by lack of understanding of its economics among many more other factors. There is a lack of understanding of the economics (costs and benefits) associated with the use of CW. Knowledge of financing options for the implementation of the CW is still limited. This Chapter gives insights on economics and financing mechanisms for the CW technology. Included in this chapter are understanding of the benefits and costs both financial and non-financial associated with this technology. Various costs and benefits elements together with analysis tools like cost benefit analysis have been briefly discussed. The Chapter ends up with examples of the cost benefit analysis that may warrant the adaptation and uptake of the CW technology.

9.1 Introduction

Many of the cost components incurred in a CW project are similar to those in many of the civil engineering projects (Kimwaga *et al.*, 2012). As with many civil engineering projects, the unit cost of the CW installation decreases with the increasing treatment capacity of the technology. For instance, Fig. 9.1 illustrates the scale dependency of the unit cost of CW construction (Kadlec and Wallace, 2008).

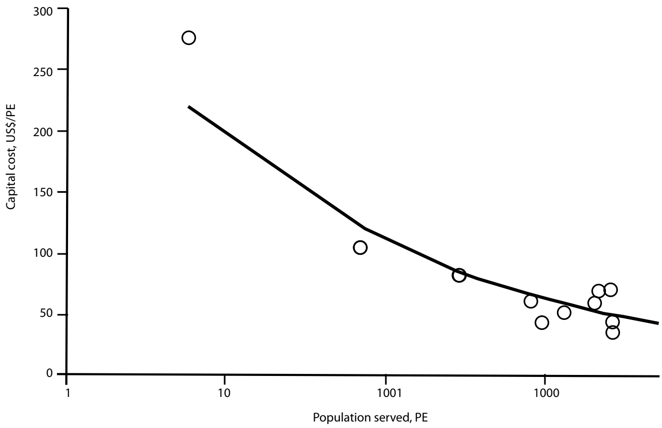


Figure 9.1: Illustration of the scale dependency of the unit cost of wetland construction (Kadlec and Wallace, 2008)

The scale cost relationship can be expected to hold true in temperate and tropical applications. In addition to the scale dependency, the cost of each constructed wetland project will vary depending on several other factors such as land value, location relative to the source of the wastewater, treatment goals, and the type of wetlands (Kadlec and Wallace, 2008)

9.2 Various Cost Categories and Elements of CWs

There are two broad categories of costs under considerations for the CW: namely capital as well as operation and maintenance costs. The description of each category is presented in the following sections.

9.2.1 Capital investment cost (Capex)

Capital costs (Capex) are those expenditures that are required to put up build a constructed wetland system and associated supporting facilities (Kimwaga *et al.*, 2012). They are exclusive of the costs required to operate or maintain the constructed wetlands throughout their lifetime. Capital investment costs consist primarily of expenditures initially incurred to install the constructed wetland including all labor, equipment, and material costs, contractor mark-ups, such as overhead and profit, associated with activities such as mobilization/demobilization, monitoring, site work, installation of extraction, containment, or treatment systems and disposal (Kadlec and Wallace, 2008; Kimwaga *et al.*, 2012). The expenditures for professional/technical services that are necessary to support the construction of constructed wetland systems are often included in the construction cost. The major construction cost elements are listed below:

- Project planning and design costs.
- Excavation and earthwork cost.
- Liner cost.
- Substrate cost.
- Construction material costs; and
- Plants and planting costs.

However, the costs of construction activities are typically estimated on an element-by-element basis. In American experience, contractor markups such as overheads and profit are generally included in these cost elements, rather than listed separately in the construction cost summary (Kadlec and Wallace, 2008). Contingency is typically added as a percentage of the total cost of construction activities (Kadlec and Wallace, 2008). Professional/technical services are typically estimated as a percentage of the total cost of construction activities plus contingency (Kadlec and Wallace, 2008). Depending on the magnitude and size of the CW, construction cost is mostly undertaken either by funds for the small units or by class VII contractors (Njau *et al.*, 2010, Kimwaga *et al.*, 2012).

9.2.1.1 Project Planning and Design Costs

Project planning and design cost vary with the size of the constructed wetland system. If a constructed wetland system is a component of an integrated wastewater treatment system with advanced primary treatment steps, the design cost of the constructed wetland system may decrease (Kadlec and Wallace, 2008). Small CW built manually or by using simple construction tools can be designed with basic technical principles by minimally spending on planning and design (Kadlec and Wallace, 2008). Planning costs for a larger CW project that demands a fleet of heavy earth moving machinery and additional site infrastructure are usually expressed as a percentage of the overall construction cost (Kadlec and Wallace, 2008). As a rule, of the thumb, 15% of the direct cost is allocated for the project planning and design (Kadlec and Wallace, 2008; Kimwaga *et al.*, 2012).

9.2.1.2 Excavation and Earthwork Cost

Although a CW can be built at any site, construction costs can be exceptionally and exceedingly high if extensive earthworks or additional structures such as flood protection dams or slope protection measures are required (Kadlec and Wallace, 2008). The cost of excavation and earthwork typically includes grading the site to produce level basins that are enclosed by earthen berms, and in the case of FWS wetlands, reserving and replacing topsoil in the bed to serve as the vegetation growth medium (Kimwaga *et al.*, 2012). For small CW systems, multipurpose small earthmoving machinery (*i.e.*, backhoes) is commonly used (Kimwaga *et al.*, 2012). The cost of earthwork includes the cost of earth moving, equipment, and the source of earth supply (on-site or imported), which is a volumetric cost (per m^3). Table 9.1 compares the cost of earthwork incurred during the construction of wetlands.

Table 9.1: The cost of earthwork for constructed wetland systems (Kadlec and Wallace, 2008)

Year	Location	Area (m^2)	Earthwork Volume (m^3)	Cost (US$/ m^3)	Source
2003	Colombia	21,770	15,634	2.2	Arias and Brown, 2009
2004	Sri Lanka	110	98	4.2	Jinadasa, 2006
2008	Sri Lanka	12,000	15,083	8.9 ± 2.7	Unpublished data*

*Estimated cost

9.2.1.3 Liner Cost

A liner is principally applied to restrict the possible contamination of groundwater and also to prevent groundwater from infiltrating into the wetland. Indeed, a proper liner should act as a barrier to gas migration. A proper liner installed in a wetland restricts the spreading of the below-ground vegetative propagule of wetland plants to the outside. While in the developed world, the liner is of synthetic materials, in Tanzania, liner materials are mostly made of concrete, blocks and ferro cement and in few cases thoroughly and well compacted clay materials consequently saving the hidden maintenance cost (Kimwaga *et al*., 2002; Kimwaga *et al*., 2003; Senzia *et al*, 2003). Usually, the liner system covers the whole water contact area of the wetland cell. Although several kinds of liner systems are available, the selection of a liner for a particular wetland should be based on site-specific characteristics and regulatory requirements (Vymazal *et al*, 1998; Mashauri and Kayombo, 2002; Vymazal and Lenka, 2008). Where on-site soils or clay provide an adequate seal, the compaction of these materials may be sufficient to line the wetland.

On-site soils can be used if they can be compacted to achieve a low permeability of $=10^{-7}$ cm/sec (Cooper 1993; Vymazal *et al*., 1998). Consequently, the laboratory analysis of on-site soils for potential use in the liner would add a small cost at the preliminary site investigation stage. However, if the existing low-permeability soil layer is thinner than 30 cm, alternative liner material should be introduced to fulfil the design goals and regulatory requirements (Kadlec and Wallace, 2008). In addition, for sites underlain by highly permeable sandy soils or gravels, fractured bedrock should be sealed by some other lining method.

The second option often considered is a liner constructed of compacted clay or other soils with appropriate amendments (Vymazal *et al.*, 1998). This type of liner may be constructed with soils from the excavation itself for soil imported from nearby sources. If the soils require amendments such as bentonite or soil dispersants, the unit cost of the compacted liner will be significantly higher than for a liner that only requires compaction to achieve a satisfactorily low permeability.

The third option is to line the wetland cell with an artificial liner material. Although small CW are often lined either by reinforced concrete, blocks or ferro-cement (Senzia *et al.*, 2002, Kimwaga *et al.*, 2002, 2004), the use of reinforced concrete structures for large CW or pond systems is not desirably recommended due to their associated high construction cost. (Hayes *et al.*, 2000) Alternatively, the use of flexible membrane liners (FML) and bentonite-enhanced geosynthetic liners would be effective (Vymazal and Lenka, 2008, Kadlec and Wallace, 2008). In addition to liner material cost, the cost occurred in synthetic liner application often requires additional works (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). Despite of their high cost, concrete structures are still widely and preferred liner materials because of their robustness and availability unlike the synthetic liners.

If the site soils contain angular stones, sand bedding or geotextile, cushions should be placed under the liner to prevent punctures (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). The liner should be covered with 8–15 cm of soil (or fine sand) to prevent the roots of the vegetation from penetrating the liner (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). The percentage cost for the synthetic liner decreases with the increase of the size of the wetland (cell) since the area of the perimeter run-out material in the liner and works on the panel seaming decreases as a percentage of the total area (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008).

The cost of the liner system of a particular wetland project largely depends on site-specific conditions and the availability of materials in the regional market (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008; Kimwaga *et al.*, 2012). Therefore, project planners should calculate the total cost including the maintenance and potential risk of CW failure (Kadlec and Wallace, 2008). A useful tool in comparing design alternatives is to evaluate unit costs (Kadlec and Wallace, 2008). The benefits of alternatives may then be compared against unit costs to aid in selecting a design alternative. Table 9.2 illustrates the cost comparison for different thicknesses of well compacted clay liners, synthetic liners, and reinforced concrete used in constructed wetland construction in tropical developing countries.

Table 9.2: Cost comparisons of design options for liner construction in medium-large scale wetlands (Kadlec and Wallace, 2008)

Year	Location	Liner type	Area (m^2)	Unit cost (US$/$m^2$)	Source
2003	Colombia	Geomembrane	24,670	1.2	Arias and Brown, 2009
2004	Sri Lanka	Cement brick wall	30	650	Jinadasa, 2006
2008	Sri Lanka	HDPE 60-mil FML	40,000	4.6 ± 2.1	Unpublished data*
2005	USA	HDPE 30-mil FML + Geotextile	297–6,141	3.6 ± 0.8 to 19.0 ± 3.2	Wallace and Knight, 2006**

*Estimated cost.

**Minimum and maximum data from eight wetland systems.

The unit costs of FML installed under temperate climates in industrialized countries are also shown in Table 9.2 for comparison purposes. The use of alternative liner materials in waste/wastewater containment facilities has grown in many rural developing countries due to high cost and the need for skilled labor for FML installations (Kadlec and Wallace, 2008). For instance, Gunarathna *et al.* (2007) introduced a low-cost liner made from pieces of waste polyethylene films and clayey soils (soils with >20% clay content). The liner composite was constructed by sandwiching a layer of polyethylene pieces between 5-cm thick clay layers, to a thickness of 15 cm, by compacting the composite manually with a turf roller. The long-term performance of the liner in a 35-m^2 landfill cell demonstrated a good resistance to flow (saturated hydraulic conductivity ~1.0 10^{-7} cm/sec) (Kadlec and Wallace, 2008). The main advantages of the liner are its low cost (~US$0.8/$m^2$) and significantly low conductivity compared to the same thickness of clay liner (Kadlec and Wallace, 2008).

9.2.1.4 Substrate Cost

The substrates in an FWS wetland are the topsoil placed on top of the liner that serves as the growth medium for the emergent vegetation in the system (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). The on-site soils can be used as the substrate media for the FWS wetlands if on-site soils exhibit the required specifications (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008).

In such cases, the on-site substrates may be used to remove debris, rocks and existing seed banks (where the on-site vegetations is not desirable to the wetland system), and may be directly filled into wetland cells (Vymazal and Lenka, 2008; Kadlec and Wallace, 2008). This work can be included as a part of the earth work cost or else as a separate job. In the case where on-site soil is undesirable for use in FWS wetlands, an additional cost account for purchasing, transporting, and handling occurs. The unit cost of these materials depends on the quality, volume needed and distance from the source to the construction site. A fleet of earth moving machineries (or off-terrain vehicles) may be required where the cell size is too large for manual application.

Instead of normal surface soils, SSF wetlands require specific types of bed substrates. The SSF bed substrate is the most expensive item in the construction of a SSF wetland and may vary depending on site-specific conditions. The construction experience with CW in the WIO region (taking Tanzania as an example) shows that 75% of the total construction cost comes from substrate (Balkema *et al.*, 2010). Table 9.3 illustrates the cost of bed substrates used for different SSF wetlands in different geographical regions. The unit costs of substrate material available in the USA are shown in Table 9.3 for comparison purposes. No such information has been gathered in the WIO region with regard to unit cost of substrate materials. Thus, they can be cautiously adapted for the WIO region.

Table 9.3: Unit cost spent on substrate materials of SSF wetlands (Kadlec and Wallace, 2008)

Year	Location	Substrate type	Area (m^2)	Unit cost (US$/$m^3$)	% of total	Source
2003	Colombia	3/4" Gravel	24,670	19.3	32.5	Arias and Brown, 2009
2004	Sri Lanka	3/4" Aggregates	100	13.4	10.1	Jinadasa, 2006
2004	Costa Rica	20-mm Rock	30	–20.0	–50.0	Dallas *et al.*, 2004
2005	USA	9–25-mm Rock	297–6,141	–15.3 to 67.6	n/a	Wallace and Knight, 2006*

* *Minimum and maximum data from eight wetland systems (Kadlec and Wallace, 2008).*

However, these figures should be used only with care and as guidance since the material used, installation, conditions, and site conditions are not comparable. Furthermore, it has been established that the major mechanisms for removing phosphorus from wastewater by constructed wetlands are chemical adsorption and sedimentation by substrates, rather than plant uptake and microbe removal (Drizo *et al.*, 1999; Westholm, 2006). Thus, the selection and assembly of substrates are very important for wetland construction especially when planning for long-term efficient phosphorus removal.

9.2.1.5 Construction Material Costs

Construction materials which are needed for CW infrastructure and facilities include cement, sand, reinforcement bars, formwork and gravel (Senzia *et al*., 2003, Kimwaga *et al*., 2004). The cost for these items should be considered and factored in, while estimating the wetland cost (Balkema *et al*., 2010; Kimwaga *et al*., 2012). Particular attention should be paid during the planning phase of the CW to establish the source of the construction materials (Kimwaga *et al*., 2012). The construction costs vary from one site to the other depending on the availability and demand (Balkema *et al*., 2010). It is important to recognize that the market price determines the construction material cost.

9.2.1.6 Plants and planting costs

There are many variables in calculating the total costs associated with the vegetation establishment phase of a wetland construction project.

However, the following generalizations can be made (Kadlec and Wallace, 2008):

- large projects have a lower unit cost (cost/plant or cost/m^2) than small ones because of discounted materials costs and reduced mobilization costs.
- projects having multiple goals (*e.g.* recreation and planting of commercial plant species) are generally costlier.
- the cost of mechanized planting is typically much less than planting by hand particularly on large sites.

The costs of plant materials are highly variable; however, the following generalizations can be made (Kadlec and Wallace, 2008):

- transplants acquired from the wild are cheap.
- direct seeding is more expensive than transplanting from nurseries.
- species that are difficult to propagate are often expensive..

Even within the regional market, the costs of plant materials can be considerably different according to the type and size of the propagule.

However, most of the costs associated with planting are linked to labour, as additional costs are related to bed preparation, soil amendments, and planting equipment if required. A rough estimate of the labour requirement for planting can be established (Huffman, 1978; Arias and Brown, 2009):

- 100–300 man-hours/ha for transplants and sprigs,
- 100–150 man-hours/ha for rhizomes, tubers, and rootstocks, and
- 10–40 man-hours/ha for seeds

9.2.2 Operation and Maintenance Cost

Although, the operation and maintenance of constructed wetland systems designed for wastewater treatment are relatively simple and require minimal time, constructed wetlands require regular maintenance to ensure that they operate optimally and efficiently. Since the wetland system itself does not require any mechanical equipment in the treatment process, most of the operation activities are limited to hydraulic control processes such as inflow and effluent outflow control, and water level control. Therefore, many aspects of the operation and maintenance of constructed wetlands are similar to those of the wastewater stabilization lagoon (stabilization ponds). However, special emphasis should be given to the operation and maintenance of influent pretreatment systems since most of the regular wetland failures are linked to the appropriate management of influent wastewaters (USEPA, 1993). The most appropriate method to ensure an economical operation and maintenance of the CW system is to formulate an operation and maintenance plan during the design of the constructed wetland system. The plan can be updated to reflect specific system characteristics learned during actual operation.

As discussed earlier in this chapter, most of the constructed wetland projects implemented in tropical developing countries are pilot-scale projects designed and maintained by institutions (*e.g.* universities) and non-government organizations (NGOs). Thus, the operation and maintenance of those facilities are carried out as part of a research/integrated project, and the cost of human resources (labour), which are the main cost constituent in the O and M of wetland, have not been separated (Senzia *et al.*, 2003; Haule *et al.* 2002). The decision to employ a permanent operator (caretaker) for a particular CW depends on the scale of the facility. Although individual cost components for operation and maintenance are difficult to illustrate, the time required to carry out the various operation and maintenance tasks for the entire wetland system can be quantified. Table 9.4 summarizes the itemized operation and maintenance requirements of a pilot plant in Masaya, Nicaragua, that serves about 1,000 people (Gauss, 2008).

Table 9.4: Frequency and duration of labour employed for routine operation and maintenance activities of an SSF constructed wetland (350 m² × 4 beds) in Masaya, Nicaragua (Gauss, 2008)

Activities	Materials necessary	Frequency	Time required
Clean filter/screen at inlet and dispose the solids	Shovel and wheelbarrow	Daily	10 min
Measure influent flow	Flow meter	Daily	5 min
Control water level within constructed wetland	Flexible hose/adjustable pipe	Daily	5 min
Clean accumulated surface scum and dispose	Surface skimmer and wheelbarrow	Every three days	15 min
Extract sludge from the bottom	Shovel and wheelbarrow	Depending on the accumulation of sludge	30–40 min
Plant harvesting	Machete, rake, and wheelbarrow	According to growth cycle	50 m^2 of area/person/day
Excavate and replace the bed media substrate of the distribution zone	Pick, shovel, and wheelbarrow; use new media of same granulometry	When superficial water flow is noted	1.5–2 m^3/person/day

Performance monitoring of the CW is an equally important activity in O &M. Monitoring should be instituted for all entities charged with taking care of the CW. Monitoring program should designed and associated costs established. The monitoring program entails determining the wastewater parameters to be monitored and their monitoring frequency. Under normal circumstances, weekly monitoring for the basic parameters such as temperature, pH, coliforms and dissolved oxygen is recommended. Chemical parameters including nitrogen, phosphorus and other chemical parameters should be monitored every fortnight.

9.3 Benefit Evaluation

Constructed wetlands perform in various modes that provide beneficial services to society (Cooper *et al*., 1996; Vymazal *et al*., 1998). According to the Wetland Reserve Program report for natural wetlands (WRP, 1994) Wetland functions can be grouped into the four broad categories of (i) improvement of hydrology/water quality, (ii) landscape enhancement, (iii) fish and wildlife habitat, (iv) recreational and educational activities (WRP, 1994). The wetland function related to hydrology and water quality includes the supply of treated water suitable to be reused in several applications, as well as an improvement increase of the surface quality and recharge of aquifers.

The development of the habitat for fish and wildlife may provide benefits related to the production of food and fiber through harvesting, protection of fisheries, aquaculture as well as educational and cultural activities (Nunes *et al*., 2001). According to the land context in which they are placed, free water surface constructed wetlands can also significantly enhance landscape aesthetics by introducing a pleasant natural element into the landscape. Closely related to the habitat and landscape functions is the provision of opportunities for recreationists.

Economic goods and services provided by CW through the four main functions are presented in Table 9.5 below. These are goods and services to which a market price is attached in relevant markets goods and services.

Table 9.5: Wetland functions good and services and valuation method (WRP, 1994)

		Wetland function	Good or service provided	Valuation Method
Market benefits		Hydrology / Water Quality	Supply of reusable water	market price
		Fish and Wildlife Habitat	Food and fiber production (harvesting) Protection of fisheries / Aquaculture	market price market price
Non-market benefits		Hydrology / Water Quality	Increase of surface water quality	contingent valuation, avoided cost analysis
		Hydrology / Water Quality	Groundwater recharge	contingent valuation, avoided cost analysis
	Use Values	Fish and Wildlife Habitat	Educational/cultural activities	contingent valuation, travel cost
		Recreation and aesthetics	Recreational activities	contingent valuation, travel cost
	Non-use values	Landscape enhancement	Land development	stated preference methods, hedonic method
		Fish and Wildlife Habitat	Existence and bequest value of biodiversity and biological resources	contingent valuation

The former includes the supply of reusable water, food and fibre production, and the protection of fisheries and aquaculture. The latter are increase of surface- and groundwater quality, aquifer recharge, educational, cultural, and recreational activities, land development and existence and bequest of biodiversity. Lambert, (2003) points out that, "market failures related to ecosystems include the fact that many wetlands (1) provide services that are public goods, (2) many wetlands' services are affected by externalities and (3) property rights related to ecosystems and their services are often not clearly defined".

9.3.1 Economic Benefit

This section discusses the possibility of evaluating in monetary terms, each of the benefits identified in Table 9.5. The focus is on two of the basic steps in Cost Benefit Analysis (CBA) proposed by Boardman *et al.*, (1996), namely;

- identifying the functions of constructed wetlands that lead to welfare impacts and selecting appropriate measurement indicators (measurement units) and
- assessing the applicability of economic valuation methods to the monetization of the impacts.

9.3.1.1 Hydrology/Water Quality

Supply of reusable water

Constructed wetlands are already in use in many wastewaters' reclamation and reuse schemes worldwide (Bixio *et al.*, 2004). The good quality of the polished effluent makes it suitable for various forms of reuse including agriculture, industry and in general medium to low contact applications.

Measurement indicators

The most obvious indicator of the benefits provided is the quantity of wastewater reused. The residual concentration of polluting substances (like nutrients, toxic elements, or suspended solids) can however highly affect the benefit of reusing the wastewater. When the polished effluent is used in agriculture, a high concentration of nutrients can induce the positive effect of reducing (or eliminating) the need to use fertilizers. These cost savings need to be included in the economic valuation.

Hussain and Singh, (2001) pointed out that in some cases the nutrients might be supplied in excess to crop requirements, and thus nutrient content value approach results may overestimate the actual economic worth of nutrients in the wastewater. When the reuse application involves contact with human beings, considerations about the risk to human health induced by the possible presence of toxic elements in the wastewater cannot be avoided in the valuation. Finally, for applications in industrial processes, residual concentration of suspended solids may lead to problems with sedimentation and clogging and thus to a reduction of the benefits.

Valuation considerations

Even when a price of water exists and it is assumed to be an appropriate indicator on which to base the valuation, difficulties in evaluating the benefits arise from the fact that water price is often not the result of market transactions, but it is kept to a sub-optimal level by political, legal or historical factors. In other words, the price of water may not reflect the true value of water to the consumer but, typically, it underestimates it. When this is the case, Hussain and Singh, (2001) suggest deriving the shadow price for water using hedonic price analysis or assuming the cost of energy required to use an alternative technology to deliver the same quantity of water.

9.3.1.2 Increase of Surface Water Quality

Constructed wetlands provide a tool to restore the "dead" treated wastewater and transform it into usable natural surface water. This aspect of the treatment with constructed wetlands has been extensively studied in the "Water Harmonica" project in the Netherlands (Kampf and Claassen, 2005). The key point of the "Water harmonica" concept is that free water surface constructed wetlands not only provide a significant reduction of key contaminants (like chemical oxygen demand, pathogens, nutrients etc.) but their effluent is much more like a natural healthy surface water than the effluent of a conventional mechanical treatment plant. A more natural daily trend in the dissolved oxygen concentration is observed and suspended solids are of a different kind, biomass instead of activated sludge flocks.

Measurement indicators

The key point of the analysis in this case is the identification of appropriate water quality standards to be used as indicators of the water quality status of the receiving surface water body. The already cited Wetland Reserve Program (1994a) reports a range of variables that have been used in 17 different methods to evaluate natural wetlands functions. The variables linked to the downstream water quality status include chemical parameters like dissolved oxygen, heavy metals nutrients, bacteria and sediments concentrations, conductivity, alkalinity, and temperature in the effluent.

Valuation considerations

Moons, (2003) reported a series of studies concerning the economic valuation of several water quality parameters. Nitrates, sulphates, and COD are valued. Most of the studies use a contingent valuation approach to assess the value of a certain improvement in the water quality standard (*i.e.* reduction of mean nitrate concentration) or of the safeguard of existing water quality. The results refer to different water uses (drinking water supply, ground, and surface water quality). In general, the results of the studies show a high variability according to the level of information provided to the respondents and to the probability of the occurrence of the prospected pollution event. Some authors (Breaux *et al.*, 1995) suggest an alternative valuation technique based on avoided cost analysis to evaluate the costs related to the water quality improvement occurring in the wetland compared the costs of traditional treatment.

9.3.1.3 Groundwater Recharge

The polishing step of treatment provided by constructed wetlands can make the treated wastewater suitable for recharging the aquifers in areas of over-exploitation of groundwater resources and thus provide a beneficial effect in the water resources management (Mato, 2002). It must be observed that the groundwater recharge does not occur in the location of the CW itself since the permeability of the wetland bottom is typically very low to avoid infiltration of polluted wastewater into the soil (Mwegoha *et al.*, 2002).

Valuation methods

Engineering costs for providing groundwater recharge with alternative technologies are generally available and can be used to value the benefits of groundwater recharge by using constructed wetlands. The benefit from the constructed wetland will equal the difference between the costs of supplying the water for the recharge utilising the constructed wetland and with the alternative source.

9.3.1.4 Fish and Wildlife Habitat.

Protection of fisheries (Aquaculture) along with Food and fibre production (harvesting)

Application of wastewater treated in polishing constructed wetlands for creating conditions suitable to aquaculture activities can be found in several installations worldwide (see for instance the Arcata Marsh and Wildlife Sanctuary, California). Research conducted on the island of Texel (Netherlands) by Kampf *et al.* (1999) shows that toxicity effects due to biomagnification of heavy metals like copper and zinc in the food chain from zooplankton to fishes are limited under normal loading conditions. The possibility of linking constructed wetlands to aquaculture schemes and using the material harvested for various applications in developing countries has been discussed by Yana (2004).

Valuation methods

Economic valuation in this case is determined by market conditions. The value of the wetland for production is given by the difference between net returns from production from wetland harvest and net returns from production from the next best alternative (WRP, 1994b).

9.3.1.5 Existence and Bequest of Biodiversity and Biological Resources

The development of a complex ecosystem rich in biodiversity within constructed wetlands is reported in many studies worldwide. Plant and animal communities can carry a significant economic value for their mere existence and/or to ensure that future generations might enjoy this biodiversity. It must be noted; however, that plant and animal communities in a constructed wetland have generally a reduced habitat value if compared to natural wetlands because of the high load of nutrients carried by the influent wastewater (Tanner *et al.*, 2002) and the presence of toxic substances.

Valuation considerations

The economic valuation of biodiversity and biological resources has been included in large number of studies. In a survey and evaluation of empirical studies, Nunes *et al.*, (2001) reported that contingent valuation is by far the most used method since it is the only method able to estimate non-use values of biodiversity like existence, option and bequest. Contingent valuation is one of the most controversial non-market valuation methods. One of the most important critics is that there cannot be the certainty that people would pay the amount stated. Nevertheless, the importance of contingent valuation is given by the fact that it is one of the few methods that allow estimating nonuser values.

9.3.1.6 Recreational and Educational Activities

Recreational activities

Recreational activities that may potentially take place in a CW include both consumptive and non-consumptive uses. In the former mainly hunting is included, while the latter refers to bird and wildlife watching (Haule *et al.*, 2002). Bird watching is probably the most important recreational activity related to constructed wetlands. Birds often use wetlands as nesting places or as feeding and resting place during the migration. As a result, constructed wetlands are often considered optimal spots for bird watching. This recreational function of constructed wetlands is closely linked to the wildlife habitat function. Recreational and cultural activities can assume a very relevant economic value.

Valuation considerations

The most used valuation method to assess the economic value of recreational activities is the travel cost method. This method has been recently applied to evaluate the recreational benefits produced by the free water surface constructed wetlands in Empuriabrava (Spain). In this installation, the wetland effluent feeds the otherwise drying out Laguna del Cortalet in the Empordà Park (Seguì, 2004). It must be observed that the use of this method involves the risk of overestimating the value of the recreational service since visiting the site may not be the only reason for travelling to the wetland area. The existence of substitutes for the recreational activities must be considered in the analysis.

Educational and cultural activities

Constructed wetlands may provide opportunities for environmental education and for raising awareness among citizens. Information centres are often created to welcome visitors and explain the scientific background of the wastewater treatment processes and the value of wetland ecosystem. An example of educational activities successfully taking place in a constructed wetland is given by the Waste Stabilisation Ponds (WSP) and Constructed Wetlands (CW) Research Group of the University of Dar es Salaam (UDSM), in which information about wastewater treatment functions of the wetlands and publications are handed out to the visitors.

Valuation considerations

Wetland Reserve Report, (1994a) points out that economic valuation is seldom attempted for these values, since "it is often difficult to separate educational/cultural services from the provision of other goods and services". Accessibility of the site and the existence of substitutes in the region are key elements that determine the educational value of a wetland.

9.3.2 Environmental Benefit

Constructed wetlands can carry high landscape values when they are integrated with recreational areas in water parks. These landscape values are higher in urban development sites than in rural areas since in urban areas free water surface constructed wetlands and water parks introduce a valuable natural element. To assess this value the existence of substitutes in the region under consideration is a key aspect that must be included in the analysis. The higher price of land in urban areas is a limitation to the implementation of such schemes.

Measurement indicators

According to the Wetland Reserve Program report (1994a), information needs to be considered for the evaluation of the size and configuration of the wetland along with the proximity to roads and other infrastructures. Regarding the configuration of the CW, open water and marshy wetlands are generally preferred from an aesthetic viewpoint to thickly vegetated swamps where visual access is impaired Wetland Reserve Program report (1994a). Similarly, irregular edges and mosaic patterns of vegetation are generally considered of a higher visual value Wetland Reserve Program report (1994a).

9.3.3 Social Benefit

Since fewer people get sick and fewer children die of diarrheal diseases the benefits of the society are much larger. This should be considered on national and international level. To strengthen the arguments for the discussions on policy making and setting soft loans and subsidies, it is important to include a societal cost benefit analysis. In the Ruaha School project in Iringa Tanzania, the students were the target population for the analysis. This is a secondary school (children aged between 12 and 18), there are no children under the age of five who are most likely to die of diarrheal diseases, and therefore no mortality rate needs to be calculated for this CBA.

- The total population at the Ruaha Secondary School is 750. The table summarizes the estimated health impacts caused by the constructed wetland installation and operation. The CW technology intervention is expected to avoid between 9 and 28 diarrheal cases as low and high respectively (Hutton *et al*., (2004). Assuming an average of three days off school per case of diarrhoea there are 27 to 84 days of school attendance gained.

These health benefits need to be translated into economic benefits as follow (Balkema *et al*., 2010):

- Patient expenses avoided due to avoided illness: The avoided costs of treatment of ill children involve the cost of medicine (ORS). The average cost of diarrhoea treatment per child in sub-Saharan Africa is Tshs. 7,200 (US$5.50).
- Value of child days gained by those with avoided illness. When a child is ill (assumed to be 3 days on average) at least one of the parents must stay at home to take care of the child; assuming that this parent is usually working, this would lead to income losses. The average daily wage of one parent is set to Tsh.4,000 (US$ 3.2) per day.
- The societal Accounting Rate of Interest (ARI) can be calculated based on the long-term interest rate on Tanzanian government bonds, which is approximately 4% ex-inflation.
- For the socio-economic CBA, the actual costs for the design of the constructed wetland which the UDSM provided for free are also needed. These costs are estimated to be 10% of the wetland construction costs.
- The shadow wage rate is approximately zero in Tanzania.

If taking these societal benefits in account in the (CBA) makes the project even more attractive to invest in, the Net Present Value (NPV) calculated is as high as 11,100,000 TSh. (8,880 US$) and the real Internal Rate of Return (IRR) is 493% (compare with the real ARI of 4%) and the payback period is as short as one year. Even if the avoided costs of the frequent emptying of the septic tank before constructing the wetland is set to zero, the NPV calculated remains positive *i.e.* 2,200,000 TSh. (1,760 US$) and the IRR remains high (106%) and the investment can still be paid back within one year. From this it is safe to conclude that investments in water and sanitation facilities should be facilitated by governments and international institutions as the cost of not financing these projects is high not only in terms of suffering but even in terms of money.

It can be concluded that not investing in water and sanitation in developing countries costs money. Hutton *et al.*, (2004) report that the total annual economic benefits of water and sanitation interventions in the East African region are estimated to be 52 US$ (2000) per person when realizing access to improved water supply and sanitation for all, and 72 US$ (2000) with addition of minimal water disinfected at point of use (Hutton *et al.*, 2004). Benefit Cost ratios for the East Africa Region are estimated to be 12 when realizing access to improved water supply and sanitation for all, and 15 for addition of minimal water disinfection at the point of use (Hutton *et al.*, 2004). These Cost Benefit ratios drop to 2 and 3 when high costs and low benefits are assumed (Hutton *et al.*, 2004). So even for the lowest estimates', benefits are twice as high as the costs Hutton *et al.*, 2004). Investments in water and sanitation in developing countries are not only needed from humanitarian point of view but are also economically viable and it makes the business case Hutton *et al.*, (2004).

9.4 Cost Benefit Analysis

As discussed in previous sections the constructed wetlands are a good solution for hygienic and sustainable sanitation for schools in Tanzania. However, finding investment capital is still a major barrier in the dissemination of the constructed wetland technology in developing countries, such as Tanzania. To strengthen the argument pro-dissemination and to select potentially attractive implementation opportunities, a cost-benefit analysis was employed. This analysis is split into two parts; the first one elaborating on the financial attractiveness from an investor's point of view; and the second one elaborating on the costs and benefits from a societal point of view. It has however to be noted that not all the costs and benefits categories identified in sections 4 and 5 have been included in this CBA. It was not possible to have all categories because of a lack of data information availability. But again, the CBA results presented below only give an indication of CB of CWs.

9.5 Financial Cost Benefit Analysis

Key Concepts in Financial Cost Benefit Analysis

Before deep diving into CBA, it is imperative to understand some of the key concepts that are used. This section explains some of these concepts (Kimwaga *et al.*, 2012).

Annuitization is the process of converting an investment into a series of periodic payments.

Assets include all forms of constructed facilities and infrastructure.

Capital expenditure (CAPEX) is the money required at the beginning of a project to finance or purchase materials, land, labour, and any other costs related to construction and project implementation.

Cost benefit analysis (CBA) considers both financial and socio-economic costs and benefits to assess the comparative advantage of different options in monetary terms.

Design life is the estimated lifespan of an asset.

Discounting is a method used to convert future costs or benefits to present values using a discount rate.

Discount rate is the annual percentage rate at which the present value of a future dollar (or other currency) is estimated to lose its value over time.

Net Present Value (NPV) is an aggregated value used in whole life cycle analysis to measure the resultant financial and economic benefit of a good or service when all costs and benefits are taken into consideration. A positive NPV indicates a net benefit and a negative NPV a net loss.

Operational expenditure (OPEX) is the money that is required to sustain a facility or activity (including labour, fuel, and all other operation and maintenance costs).

Planning horizon is the duration over which the whole life cycle costs are evaluated.

Whole life-cycle analysis involves a long-term perspective considering all the costs incurred and the benefits received over the total duration of a project up until the planning horizon is reached.

9.6 Financing of CW

For the CW technology to be effectively adapted there must be financial mechanisms in place. Financial mechanisms, in this context, mean sources of funds for both capital costs and operation and maintenance costs. This study has identified some financial mechanism available in Tanzania for easy adaptation of CW technology. The financial mechanisms can be available at different levels as explained below (Kimwaga *et al.*, 2012).

9.6.1 National Level

At the national level, financing can be accessed by the national government through city, municipal, district and town councils whose functions will be to; (Kimwaga *et al.*, 2012):

- allocate funds for sanitation and hygiene education.
- lobby external support agencies for discretionary terms for financing waste management, hygiene promotion and sanitation.
- provide financial incentives to local governments which can deliver efficient and effective sanitation and hygiene promotion programs.
- develop and finance micro-credit schemes managed by non-governmental organization (*e.g.* SACOSS) or the private sector to target households and work with private sector leaders and product manufacturers to create programs for extending credit to members of the most vulnerable communities.
- provide loan security to households that have no collaterals.

9.6.2 Local level

At the local level, local government authorities (participating wards) will be responsible for financing, whose functions will be defined as follows (Kimwaga *et al.*, 2012):

- review the effectiveness of sanitation and hygiene promotion programs and ensure that funds are not used to finance high-cost, low-impact investments.
- make subsidy programs clear and transparent.
- create incentives to develop new technologies to reduce cost.
- create micro-credit and credit guarantee programs to target households and provide incentives for local manufacturers to extend credit to the poorest households.

9.6.3 Communities and Civil Societies Level

At this level, the communities and societies will have the following functions (Kimwaga *et al.*, 2012):

- scrutinize public accounts and check on reported spending on sanitation and hygiene promotion to help increase accountability and reduce wastage.
- propose alternative institutional and technical approaches that could reduce costs and ensure that these are well-known and well publicized.
- develop micro-credit schemes to fund household sanitation improvements and create mechanisms for generating user fees for funding continuing operation and maintenance of facilities.

9.6.4 Household Level

The household level will have the following functions (Kimwaga *et al.*, 2012):

- participate in community schemes and/or micro-credit schemes.
- pay back loans to loan providers.
- contribute maintenance fee to user groups.

9.6.5 Entrepreneurship Level

The functions for this level will be to; (Kimwaga *et al.*, 2012):

- offer poor households with low-interest credit to purchase their products (*e.g.* CW etc.)
- work with local governments, non–governmental organization and/or banks to develop micro-credit schemes.
- develop cost-effective products and services for poor communities and households.

9.6.6 Financial Institutions Level

These financial institutions will give soft loans for sanitation (*e.g.* CW) activities and investments (services and facilities installation)

9.6.7 International Organizations and External Funding Agencies Level

These agencies will have the following functions:

- allocate sufficient resources to the sector.
- mobilize other development partners to contribute funds.
- compile and disseminate information on a variety of cost-effective sanitation alternatives and effective behaviour change strategies.

It is important to recognise that none of the above-mentioned financial mechanisms is and can be implemented alone. Various financial mechanisms must be considered together to create the complementarily of one another.

9.7 Cost and Benefit Analysis Example

The presented example to illustrate the CBA is based on the study by Balkema *et al.*, (2010) titled Socio-economic analysis of constructed wetlands systems for hygienic sanitation in Tanzania and published in Water practice and technology. According to Balkema *et al.*, (2010), the following data and assumptions were made:

The project lifetime is set to 10 years, assuming that a constructed wetland (CW) will last longer than that, the residual value of the CW at the end of the project lifetime is set to half the construction value in year 0.

The average expected inflation rate in Tanzania is set at 8.7%.

The interest on a commercial loan for a period longer than 5 years is 15.7%.

The following cash outflows for the non-financial operations for a constructed wetland project are distinguished: (1) design costs of the Constructed Wetland (in year 0); (2) building materials (in year 0); (3) other construction costs such as wages (in year 0) and (4) Operation and Maintenance costs (in year 1 through 9).

The cash inflows of the non-financial operations of the project consist of all direct and indirect cash inflows caused by implementing the project, in this case: the reduction of sanitation costs caused by the constructed wetland. For instance, avoidance of costs of waste dumping; or avoidance of cleaning costs of the existing system which is replaced by or extended with the newly constructed wetlands. In most cases, these are avoided costs by not having to empty the septic tank as often as before. For the case study of constructed wetlands at Ruaha Secondary School in Iringa.

In Tanzania, the following data was collected (Balkema *et al*., 2010):

The initial costs of the project are completely covered by grants.

The total construction costs for the CW are relatively low, because the UDSM does not charge for the design of the wetland, furthermore the construction is taken care of by students and employees of the school. Therefore, the only construction costs are the TSh. 3,121,250 (US$ 2,500) for construction materials.

Operation and Maintenance of the Wetland is TSh. 420,000 (US$ 340) per year for wage costs and costs of measuring the water quality on various indicators.

The introduction of the CW reduces the cleaning cost of the school's septic tank that was its dominant sanitation technology until then: instead of emptying the tank 4 times a month, it now needs to be emptied only once a year. Emptying the septic tank costs TSh. 25,000 (US$ 20).

In the case of Ruaha Secondary School, the constructed wetland is financially feasible because of the relatively high avoided costs of not having to empty the septic tank as often as before implementing the wetland. The calculated Net Present Value (NPV) is 2,807,000 TSh. (US$ 2,250), the Internal Rate of Return (IRR) is 33% (compared to the nominal interest rate of 16%) and the Pay Back Period (PBP) lies between 4 and 5 years (Balkema *et al*., 2010). As a sensitivity analysis, switching values are calculated indicating at what rise investment or maintenance costs or a drop in benefits (less avoided costs) the NPV will become zero. In the case of the Ruaha Secondary School investment costs higher than 7,047,000 TSh. (5,640 US$) (2, 3 times the realized investment costs) would make the project financially unattractive (NPV = 0) (Balkema *et al.*, 2010). Similarly, doubling the operation and maintenance costs would make the project financially unfeasible (NPV = 0) and 35% lower avoided costs would make the project financially unfeasible (NPV = 0) (Balkema *et al.*, 2010). From these indicators for sensitivity, we conclude that the project is a rather safe investment in financial terms. In addition, the investment costs for the Ruaha Secondary School constructed wetland project were granted, as such the project was without a doubt a financial success (Balkema *et al.*, 2010).

Based on the Ruaha case study, it is conclude that in scenarios where relatively high cost can be avoided by implementing a CW technology, the investment will be regarded as financially feasible. In Ruaha, the avoided cost, on a yearly basis, was as high as 38% of the initial investment. In the literature, no comparable analyses were found using similar avoided cost situations, although reference can be found on the comparison of costs for different wastewater treatment systems. For instance, in his economic analysis (Chapter 7) Okurut (2000) compares the costs for a constructed wetland with a waste stabilization pond for the treatment of wastewater for 4000 p.e. in Uganda and concludes that constructed wetlands are economically competitive. Land costs for the WSP was estimated to be 30% higher as a larger area is required, while the operating and maintenance costs are similar for both systems (Okurut, 2000), therefore making constructed wetlands the most attractive option.

Mannino *et al.*, (2008) compare the costs of semi natural free water surface wetlands (SNFWS) to activated sludge wastewater treatment plants and conclude that the wetlands were more economical. Despite high development costs, estimated to be six- to nine-fold higher for the wetlands than for the activated sludge plants (Mannino, 2009) and this excluding land costs. The total cost needed to give an annual wastewater treatment service per person *i.e.* were calculated to be two- to eight-fold lower over the entire 20 years' lifespan, respectively based on a discount rate of 5 and 10% (Mannino, 2008). Mainly due to lower maintenance costs, the higher development costs were more than offset in 2 to 3 years (Mannino, 2008). These findings are more promising because they are nearly similar to those reported elsewhere.

Cost-Benefit of Improved Water Supply

- The most common approach in health economics.
- Based on the concept of Disability-Adjusted Life Year (DALY).
- DALY is a health gap measure that extends the concept of potential years of life lost due to premature death (PYLL) to include equivalent years of 'healthy' life lost by virtue of being in states of poor health or disability.
- One DALY can be thought of as one lost year of 'healthy' life. The burden of disease is measured as the gap between the current health status and an ideal situation where everyone lives into old age free of disease and disability.

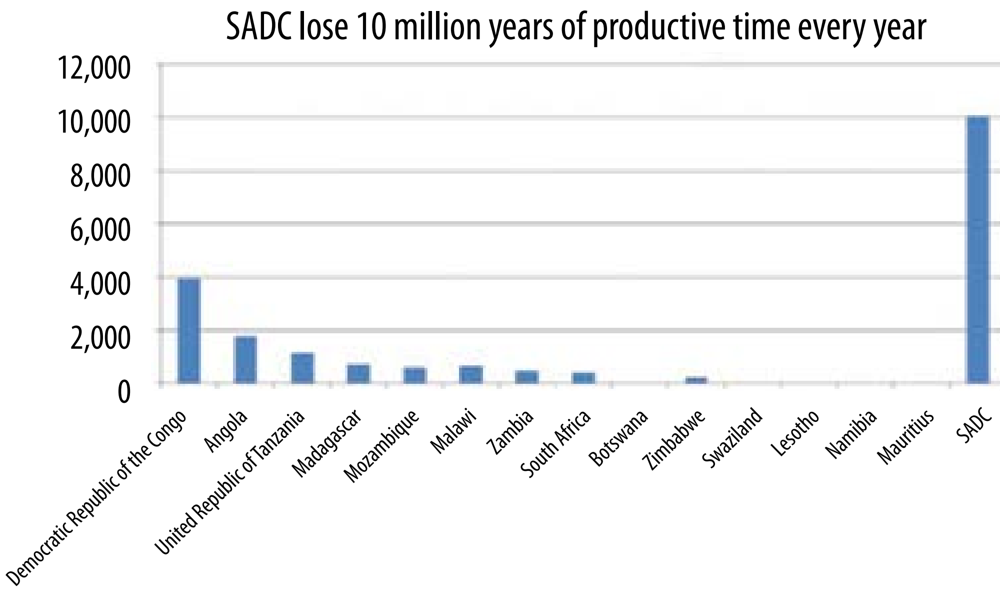


Figure 9.2: Total DALYs due to Diarrhoeal Diseases ('000)

9.8 References

Arias, M. E., and Brown, M. T. (2009). Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia. *Ecological Engineering*, 35(7), 1070-1078.

Balkema, A., Njau, K. N., Romijn, H., and de Ruijter, R. (2010). Socio-economic analysis of constructed wetlands systems for hygienic sanitation in Tanzania. *Water Practice and Technology*, 5(1), wpt2010022.

Bixio D., De Heyder B., Chikurel H., Muston M., Miska V., Joksimovic D., Schäfer A.I., Ravazzini A., Aharoni A., Savic D. and C. Thoeye (2004) In: Proc. 4th IWA World Congress; 19-24 September 2004, Marrakech, Morocco.

Boardman, A., Greenberg, D., Vining, A., and Weimer, D. (1996). Cost-Benefit Analysis: Concepts and Practice. Upper Saddle River. NJ, Prentice Hall.

Breaux, A., Farber, S., and Day, J. (1995). Using natural coastal wetlands systems for wastewater treatment: an economic benefit analysis. *Journal of environmental management*, 44(3), 285-291.

Cooper, P. F. (1993). The use of reed bed systems to treat domestic sewage: the European design and operations guidelines for reed bed treatment systems. Pages 203–217 in G. A. Moshiri, ed. Constructed wetlands for water quality improvement. Lewis Publishers, Boca Raton, FL

Cooper, C. M. and. Knight, S. S. (1996). Insecticide and metal contamination of a mixed cover agricultural watershed. Water Science and Technology, 33(2), 227-234.

Drizo, A., Frost, C. A., Grace, J., and Smith, K. A. (1999). Physico-chemical screening of phosphate-removing substrates for use in constructed wetland systems. *Water Research*, 33(17), 3595-3602.

Gauss, M. (2008). Constructed wetlands: a promising wastewater treatment system for small localities: experiences from Latin America. World Bank Policy Research Working Paper, (44120).

Gunarathna, H. A. Y. R., Kapukotuwa, A. S. B., Karunarathna, A. K., and Basnayake, B. F. A. (2007, September). Construction and Evaluation of a Low Cost, Waste Polyethylene Based Liner for Small Landfills. In Proceedings of the International Conference on Sustainable Solid Waste Management, Chennai, India (pp. 226-233).

Haule, K. S., Johnsen, F. H., and Maganga, S. L. S. (2002). Striving for sustainable wildlife management: the case of Kilombero Game Controlled Area, Tanzania. *Journal of environmental management*, 66(1), 31-42.

Hayes, D. F., Estes, T. J., Fischenich, J. C., & Palermo, M. R. (2000). Wetlands engineering handbook.

Huffman, R.T. (1978). Wetland habitat development with dredged material: engi- neering and plant propagation. US Army Engineer Waterways Experiment Station, Vicksburg, MS. Technical Report DS-78–16, NTIS No. AD A073 493.

Hussain, S., and Singh, R. K. (2001). Bench mark ecological status of wetlands of Ladakh. Study report-2000, Wildlife Institute of India, Dehradun.

Hutton, G., Haller, L., Water, S., and World Health Organization. (2004). Evaluation of the costs and benefits of water and sanitation improvements at the global level (No. WHO/SDE/WSH/04.04). World Health Organization.

Kadlec, R. H., and Wallace, S. (2008). Treatment wetlands. CRC press.

Kampf, R., and Claassen, T. (2005). The use of treated wastewater for nature: the Waterharmonica, a sustainable solution as an alternative for separate drainage and treatment. 2nd IWA Leading-Edge on Water and Wastewater Treatment *Technologies*, 341-350.

Kampf, R., Schreijer, M., Toet, S., and Verhoeven, J. T. (1999). The Everstekoog constructed wetland. In A four year research project on full scale to change effluent from an oxidation ditch to (re) usable surface water, this conference.

Kimwaga, R. J., Mashauri, D. A., Mbwette, T. S. A., Katima, J. H., and Jørgensen, S. E. (2004). Use of coupled dynamic roughing filters and subsurface horizontal flow constructed wetland system as appropriate technology for upgrading waste stabilisation ponds effluents in Tanzania. *Physics and Chemistry of the Earth*, Parts A/B/C, 29(15-18), 1243-1251.

Kimwaga, R., Mashauri, D., and Mbwette, T. (2003). Meeting health improvement indicators in waste stabilization ponds effluents by a coupled dynamic roughing filters and subsurface horizontal flow constructed wetland in Tanzania. Prospective College of Engineering and Technology, University of Dar es Salaam, Dar es Salaam, Tanzania.

Kimwaga, R.J., Mbwette, T.S.A., Mashauri, D.A., Katima, J.H.Y., and Jørgensen, S.E., 2002. Mathematical modelling of the TSS removal in a coupled dynamic roughing filter and subsurface horizontal flow constructed wetland system treating WSP effluent, in: Proc s. 8th Internat. Conf. Wetland Systems for Water Pollution Control, University of Dares- Salaam, Tanzania and IWA, pp. 843-857.

Lambert, A. (2003). Economic valuation of wetlands: an important component of wetland management strategies at the river basin scale. Conservation Finance Guide, Washington.

Manase, G. (2010). Economic Accounting of Water Use Namibia Pilot Report (Final report). *Egis Beceom International*, (9), 28p.

Mannino, I., Franco, D., Piccioni, E., Favero, L., Mattiuzzo, E., and Zanetto, G. (2008). A cost-effectiveness analysis of seminatural wetlands and activated sludge wastewater-treatment systems. *Environmental Management*, 41, 118-129.

Mashauri, D. A., and Kayombo, S. (2002). Application of the two coupled models for water quality management: facultative pond cum constructed wetland models. *Physics and Chemistry of the Earth*, Parts A/B/C, 27(11-22), 773-781.

Mato, R. R. A. M. (2002). Groundwater pollution in urban Dar es Salaam, Tanzania: Assessing vulnerability and protection priorities.

Moons, E. (2003). The Development and Application of Economic Valuation Techniques and their Use in Environmental Policy, a Survey. Energy, Transport and Environment Working Papers Series ete0307, Katholieke Universiteit Leuven, Centrum voor Economische Studiën, Energy, Transport and Environment.

Nunes, P. A., and van den Bergh, J. C. (2001). Economic valuation of biodiversity: sense or nonsense?. *Ecological economics*, 39(2), 203-222.

Okurut, T. O. (2000). A pilot study on municipal wastewater treatment using a constructed wetland in Uganda. CRC Press.

Seguí Amórtegui, L. A. (2004). Sistemas de regeneración y reutilización de aguas residuales. Metodología para el análisis técnico-económico y casos. Universitat Politècnica de Catalunya.

Senzia, M. A., Mashauri, D. A., and Mayo, A. W. (2003). Suitability of constructed wetlands and waste stabilisation ponds in wastewater treatment: nitrogen transformation and removal. *Physics and Chemistry of the Earth*, Parts A/B/C, 28(20-27), 1117-1124.

Senzia, M. A., Mashauri, D. A., Mayo, A. W., Mbwette, T. S., Katima, J. H., Pratap, H. B., and Nielsen, S. N. (2002, September). Performance of horizontal subsurface flow constructed wetlands located downstream of primary facultative and maturation ponds in Tanzania. In Int. Conf. on Wetlands Systems for water Pollution Control, Arusha, Tanzania.

Tanner, C. C., Kadlec, R. H., Gibbs, M. M., Sukias, J. P., and Nguyen, M. L. (2002). Nitrogen processing gradients in subsurface-flow treatment wetlands—influence of wastewater characteristics. Ecological engineering, 18(4), 499-520.

USEPA (U.S. Environmental Protection Agency): 1993, Clean Water Act. Section 503. Vol. 58. No. 32 US EPA, Washington, DC

Vymazal J., Brix H., Cooper P.F., Green M.B., Haberl R. (1998) Constructed Wetlands for Wastewater Treatment in Europe. Backhuys Publishers: Leiden, The Netherlands.

Vymazal, J., and Kröpfelová, L. (2008). Wastewater treatment in constructed wetlands with horizontal sub-surface flow (Vol. 14). Springer science & business media.

Westholm, L. J. (2006). Substrates for phosphorus removal—Potential benefits for on-site wastewater treatment?. *Water research*, 40(1), 23-36.

WRP, Wetland Reserve Program (1994) “Procedures for evaluating wetlands non-market values and functions”, WRP Technical Note WG-EV-2.1, May 1994.

WRP, Wetland Reserve Program (1994a) “Methods for evaluating wetland functions”, WRP Technical note WG-EV2.2, May 1994.

Yana B.B. (2004). “Could the Waterharmonica play its role in the developing world? A review of practical experiences, successful, and less successful experiences”, presentation at the 7th INTECOL International Wetlands Conference in Utrecht, The Netherlands, 25-30 July 2004.

Kimwaga; Richard, Leonard Gastory, Chacha Nyamboge, Francis Mutabazi Njau (2012): Financial or Socio-Economic Mechanisms Controlling the Constructed Wetlands Service Chain in Tanzania; Final Report, VLIR PROJECT

Mwegoha, W., Katima, J. H. Y., Mbwette, T. S. A., Njau, K. N., Jorgensen, S. E., and Nielsen, S. N. (2002). Modeling the effects of suspended solids accumulation on the hydraulic conductivity of gravel packed horizontal subsurface flow constructed wetlands. University of Dar es Salaam, PO Box, 35131.

This page is intentionally blank

Chapter 10: Constructed Wetlands Case Studies in Western Indian Ocean Region

(Tanzania, Kenya, Mauritius, Madagascar)

By Richard Kimwaga
University of Dar es Salaam, Tanzania

HIGHLIGHTS

Adequate and comprehensive knowledge, best practices and experience in CWs sharing is imperative for their success and smooth adaption and uptake at a scale through buy in by policy and decision makers and the public at large. This approach helps to inform the success and failure stories in terms of what is and isn't working for the CW technology elsewhere. Various countries in the WIO region, have implemented CW technology either as research facilities to generate evidence-based performance or as practical application to address a real-life problems. This chapter which is contributed and compiled by the lead author has presented the WIO CW case studies in four countries namely Kenya, Madagascar, Mauritius, and Tanzania. While Madagascar and Mauritius represent the island states, Kenya and Tanzania represent the mainland countries whose coastal areas are heavily impacted by pollution from land-based activities. While it was difficult to get the data for the full-scale operational CW in Madagascar and Mauritius, the pilot CW research results were sufficient to describe the applicability and desirability of CW technology as nature-based solutions. Evidently, in all the four case studies presented in this Chapter, CW technology has convincingly demonstrated and confirmed to be an appropriate green, low-cost technological option for controlling the pollution from land-based sources and activities in the WIO region countries. Appropriate, adequate, and relevant enablers should be reviewed to explicitly recognize the CW technology as a truly green solution in the WIO region and in order to promote and encourage its uptake and adaptation at a scale. Furthermore, thorough planning for the CW technology is crucial for its success in the design, construction as well as operation and maintenance. The four CW case studies have been comprehensively and deeply presented in this Chapter in the following sections. The book is one of the remarkable, valuable and useful resources in the WIO region to control and prevent the coastal and marine ecosystem.

10.1 Ten Years Experiences of Using Engineered Wetlands Systems for Onsite Treatment of Wastewater by the Local Communities in Tanzania

ABSTRACT

The Tanzania CW technology case study on the design, operation and maintenance experience has been well discussed in research work by Njau *et al*., (2011). The case study for Tanzania is about Ten years' experience of using engineered wetlands systems for onsite treatment of wastewater by the local communities. The discussion presented in this book is solely derived from the research work by Njau *et al*., (2011) published in the Journal of Water Technology and Practice. Njau *et al*., (2011) describes the abstract of their work by contextualizing the case study that for the decades now, constructed wetlands (CW) technology has been widely acknowledged and recognized as a green, nature-based solutions and alternative to the conventional wastewater treatment systems globally. With an ever-increasing socio-economic development with resultant increase in the great amount of wastewater and faecal sludge generation, CW will remain one of the promising and reliable solutions in the developing regions. In Tanzania, the use of constructed wetlands (CW) technology as an alternative to wastewater treatment began way back in 1998. This case study presents the ten years' experience of designing and using CW technology for wastewater treatment in local communities in Tanzania. Since its inception about 10 years ago, Constructed Wetlands (CWs) technology has been well received in Tanzania due to a wide range of multiple benefits including low cost and simple technology in terms of operation and maintenance. CWs are used to treat wastewater from various sources of municipal systems, pulp and paper industries, prisons, schools, and colleges. Among the beneficiaries and the adaptors of CWs are the Moshi Urban Water and Sewerage Authority (MUWSA) for polishing the effluent from the Waste Stabilization Ponds, Kibo Paper Mills for treating industrial effluents, Shinyanga, Malya and Bariadi Prison and Kleruu Teachers College and Ruaha High School for the treatment of domestic wastewater. All these systems are Horizontal Sub-Surface Flow Constructed Wetlands. This case study, earlier compiled by CW researchers at UDSM, reports the results of a survey of six operating CW systems, focusing on the existing situation as well as the observed operation and maintenance challenges and needs. The survey was carried by visiting the CWs and sampling for the determination of BOD_5, COD, PO_4^{2-}, NO_3^-N, and NH_3-N. Results from the survey and laboratory analyses in three of these CWs indicated the lack of general and site-specific operation and maintenance guidelines, which seriously affected life cycle of these systems, aesthetics, and performance in terms of pollutant removal. This is evidenced by failure of these systems to meet local and international permissible discharge limits into the receiving water bodies.

Keywords: Constructed wetland, Maintenance, Operation, Performance, Wastewater

10.1.1 Introduction and Rationale for Constructed Wetlands

For decades now, constructed wetlands (CW) technology has been widely acknowledged and recognized as a green, nature-based solutions and alternative to the conventional wastewater treatment systems globally (Vymazal *et al*, 1998) with the ever-increasing socio-economic development and the resultant increase in the great amount of wastewater and faecal sludge generation, CW will remain one of the promising and reliable solutions in the developing region. In Tanzania, the use of constructed wetlands (CW) technology as an alternative to wastewater treatment dates back in 1998. Since there has been no documentation, this case study presents the ten years' documented experience of designing and using CW technology for wastewater treatment in local communities in Tanzania.

Since its inception about 10 years ago, Constructed Wetlands (CWs) technology has been well received in Tanzania due to a wide range of multiple benefits including low cost and simple technology in terms of operation and maintenance. CWs are used to treat wastewater from various sources of municipal systems, pulp and paper industries, prisons, schools, and colleges. Among the beneficiaries and the adaptors of CWs are the Moshi Urban Water and Sewerage Authority (MUWSA) for polishing Waste Stabilization Ponds effluents, Kibo Paper Mills for treating industrial effluents, Shinyanga, Malya and Bariadi Prison and Kleruu Teachers College and Ruaha High School for Treatment of domestic wastewater. All these systems are Horizontal Sub-Surface Flow Constructed Wetlands.

Constructed Wetlands (CW) must be adequately and properly managed if they are to perform well (Beharell, 2004). Thus, CW require regular monitoring and maintenance to ensure it remains functional and in a 'healthy' condition. Development of Operation and Maintenance (O&M) guidelines should be consistent with the purposes and intended life of the wetland, which includes the requirements for safety, water management, cleanout of sediment, maintenance of structures, embankments, and vegetation, control measures for vectors and pests, and containment of potential pollutants during maintenance operations (Kuginis, 1998; Beharell *et al*., 1998; Beharell, 2004). In Tanzania, CW technology dates to 1998 when the first research group was launched at the University of Dar es Salaam under DANIDA funding. The group conducted research on the feasibility of using Horizontal Sub-surface Flow Constructed Wetlands in Tanzania. Ten years of successful research and awareness-raising on the pollution control potential of these systems has resulted in widespread acceptance by the local public. Several projects on the use of CW systems for wastewater treatment were developed notably in Iringa, Moshi, Shinyanga, Dar es Salaam and Mwanza. However, the major challenge facing these systems is lack of guidelines on operation and maintenance to ensure optimum performance and long-life span of these systems. Therefore, this study reports on needs assessment for operation and maintenance of CW systems in Tanzania. Together with the performance data, this could pave way to developing operation and maintenance guidelines for maintaining consistently good performance and longer life span of this technology.

10.1.2 CW System Description (size, type of CW, the design, and operating conditions)

Kleruu Teachers Training College (TTC) CW:

The CW system is located within the Kleruu TTC campus and has been operational since 2003. The college owns a Horizontal Subsurface Flow Constructed Wetland (HSSFCW), consisting of baffled system with 4 cells and a total area of 625m^2 planted with *Phragmites Mauritianus*, although several other species have emerged due to overland flows, phasing out the originally planted species. The system was designed with the capacity to treat wastewater of 800 people. Before the realization of the constructed wetland, the Kleruu TTC used a mechanical aeration chamber. The function of the mechanical aeration chamber was to remove organic loading and suspended solids from wastewater prior to entering the oxidation pond downstream. However, the mechanical aeration system is not functioning due to failure by the college to meet running costs especially electricity. CW was installed to replace the pond in the understanding that the mechanical aeration system was replaced by septic tank. The college however, failed to secure funds to complete the project. Thus, the CW system practically receives untreated domestic wastewater, causing clogging and overland flow as a result of high nutrient, suspended solids and organic loading. The CW effluent is discharged via a chamber to an open channel which is also used for irrigation of vegetable gardens.

Ruaha Secondary School CW: Ruaha Secondary School has a HSSFCW system consisting of two cells of 20 m×10m planted with *Phragmites Mauritianus*. One cell was constructed in 2004 and the other built one year after. The system receives wastewater of domestic nature from student dormitories, offices, and kitchen, pre-treated in a septic tank before entering the wetland. Each cell was designed to treat wastewater for up to 600 people, bringing the total treatment capacity to 1,200 population equivalent. The treated effluent is used for irrigation of elephant grass, which is a source of fodder for cattle owned by Ruaha Secondary School.

Moshi Urban Water Supply and Sewerage Authority (MUWSA) CW: Moshi municipality has a HSSFCW system consisting of one cell of 57 m × 27 m and depth of 0.6 m planted with *Phragmites Mauritianus*. The wetland was designed to polish domestic and industrial sewage from the waste stabilization ponds. The wetland is connected to the second maturation pond in a ponds system having 6 cells. The overall system consists of HSSFCW, Fishpond (FP), and Paddy Farm (PF). This integrated system was designed and constructed in 2004 which treats effluent from the primary facultative pond. The flow rate into the HSSFCW is 400m^3/day. The effluent from the HSSFCW is reused for irrigation in the pilot paddy farm and aquaculture farming (fishpond).

Kibo Paper CW, Moshi Municipality: Kibo paper mill located in the outskirts of Moshi Municipality, close to Kranga river which originates from Mount Kilimanjaro catchment area. The CW system consists of a baffled system for treatment of sewage from paper milling industry. The Kibo paper HSSFCW consists of baffled system with three cells of 128m × 42 m planted with *Phragmites Mauritianus* with the total covered area of 5376 m^2. The designed flow rate was 81 L/sec with the operational flow rate of 80 L/sec. Wastewater influent into the CW has a very strong organic load in form of suspended solids that are discharged from industrial processes, which is a major reason for clogging and overland flow in the system. The treated wastewater from this system is discharged to a nearby river and also used for irrigation of soy and vegetable farms in the vicinity of the area.

Shinyanga Prison CW: Shinyanga prison has a HSSFCW system consisting of one cell of 50 m x 15 m x 0.6 m planted with both Phragmites Mauritianus and Typha latifolia. The wetland cell was constructed in 2001 and designed for the purpose of treating sewage from the prison. The average flow rate to the system is 50 m^3/d.

Malya Prison CW: The Malya Prison CW system consists of one HSSFCW cell planted with Phragmites Mauritianus, designed to treat wastewater from the septic tanks serving the Malya prison community. The size of the system is 55m × 20m wide with the area of 1100m^2 designed and constructed for treating domestic sewage. The average flow rate to the system is 50m^3/d. The system also experiences clogging and overland flow (flow channelling). Several native plant species which were not originally planted have emerged, making diverse plant community.

Bariadi Prison CW: The Bariadi Prison CW consists of two HSSFCW cells packed with gravel and no vegetation. One cell was designed to treat sewage from septic tanks of the prison community. The size of the system is 45 m x 20 m with the total area of 900 m^2. The system has the flow rate of 50 m^3/d.

Site visit and questionnaire survey

A total of seven (7) constructed wetland sites were visited and assessed. These sites are located at Shinyanga Region (Shinyanga Prison and Bariadi Prison), Mwanza (Malya Prison), Iringa (Kleruu Teachers Training College and Ruaha Secondary School) and Moshi (MUWSA and Kibo Paper Mill). The field visits were conducted for data collection on baseline information regarding the current condition of CW systems through physical observation, conducting structured questionnaire survey and focused group discussions. Comprehensive surveys and interviews were conducted for the users of CW technology at each of the visited site to identify specific needs related to operation and maintenance. In addition to field observations, the questionnaires and interviews were designed in such a way to capture important site-specific issues such as wetland specifications, current operational problems, fencing, and status of plant and vegetation health, existing weeds and unwanted plant control programs and existence of local operation procedures.

Wastewater Sampling and Analytical Methods

Wastewater samples were collected from three CW sites between January and December 2009 for determination of wastewater physio-chemical parameters. A total of twelve (12) samples were taken from Shinyanga Prison, 10 samples from MUWSA and nine (9) from Ruaha Secondary School. Wastewater samples from the three sites were analysed at close-by Government Water Laboratories in Mwanza and Iringa and at the MUWSA Water Quality Laboratory. Temperature, pH and electro conductivity were measured in situ, and the determination of other physio-chemical parameters was in accordance with the Standard Methods for Examination of Water and Wastewater (APHA, 1998).

10.1.3 CW System Pollutants Removal Performance

Physico-chemical parameters: The results in Table 10.1 show the physio-chemical parameters for the inlet and outlet wastewater for the three CWs surveyed.

Table 10.1: Physico-chemical parameters at Three CW systems in Tanzania

Site	Location	Temp. °C	pH	EC mS/cm	TSS mg/L	BOD_5 mg/L	COD mg/L	Ortho phospate mg/L	Ammonia Nitrogem mg/L	Nitrate Nitrogen mg/L	Discharge (Q)) m³/sec
Shinyanga Prison	In Out	28.01±1.57 26.56±1.58	6.88±0.26 7.24±0.27	1023.25±149.28 852.56±180.56	128.11±63.81 31.72±8.12	432.18±156.16 146.18±59.05	917.50± 352.67±341.27	8.54±0.79 6.72±1.20	26.57±16.15 17.48±7.56	1.05±0.85 1.12±0.57	(3.28±1.50) x10^3 (2.27±2.02) x 10^3
Moshi UWSA	In Out	25.00±1.09 25.10±1.09	7.47±0.29 7.45±0.26	684.00±100.54 707.52±94.73	25.02±16.21 14.31±9.65	67.05±28.35 35.19±12.36	104.2±31.36 66.9±28.68	56.6±9.22 39.9±7.24	24.87±5.39 10.35±4.26	26.30±11.35 11.44±5.02	(3.00±0.01) x10^3 (2.11±0.03) x 10^3
Ruaha secondary School	In Out	21.5±1.16 21.5±1.05	8.3±0.43 7.6±0.46	1534.6±744.91 996.0±618.77	0.3±0.25 0.1±0.06	200.00±155.56* 41.00±9.98a	250±194.5* 51.3±12.4a	44.5±10 18.1±5.76	77.3±43.51 33.0±23.72	35.3±15.7 11.3±4.15	ND (0.4±0.22) x 10^3

u=12
ND Not Determine
n=2

The discharge levels for BOD_5, COD, orthophosphate, and ammonia were above the recommended Tanzanian Standards (Water Utilization Act No. 10 Tanzania, 1981) discharge limits to receiving water bodies. The Shinyanga Prison, MUWSA and Ruaha Secondary School CW wetlands respectively were able to achieve medium to moderately high removal efficiency for BOD (66.2%, 47.76% and 79.5%); COD (61.6%, 36.54% and 79.6%). High TSS removal efficiency was achieved at Shinyanga Prison (75.78%) although the actual concentration of TSS in the effluent was of inferior quality compared with the effluents from MUWSA and Ruaha Secondary School, whose influent TSS concentrations were also lower.

Nutrient removal efficiency was generally low in all CWs studied, although the actual effluent concentration of NO3-N was low enough to meet the recommended discharge standards for Tanzania, ranging from 1.12, 11.3 and 11.44 mg/L for Shinyanga, Ruaha and MUWSA, respectively. The concentrations of phosphate in the effluents ranged from low (6.73 mg/L for Shinyanga Prison), medium (18 mg/L for Ruaha Secondary School CW) to high (39.9 mg/L for MUWSA). High nutrient content in the MUWSA CW is the reason for successful reuse of CW effluents for rice padding by the farmers around the wastewater treatment facility. Regarding the NH3-N, effluent removal efficiencies were 34.7% for Shinyanga Prison, 57.31% for Ruaha Secondary School and 60% in MUWSA CWs. However, the highest concentration in the effluent was 33 mg/L from Ruaha Secondary School CW.

Operational Procedures: Out of seven systems surveyed on the water flow and levels, five were periodically inspected and two out of seven systems were less often inspected. For those systems assessed, sampling for water quality determination is done frequently in one system. In the other two systems, sampling is done less often. Sampling is not done at all in three CW systems. Daily checking up of debris and development of short circuits/dead zones are effectively carried out in all CW systems surveyed. This ensures longer life span and effective operation of the systems. Findings indicate that cleaning and maintenance of inlet and outlet structure, valves and monitoring devices are done in five out of seven systems. Maintenance and cleaning is done less often only for two systems. In the period of unusual flow due to a weather event, six out of seven CW systems are usually inspected. The number of operators is adequate in six out of seven CW sites. The assessment also revealed that facilities and equipment are adequate in two CW sites and inadequate at three sites. CW users at two sites had no idea on the necessary facilities and equipment for maintenance of CW systems. Results indicate further that out of seven respondents, on education, skills, and training, three indicated that there is inadequate education, skills and training on CW among owners and operators of CW. The responses evaluation on motivation to operators shows that one out of seven responses indicated that the motivation is inadequate and three out of seven did not respond to the query.

10.1.4 Observed and Documented Design and Operational Challenges Common CW Problems

The results indicate that 86% of the surveyed CWs experience various forms of operational problems. The major problem experienced in most of these systems is a combination of blockage and flooding/overland flow (Figure 10.1).

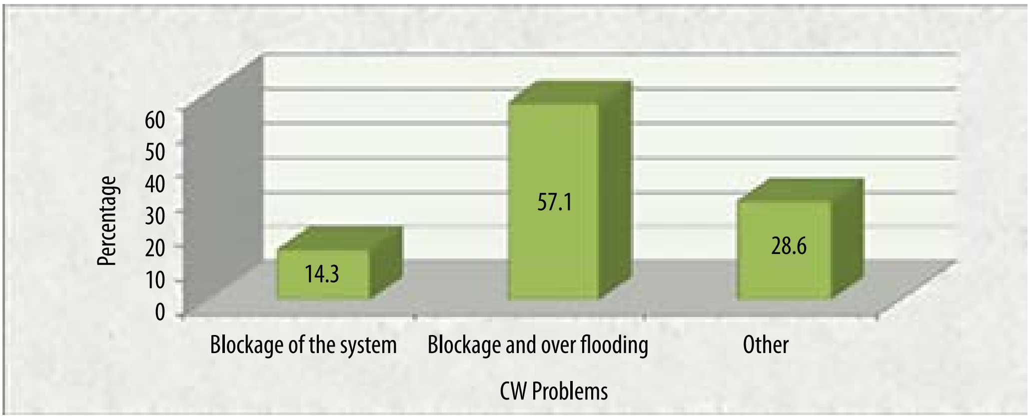


Figure 10.1: Common Operational Problems in Constructed Wetlands in Tanzania.

Other operational problems include seepage through the walls or leakage, storm water runoff especially during and after rainfall events and, cracks. The main causes of blockage of the system range from solid wastes introduced accidentally, solid wastes introduced intentionally to solids deposition and biological growth. For situations where there is both blockage and over flooding of the systems, major causes have been identified to be the lack of drainage system (50%) and hydraulic overloading (33%). The frequency of occurrence of blockage and overland flow/over flooding varies from one system to another, ranging from once per week to once per year depending on site –specific conditions.

Plant Maintenance: Six out of seven CW systems surveyed are planted with *Phragmites Mauritianus*. Bariadi Prison wetland was not planted at the time of visit, due to lack of specific instructions for planting. Plant health condition at Kleruu TTC wetland was poor at the time of visit. The poor health condition of Kleruu plants may be attributed to the fact that the wetland receives untreated sewage that contains high organic loading content and high amount of suspended solids. All surveyed CWs systems that are planted have age of more than three years.

Three out of seven CWs have their own locally developed plant maintenance program. The maintenance program is developed from within. As stated earlier, Bariadi Prison and at Kibo Paper Mill CW systems had no plant maintenance program whatsoever. Owners of MUWSA and Shinyanga Prison CWs only prune some of the trunks. Pruning is done as needs arise (normally once per two or three months) by cutting unwanted plant trunks. At Malya Prison, they perform watering in periods of no flows and periodic replacement of unhealthy plants. Watering is done once per week and periodic replacement of unwanted plants is done once per month. At Ruaha Secondary School, harvesting of plants, uprooting of unwanted weeds, and pruning of some trunks is practiced. Harvesting of plants is done once per year and is done by cutting the plants at 10-30 cm above the surface of substrate. The harvested plants, litter and debris are removed from wetland bed and burned.

Uprooting of unwanted weeds is done at the time when the plants are short to ensure accessibility. Pruning is done especially to stop the plant trunks from covering the inlet and outlet zones of the wetland. This is mostly done once per month. At Kleruu TTC, plant harvesting upon removing the substrates for cleaning, was done after every nine months of operation. The weeding of unwanted plants was done as need arose. About 57% of harvested plants were disposed onsite. Five out of seven CW owners requested to be provided with standard plant maintenance guidelines. At present, the cost of plant maintenance ranges from USD 45 to 90 per operation. About 75% of maintenance funds are raised by CWs owners.

Fencing constructed wetland premises: Results show that out of seven surveyed CWs, three systems were fenced. While fenced systems (Ruaha, Kleruu and Kibo Paper) are situated at more risk areas where people and livestock can easily intrude the systems, non-fenced CW systems belong to a more controlled and monitored authorities like the Prisons and the MUWSA. For the fenced systems, the materials used were wire mesh and barbed wires supported by concrete and wooden poles, and in general, they were found in a good condition at the time of visit, with minor damages that occurred less frequently. Nevertheless, 71.4% of respondents acknowledge the importance of fencing CW system in order to minimize encroachment from livestock and humans. The rest didn't acknowledge the importance of fencing the CW based on cost implications borne upon fencing. However, all respondents had no idea of the costs for building and maintaining a fence for the CW systems.

Weeds and Unwanted Plant Control: Out of seven CW systems surveyed, five systems experience operation problems related to weeds. The study also established that almost all operators of CWs do not have a structured and defined weeds control program rather they address the problem when it arises to a certain level. Weeds are removed from CW systems by manual uprooting. Sometimes, especially when the system is totally clogged (a case of Kleruu Teachers Training College), weeds are removed during the process of removing substrate materials. Removed weeds are dumped around the CW system and left to dry before open fire burning. The actual or indicative cost for removing weeds from CW systems is still unknown among CW owners and operators.

Operational Procedures: Out of seven systems surveyed on the water flow and levels, five were periodically inspected and two out of seven systems were less often inspected. For those systems assessed, sampling for water quality determination is done frequently in one system. In the other two systems, sampling is done less often. Sampling is not done at all in three CW systems. Daily checking up of debris and development of short circuits/dead zones are effectively carried out in all CW systems surveyed. This ensures longer life span and effective operation of the systems. Findings indicate that cleaning and maintenance of inlet and outlet structure, valves and monitoring devices are done in five out of seven systems. Maintenance and cleaning are done less often only for two systems. In the period of unusual flow due to a weather event, six out of seven CW systems are usually inspected. The number of operators is adequate in six out of seven CW sites. The assessment also revealed that facilities and equipment are adequate in two CW sites and inadequate at three sites. CW users at two sites had no idea on the necessary facilities and equipment for maintenance of CW systems. Results indicate further that out of seven respondents, on education, skills, and training, three indicated that there is inadequate education, skills, and training on CW among owners and operators of CW. One out of seven responses indicated that the motivation was inadequate and three out of seven did not respond to the query.

10.1.5 Lessons Learnt (Worst Case and Best-Case Scenarios)

The challenges that have been found for the CW systems in operation are the general lack of specific operation and maintenance (O&M) plans/guidelines. Despite the lack of O&M plans and guidelines among the CWs owners, the performance data in three CWs showed some substantial reduction of organic and nutrient loads, albeit failing to meet the desired discharge limits to the receiving environment. Appropriate guidelines could only help in improving the performance of these systems and ensure longer life span. The results from this study have helped in developing an Operation and Maintenance Manual that has specific instructions to meet the needs of CW owners and operators in East Africa. The level of detail of the O&M, has taken into consideration the site-specific aspects such as size and complexity of the CW systems visited and studied.

10.1.6 References

APHA, AWWA and WEF (1998). Standard Methods of Examination of Water and Wastewater. Lenore S. Clescerl, Arnold E. Greenberg, Andrew D. Eaton. American. Public Health Association. Washington DC. ISBN: 0875532357 DDC: 628.161.

Baharell, M. (2004). Operation and maintenance of constructed wetland. In: Wetland Ecosystems in Asia: Function and Management (M. H. Wong, ed.). Elsevier B.V. pp 347–359.

Baharell, M., Kuginis, L., and White, G. (1998). Operation, Maintenance and Monitoring. NSW department of land and water conservation constructed wetlands manual. Orbital Offset Press Pty Ltd., Sydney, 339-413.

Kuginis, L. (1998). Aquatic ecosystem health. NSW department of land and water conservation constructed wetlands manual.

Njau, K. N., Mwegoha, W. J. S., Kimwaga, R. J., and Katima, J. H. Y. (2011). Use of engineered wetlands for onsite treatment of wastewater by the local communities: Experiences from Tanzania. *Water Practice and Technology*, 6(3), wpt2011047.

Vymazal J., Brix H., Cooper P.F., Green M.B., Haberl R. (1998) Constructed Wetlands for Wastewater Treatment in Europe. Backhuys Publishers: Leiden, The Netherlands.

10.2 Treatment Constructed Wetlands in a Community Setting in Mombasa, Kenya

ABSTRACT

The Kenya CW case study is based on the information which was comprehensively discussed by Sarah den Haring in her work published in the book by Stefanakis (2020), Sarah den Haring's abstract is that the constructed wetlands (CW) in the East African Region have primarily been implemented in private institutions such as hotels/ lodges, individual homes, schools, flower farms and tea/coffee estates. The systems have proved to be robust, effective, and low-cost, consistently achieving the Kenyan National Environment Management Authority (NEMA) "discharge to environment" water quality standards. A CW built for a private developer serving a housing estate of 2,650 people in Mombasa has also performed consistently since its construction in 2007 but has encountered a number of issues due to the unique socio-environmental context of the system in terms of management, population growth and sustainability: (1) management; the CW serves a community but no service fee is levied on the users for its operation and maintenance, (2) population growth; the area surrounding the CW has become increasingly populous since its construction causing conflict with the outside community, and (3) sustainability; illegal construction over a seasonal water course restricts all outflow from the system, including natural drainage (storm flow). This chapter aims to demonstrate that privately operated CWs can be a valuable and effective means of decentralized wastewater treatment in rapidly urbanizing areas in the tropics, but that socio-environmental factors in a community setting must be prioritized to ensure CW longevity.

Keywords: Constructed wetlands, Private sector, Wastewater treatment, Decentralized wastewater treatment (DEWATS), Community sewerage Urban planning, NIMBY, Nature-based solutions.

10.2.1 Introduction and Rationale for Constructed Wetlands

den Haring work in Stefanakis (2020), introduces that sewer systems serve only 9% of the Mombasa population (approximately 100,000 people), the majority of whom are located within 5 km of the Central Business District (CBD) (WASREB, 2019). High costs of infrastructure development and the limited financial capacity of the local water utility, Mombasa Water Supply and Sanitation Company (MOWASSCO), make centralized sewerage and wastewater treatment plant provision hard to achieve for the remaining population (den Haring, 2022).

Decentralized systems therefore play an essential role in the collection and treatment of wastewater, especially considering an un-served population of approximately 1,100,000 (Stefanakis, 2019). Traditionally, in the Mombasa, wastewater is managed using pit latrines or septic tanks followed by direct discharge to the environment, usually via a hand dug soak pit, a combination that achieves primary treatment but poses a risk to underlying aquifers due to discharge of only partially treated water (Munga *et al.*, 2006). This is particularly serious in high-density areas where multiple soak pits result in an irreversible contamination of the groundwater (Hinga, 2016). This could potentially render the groundwater completely unusable for human consumption or that boreholes must be deeply drilled to extreme depths to locate clean water (Chakava *et al.*, 2014). Additionally, where areas are underlain by low infiltration soils such as heavy clay, these structures are ineffective and alternative treatment/disposal options are essential. The practice of constructing soak pits is not encouraged by the National Environmental Management Authority (NEMA) but many landowners are often not aware of alternative options so continue to build them (Munga *et al.*, 2006).

Several decentralized (onsite) wastewater treatment systems have entered the market in Kenya over the last 20 years and the compilation and subsequent enforcement of the Environmental Management and Co-ordination Act 1999 (requiring sites to comply with wastewater discharge criteria) has resulted in many sites utilizing these (den Haring, 2022). The systems range in technical complexity, installation cost and operational and maintenance requirements and may be broadly grouped into “under-ground” or “surface” installations. Underground systems are containerized (off-the- shelf) or masonry (custom built) structures, which usually incorporate a settling chamber and an active (aeration pump) or passive (high surface area media) chamber (den Haring, 2022). They are often used in urban areas where space is a premium and other activities may occur very close to, or even on top of them.

Surface installations include Nature-based Solutions (NBS) such as constructed wetlands (CW) (Stefanakis *et al.*, 2021; Oral *et al.*, 2021). The systems utilize natural processes to create various environments conducive for the removal of pollutants including biochemical degradation by microbes, adsorption and absorption to the gravel matrix, plant uptake and physical filtration (García *et al.*, 2010; Stefanakis, (2020)). As nature-based systems, CWs provide a sustainable and also cost-effective solution Stefanakis, (2019), even when applied under hot or arid environments (Stefanakis (2020), Zahui *et al.*, 2021). A growing number of sites are now utilizing CW since their value was initially identified in a system treating domestic effluent at the Carnivore Restaurant and Splash Water Park in Nairobi in 1994 (Matiru *et al.*, 2002). CW are designed on a site-by-site basis and have been used successfully to treat not only domestic but also industrial, commercial, and agricultural effluent in Kenya (Nzengy'a and Wishitemi, 2001; Bodin and Persson, 2012; Mburu *et al*., 2013; Bundi and Njeru, 2018; Makopondo *et al*., 2020).

Despite good results achieved from CW in Kenya, there are still barriers preventing their uptake on a larger scale. GreenWater (GW), one of the companies in Kenya with sufficient capacity to design and construct CW, reported over 15 yearsof operation they experienced lack of awareness of CW within water utilities as a viable option and reluctance by NEMA to approve the systems. These barriers appear to be associated with lack of information about CW.

The value of the CWs has, however, been recognized by private companies/ individuals who collectively have built approximately 40 CW in Kenya, one of which is in the Mombasa area. Located more than 10 km from the nearest sewer network, the housing estate to the north of Mombasa town in Kenya has three decentralized on-site wastewater treatment systems that serve a total population of more than10,000 people. Despite the lack of wastewater regulations or municipal services during construction in the 1980s, the developer recognized the importance of making provision for the conveyance, treatment, and disposal of wastewater generated by their housing. As such, areas of land at the lower end of the estate were left for the purpose of on-site wastewater treatment. The systems comprise waste stabilization ponds, oxidation ponds and a CW; each serving a distinct part of the estate. Despite the forward thinking of the developer in respect to wastewater treatment, the social environment has significantly changed since project inception. Annual population growth in Mombasa between the years 2007–2020 was 3–3.5%, representing a population increase from 854,000 to 1.25 million. This is a little higher than the national population growth rate of 2.5% due to the enhanced movement of the population towards urban centres. This is particularly noticeable in the housing estate area, the population density of which was 2029 people/km^2 in 2009 and is projected to be 10,000 people/km^2 in 2040, almost a 500% increase (JICA, 2015).

Mombasa is a typical example of many cities in Less Developed Countries (LDCs) with high urbanization rates. Infrastructure services, such as sewer systems and wastewater treatment plants, are often inadequate or missing for the existing population, l*et al*one the new arrivals (den Haring, 2022). Decentralized wastewater treatment plants such as CW can therefore play a vital role in bridging the gap between private developers and public water and sanitation service providers, though for this arrangement to be successful in the long-term a certain enabling environment must be in place (Oral *et al*., 2021). The CW at Mombasa housing estate that presented in this chapter is a unique example of a CW in such a setting and over the last 14 years has highlighted a number of valuable insights, pitfalls and lessons that may be applied to comparable settings (den Haring, 2022).

10.2.2 CW System Description (location size, type of CW, the design, and operating conditions)

10.2.2.1 Location

Mombasa lies at 4.04°S 39.66°E on the southeastern Kenyan coast. It experiences a tropical monsoon climate with south westerly trade winds blowing up the coast from April to September and a north easterly wind blowing the opposite direction from October to March (den Haring, 2022). The rain is distributed between two rainy seasons, the "long rains" in April to June and the "short rains" from October to November with an annual total of 997 mm. Average annual temperature is 26.1 °C with a range of 24.3–28.0 °C. A maximum temperature of 31.9 °C is experienced in February and minimum of 22.4 °C in August. Humidity is high throughout the year at an averageof 77% with a variation of +/−4% (den Haring, 2022).

10.2.2.2 Constructed Wetland Design and Operation

The project location is indicated in Fig. 10.2. The Mombasa CW serves the oldest part of a housing estate where quality affordable houses constructed between 20 – 40 years ago have now been sold to individuals or managed on a letting basis. Current house value is approximately 50,000 –75,000 USD and rental value between 200 – 400 USD per month (. den Haring, 2022). The developers constructed a sewer system and septic tank for the estate, but the underlying heavy clay prevented the use of soak pits for final disposal. The result was the utilization of a series of informally operated shallow infiltration ponds to absorb and evaporate the septic tank effluent. In 2007, the ponds were failing to adequately manage (absorb) this water so GreenWater (GW),a Kenyan based CW design and construction company, was engaged to rehabilitatethe system to operate correctly as a CW and improve the effluent quality to meet NEMA discharge to environment and irrigation standards (den Haring, 2022 and Stefanakis (2020)).

Wastewater generated from 638 households (approximately 2338 people) in thesouthern part of the estate is directed to the CW system via a sewer network as shown on Figure 10.2 (den Haring, 2022). A further input of water was discovered illegally connecting an additional plot comprising approximately 300 people in 73 households). No data was available regarding volumes of wastewater entering the existing system, so estimates were generated using water bills and industry average figures (den Haring, 2022).

Figure 10.2: Location of constructed wetland (CW) in Mombasa, Kenya. (Google maps 2021 (den Haring, (2022) in Stefanakis (2020))

Water supply (consumption) data per capita was collected by GW through enquiries to several families about their water bill costs and equated to a volume based on the progressive pricing scale of the municipal water company (den Haring, 2022). This gave a volume of 100 L/person/day, in line with available literature regarding peri-urban housing in developing countries (Mara *et al*., 1992; Kayombo *et al*., 2004; Von Sperling, 2007) and). The contributing population of 2,633 people consumes an estimated total of 263,000 L/day (263 m^3), of which about 80% is expected to enter the wastewater drainage system—approximately 210 m^3/day. This is equivalent to 1400 PE based on hydraulic loading (British Water, 2013).

The CW was constructed utilizing the available area of approximately 10,000 m^3 and indicated on Figure 10.3. Sewage arrives at the treatment area and enters a septic tank (volume of 350 m^3) with internal baffle walls. Settled effluent is then passed to a holding tank from where it is pumped up into the first stage of the CW. After this point the system operates entirely by gravity (S. den Haring, 2022).

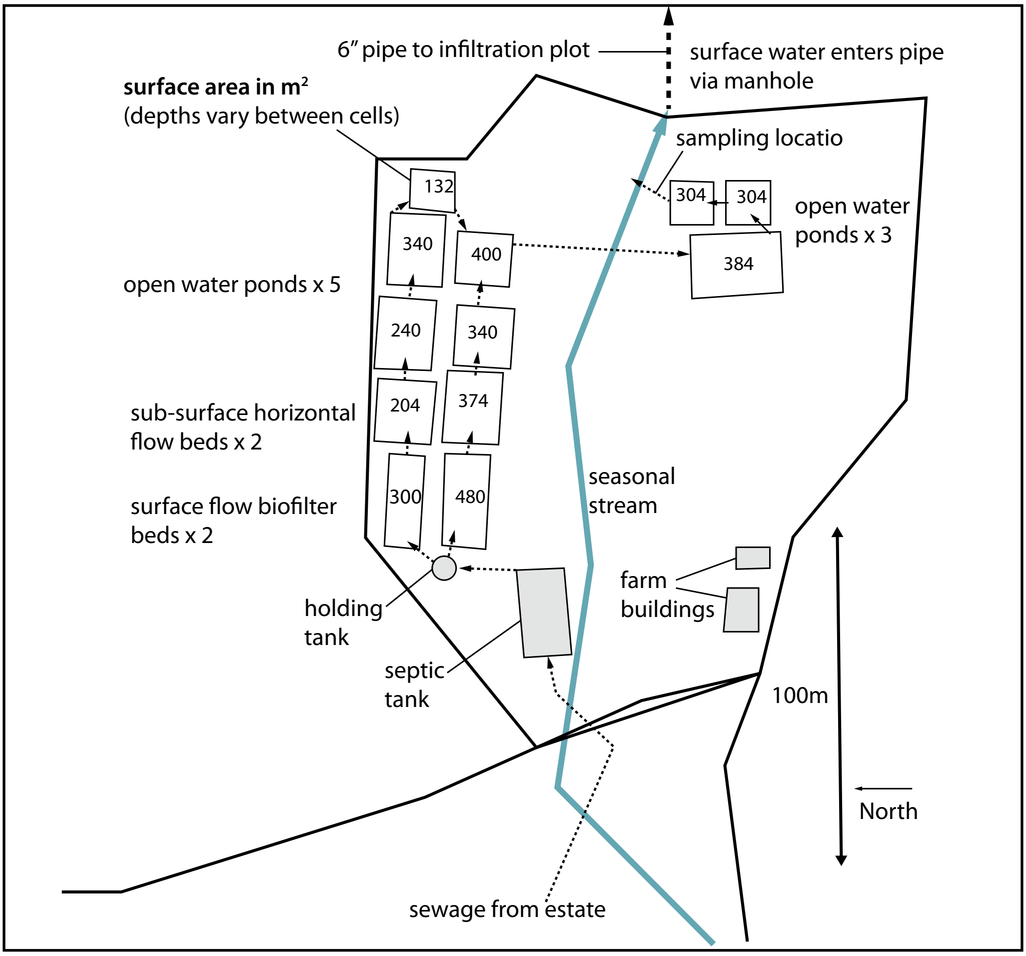


Figure 10.3: Constructed wetland layout (den Haring, 2022)

The first stage beds have been dividedinto two parallel sections so that water may be directed along lines, one, or neither, depending on flow rates and maintenance requirements. The two lines joinfor the second stage ponds. All water passes through the following system cells (den Haring, 2022):

- *Surface flow biofilter*: rows of Vetiver grass (*Chrysopogon zizanioides*) entrap fats,oils, and greases (FOG) and scum.
- *Sub-surface horizontal flow CW*: 40 cm deep, 1–2" washed gravel planted with Typha grass (*Typha latifolia*).
- *Open water ponds*: 60 cm deep ponds with floating plants and Vetiver grass along margins, followed by 30 cm deep ponds to enhance UV action with planted ***hyacinth*** along margins.

The theoretical hydraulic retention time (HRT) of the system is 6.8 days. The wastewater sampling point is the outlet from the final pond prior to discharge into the seasonal watercourse as indicated on Figure 10.3. The treated effluent has been sampledsince rehabilitation in 2007 on a quarterly basis in line with NEMA requirements representing a total of 34 samples (den Haring, 2022). Sampling parameters and their corresponding limits are specified by the NEMA Environmental Management and Coordination,(Water Quality) Regulations 2006 as per Table 10.2. The samples were collected under ISO 5667-16:2017 and tested under the methodology detailed in Table 10.4 byNEMA approved laboratory. The developer is responsible for all costs relatingto sampling (den Haring, 2022).

Intermittent municipal water supply in the estate occasionally causes water shortages, resulting in low volumes of wastewater, reduced water levels in the pondsand zero flow at the outlet. In this instance, sampling is delayed until the outlet is discharging (den Haring, 2022).

Table 10.2: Water sampling parameters, limits and testing methodology (den Haring, 2022)

Parameter	Unit	NEMA limit	Test method
pH	pH scale	6.5–8.5	APHA 4500-H*B
Biological oxygen demand (BOD)	mg/L	30	AOAC 973.44
Chemical oxygen demand (COD)	mg/L	50	APHA 5220B
Total suspended solids (TSS)	mg/L	30	APHA 2540D
Total dissolved solids (TDS)	mg/L	1200	APHA 2540C
Total coliforms	CFU/100 mL	1000	KS 05459
Escherichia coli	CFU/100 mL	Nil	APHA 9221G
Colour	Hazen units	15	APHA 2120B
Ammonia	mg/L	100	APHA 4500 NH_3
Oil & grease	mg/L	Nil	APHA 5520C
Total phosphorus	mg/L	2	APHA 4500 P E
Copper as Cu	mg/L	1.0	APHA 3111B

10.2.3 CW System Pollutants Removal Performance

10.2.3.1 System Pollutants Removal Performance

Effluent results for the last five years (a total of 13 samples) are summarized in Table 10.3 for the indicator parameters pH, BOD, COD and TSS (den Haring, 2022). The results show the CW is achieving removal efficiencies for BOD of 86%, COD of 96% and TSS of 94% (den Haring in Stefanakis (2020), 2022). The average values of the treated effluent at the outlet are mostly within the NEMA discharge to environment levels (Environmental Management and Coordination, Water Quality Regulations 2006), the only exception to this is COD with an average outlet concentration of 54 mg/L, marginally higher than the NEMA limit of 50 mg/L (den Haring in Stefanakis (2020), 2022)The elevated average value is due to a single sample on 14th November 2018 that had a COD of 224 mg/L and BOD of 75 mg/L, the only instance out of 13 samples where any parameters failed (den Haring in Stefanakis (2020), 2022). A field inspection in December 2018 by GW suggested these elevated results could be because of surface water entering the CW from drainage failure due to solid waste blockages at a time when maintenance staff had been reduced (den Haring in Stefanakis (2020), 2022)

The single sample failure over the five-year period indicates the CW is perform ing to a satisfactory level in terms of design and operation, but that continual maintenance of the CW and neighbouring area is necessary to avoid failure (den Haring in Stefanakis (2020), 2022).

10.2.3.2 Operation and Maintenance of the CW

A team comprising 3 – 6 men is responsible for the daily management and operation of the system, maintaining the pump and plants and clearing blockages along the sewer system (den Haring in Stefanakis (2020), 2022). This team is paid directly by the developer. A local Non-Governmental Organization (NGO) lends support on an occasional basis with 2 or 3 people for large jobs such as clearing surface channels of solid waste or removing large areas of biomass from the treatment systems (den Haring in Stefanakis (2020), 2022). Activities for the regular maintenance team include (den Haring in Stefanakis (2020), 2022):

- Monthly plant trimming (wetland plants around pond margins)
- Quarterly plant removal (floating plants in ponds)
- Bi-annual trimming of plants in gravel bed
- Ensuring unrestricted flow of wastewater through network into treatment systems (fixing blockages and broken pipes)
- Ensuring unrestricted flow of storm water along surface drains into water courses (clearing channels and fixing pipes) and repairing inspection chambers when damaged
- Managing the pump to control inflow of settled effluent into the CW

Table 10.3: Water sampling results (average values) (den Haring in Stefanakis (2020), 2022)

Parameter	Unit	NEMA limit	Inlet (aver.)	Outlet (aver.)	Standard deviation (n = 13)	Min- Max	Removal %
pH	–	6.5–8.5	7.67	7.5	0.6	6.8–8.1	n/a
BOD	mg/L	30	146	20	13	6–75	86
COD	mg/L	50	1500	54	25	16–224	96
TSS	mg/L	30	225	13.2	4.5	6–21.6	94

Note: *n/a* not applicable

Other costs associated with operation of the CW are the annual NEMA license fee, quarterly sampling fees, consultant advisory costs and emptying of sludge from the septic tank as detailed on Table 10.4 (den Haring in Stefanakis (2020), 2022)

Table 10.4: Monthly operation and maintenance costs for the CW in USD (den Haring in Stefanakis (2020), 2022)

Item	Details	Cost (USD)/month
Labour	Clearing drains/CW upkeep	450
Consultancy	GW oversight	75
Power	Electricity for pump	300
Effluent discharge license	NEMA	85
Water analyses	Laboratory analyses for NEMA	130
Materials	Plumbing items, maintenance equipmentetc.	200
Sludge removal	Septic tank volume 350 m^3, every 5 years	98
	Total monthly cost =	1338

In addition to running costs, the construction cost of the system must also be considered in terms of developer investment. This includes the relative value of the land (900,000 USD) and cost of rehabilitating the CW in 2007 (50,000 USD) (den Haring in Stefanakis (2020), 2022). The original construction cost was not available for inclusion in the calculation. The total investment of the developer in this CW since 2007 (land, system rehabilitation and running costs) is therefore approximately 1,160,000 USD. None of this is recovered from the residents served by the CW (den Haring in Stefanakis (2020), 2022).

10.2.3.3 Management and Regulation of the CW

Societal factors governing the operation of this CW influence the long-term sustain-ability of the system whilst the CW has achieved adequate wastewater treatment since its rehabilitation in 2007, several socio-environmental issues are now impacting the acceptability and viability of the system (den Haring in Stefanakis (2020), 2022). These are underpinned by the responsibilities and relationships between the developer, the community, regulatory organizations and the County Government. The roles of these groups are considered below with respect to concerns and solutions raised regarding the CW (den Haring in Stefanakis (2020), 2022).

10.2.3.3.1 Role of the Developer

The Developer's role is not clearly defined as they have informally assumed the role of service provider of the estate by default. There have been no agreements made with the homeowners regarding the provision of drainage services (for sewage and storm water) or payments requested for these services. Should there be an issue in the system (such as a blockage); residents lodge the complaint at the developer's public office after which the maintenance team respond. There is no fee charged for this service (den Haring in Stefanakis (2020), 2022).

The developer has no jurisdiction regarding illegal connections to their sewer line. The extent of these connections is not known but was estimated at an additional 13% of the estate load in 2007 (den Haring in Stefanakis (2020), 2022). Ongoing construction in the proximity of the sewer line since that time may have increased this figure as pressure on land is intense and space for septic tanks and soak pits limited, combined with the impermeable nature of the soil resulting in limited absorption capacity of soak pits. Building regulations are not always enforced by the City Council allowing unlicensed contractors to take a short cut by connecting to the neighbour's sewer and save themselves the cost of septic tank and soak pit construction (den Haring in Stefanakis (2020), 2022).. For a 3 bedroomed home this would be approximately 1500 – 4000 USD Bio septic Sewerage Systems (2021).

10.2.3.3.2 Role of Authorities

The National Environment Management Authority (NEMA), the Water Resource Authority (WRA), the County Government of Mombasa and MOWASSCO are involved with the operation of any sewer and wastewater treatment plant. Their roles are detailed below (den Haring in Stefanakis (2020), 2022).

NEMA is the regulator for all issues relating to wastewater management. NEMAissue Effluent Discharge Licenses (EDLs) to sites discharging wastewater once they have applied and paid an annual fee of 1000 USD (den Haring in Stefanakis (2020), 2022). Quarterly monitoring results must be provided and should these fall out with the Discharge to Environment standards (as stipulated in the Environmental Management and Coordination, Water Quality Regulations 2006), NEMA may issue an Improvement Order (IO). Should the IO not be adequately addressed, NEMA may then act to close site activities, sometimes enforced with the aid of the armed Administration Police. NEMA are also responsible for the approval of an Environmental and Social Impact Assessment (ESIA), due at project inception (den Haring in Stefanakis (2020), 2022).The ESIA includes a review of the surrounding land use at the time and requires inter- views with residents. This CW was constructed in advance of the regulations being enacted and therefore an ESIA was not completed (den Haring in Stefanakis (2020), 2022). To date, NEMA has been involved with the site only during issues of conflict resolution with neighbours andprovides no advisory service. WRA have the responsibility to oversee all issues in relation to water supply as provided under Sections 12 and 13 of the Water Act, 2016.

These are to (den Haring in Stefanakis (2020), 2022).

- Formulate and enforce standards, procedures, and regulations for the management and use of water resources and flood mitigation.
- Regulate the management and use of water resources.

WRA are involved in the site from the point of view of the seasonal watercourse (den Haring in Stefanakis (2020), 2022).. This passes through the centre of the plot and is dry for approximately 6 months of the year. During the rainy season, surface water from the upstream catchment area naturally fills this channel and is directed towards the southeast to the sea. Several constructions now block this channel and prevent the free flow of water causing flooding. No solution has been achieved with this issue to date (den Haring in Stefanakis (2020), 2022).

MOWASSCO are responsible for the provision of water and sanitation services.At this location no sanitation/sewerage services have yet been provided by them. The development of future sewerage services in the Mombasa area has beenincluded in the MOWASSCO Master Plan but this only allows for the construction of public and community toilets and septic tanks by 2030 that will not affect this location's sewer system JICA (2015). Drinking water is supplied via the freshwater distribution network, originating from either Mzima Springs 240 km to the northwest, Tuiborehole to the south, Malele Spring 50 km to the south and or Baricho Dam 105 km to the north (den Haring in Stefanakis (2020), 2022).

The County Government of Mombasa is responsible for all aspects of land use, planning and infrastructure (roads, streetlights, storm drainage and solid waste management) (den Haring in Stefanakis (2020), 2022). Urban planning is defined as: a technical and political process concerned with the development and design of land use and the built environment, including air, water, and the infrastructure passing into and out of urban areas, such as transportation, communications, and distribution networks (McGill University, n.d). Urban planning was not widespread in the 1980s when the estate was constructed and even now is not always fully integrated into project planning and infrastructure development in Kenya, despite advances in legislation and enforcement.

The County Government collect annual Land Rates from all homeowners in the order of 10–20 USD for a typical house in the estate, irrespective of actual services provided. (den Haring in Stefanakis (2020), 2022). Some of these services such as drainage, sewerage and wastewater treatment are being provided by the developer. Whilst the developer has made requeststo the Council to take responsibility for the maintenance of the sewage and wastewater treatment system, this has not occurred as the system was privately constructed and the mechanisms for handing over are not in place (den Haring in Stefanakis (2020), 2022)..

10.2.4 Observed and Documented Design and Operational Challenges

Several issues were identified by GW as impacting on the efficacy of the CW since their involvement commenced in 2007 (den Haring in Stefanakis (2020), 2022).

10.2.4.1 Operational Issues

CW operation may be compromised by irregular flow into the system. This is experienced during times of excessively high or low flows in the sewer system and power and labour availability restricting operating hours of the CW system. Faecal sludge management is also problematic for several reasons detailed below (den Haring in Stefanakis (2020), 2022).

Operational issues are encountered during heavy rains. Despite the provision ofsurface water drainage to direct stormwater safely away from the estate, some areas inevitably experience flooding, often due to solid waste blocking drainage channels (den Haring in Stefanakis (2020), 2022). Residents in these areas occasionally endeavour to drain the flood water from their plots by breaking open the sewer lines at nearby inspection chambers. This results in surges of flow into the CW with a reduction of HRT (den Haring in Stefanakis (2020), 2022). Reduced HRT may result inreduced treatment despite the issue of dilution (Schultze-Nobre *et al.*, 2017; Gomes *et al.*, 2018; Ramírez *et al.*, 2019).). The maintenance team monitor the occurrence of flooding and bypassing into the sewer network and aim to discuss this with residents when fixing these areas (den Haring in Stefanakis (2020), 2022).

Water scarcity is also often experienced at the site during the long dry season of December to March when the supply is interrupted due to reduced water levels at (den Haring in Stefanakis (2020), 2022). Interruptions with the municipal water supply in the estate result in very low or no flow of wastewater passing through the CW, causing the final stage shallow ponds to dry out completely and outflow to reduce to zero. This causes plants to dieand impacts on the microbial population that comprise an essential component of the CW (den Haring in Stefanakis (2020), 2022).

Issues regarding power supply have been experienced since project rehabilitation in 2007. The system is reliant on power to pump water into the first ponds (den Haring in Stefanakis (2020), 2022). The electricity supply in this area was erratic until 2019, with users experiencing periods between a few hours and a few days without power. In addition, the pump is manually operated and the absence of a nighttime operator means the pump may only run from 7 am till 6 pm (den Haring in Stefanakis (2020), 2022). Lack of power results in the water level of the holding tank rising as wastewater is no longer lifted into the CW. Once at a certain height, wastewater reaches an overflow pipe and is directed around the CW to a soak pit on the site where water slowly infiltrates, providing the flow is not of an extended duration. In 2012–14, power cuts lasting more than 3 days were experienced on a regular basis, oversaturating the soak pit and leading to a number of sewage overflows into the watercourse (den Haring in Stefanakis (2020), 2022). Complaints were lodged with NEMA by the downstream neighbours who observed the deterioration of water quality in the surface water channel passing their properties. To address these periods of no power, the developers considered in 2014 the addition of a solar system to maintain operations (den Haring in Stefanakis (2020), 2022). The approximate purchase and installation cost of this was 13,000 USD Existing annual power costs to run the pump are 3600 USD meaning the system would cover its investment cost after 4 years. Retaining the existing pump and engaging a night-time operator would allow for continual operation of the pump and inflow to the CW be distributed equally across 24 hours. The

Figure 10.4: Comparison of the project site in 2008 (left) and 2021 (right). (Google Earth Images 2008 and 2021)

developers have not had sufficient capital to invest in this initiative (den Haring in Stefanakis (2020), 2022)

There is no provision for faecal sludge management (FSM) at the site (den Haring in Stefanakis (2020), 2022). Sludge is generated within the septic tank and must be removed on a periodic basis, representing a high cost to the developer (approximately 6000 USD). Due to lack ofrevenue collected by the developer, sludge removal is not performed regularly, resulting in reduced quality effluent emanating from the septic tank as operational volume, residence time and retention of particles are reduced (den Haring in Stefanakis (2020), 2022). Poor final effluent quality was associated with this excessive sludge build up (observed by GW) and rectified in 2014, after which the final effluent improved to within Discharge to Environment levels (den Haring in Stefanakis (2020), 2022).

10.2.4.2 Societal Issues

Several issues have developed from lack of successful community engagement over the last two decades, resulting in suspicion and resentment directed towards the (den Haring in Stefanakis (2020), 2022). The "not in my back yard" (NIMBY) attitude has grown as the land usesurrounding the CW has changed from agricultural to residential as shown in Figure 10.4.

Specifically, five complaints have been lodged with NEMA in the last10 years by nearby residents regarding the CW, to the south where residents object to treated effluent and storm water flowing through this area (den Haring in Stefanakis (2020), 2022). These houses are downstream of the CW and outside the estate, so do not benefit from thesewer system. Some of these houses have been constructed over the seasonal waterway without the consent of the County Council and WRA, resulting in flooding during the rainy season (S. den Haring, 2022). Many of the houses are for rent, so landlords often lodge complaints when they feel their environment has been disturbed or their house valuecompromised (). Complaints are also lodged due to suspicion of the treated effluent as residents do not have access to the sampling results and fear an impact to their health (den Haring in Stefanakis (2020), 2022). Other residents bordering the northern site boundary have built houses on former agricultural land adjacent to the CW and are located as close as 5 m from the ponds (These residents have raised concerns about odours and pests emanating from the CW, also submitting their complaints to NEMA (den Haring in Stefanakis (2020), 2022).

10.2.5 Lessons Learnt.

The operational and societal concerns have highlighted several issues regarding operating a CW in a rapidly urbanizing location (S. den Haring, 2022). In the case of the Mombasa hous ing estate, urban planning in the 1980s was primarily completed by the individual (the developer) and there was no mechanism to include community consultation (den Haring, 2022). At this time, they received no support or input into the proposed development from other planners such as NEMA and WRA as these bodies had not yet been formed. The water utility MOWASSCO (formerly Mombasa Water and Sewerage Company) had limited legislation on sewerage, no operations in the vicinity and no capacity for supporting private wastewater treatment systems. Mombasa City Council approved engineering designs of the septic tank but did not incorporate or endorse any treatment system following the tank (den Haring, 2022).

Whilst a public utility would have a procedure for citizens to lodge and resolve complaints, no such structure exists for the private developer. When environmental issues relating to the CW arise, these are all directed at the developer as they are identified as the primary service provider (den Haring, 2022). The developer is not an infrastructure provider, recognized in any way by law, but has retained the responsibility of providing this service for the houses they have built Additionally, having provided drainage for storm water and wastewater, residents usually expect the developer to also assume the roles of the municipality (currently lacking) and provide solid waste collection and other services (den Haring, 2022).

In the current light of increased pressure on land from the surrounding population, the developers are currently under pressure to close the CW. The local water utility, MOWASSCO, have not indicated a main line sewer will be provided in this area within their Master Plan so a decentralized system will still be required (den Haring, 2022). An alternative system acceptable in a densely population area could be a contained treatment system with all treated effluent being utilized for irrigation within the site boundaries. This would result in reduced odours and zero discharge off site of treated effluent, but storm water runoff would still need access to pass along its original route (den Haring, 2022).

A rotating biological contactor (RBC) system was considered in 2007 in comparison with the CW, at an installation cost of 200,000 USD with estimated electricity costs of 675 USD/month (den Haring, 2022). This system comprised a settling chamber, two RBCs and a final clarifier. Due to high operational costs and specialist personnel requiredby the RBC, the developer decided that a CW was a more appropriate solution at this time. Despite the RBC becoming increasingly appropriate in the current environment, it is unlikely that the developer would implement an investment of this scale without financial support and a mechanism to allow revenue collection. The most viable long-term solution for the site is to continue CW operations with improved relations with the community, potentially with zero discharge of treated effluent (re-use within the site) (den Haring, 2022). This would be of benefit to the agricultural activities practiced within the site where several banana plants, flowers and fruit trees are grown. Water quality parameters in addition to those for the Discharge to Environment guidelines must be measured to comply with NEMA Eighth Schedule (Microbiological Quality Guidelines for wastewater use in Irrigation) and Ninth Schedule (Standards for Irrigation Water) (den Haring, 2022).

Conflict with the community also occurs due to security and vandalism (den Haring, 2022). Concrete manhole covers are often removed to retrieve and sell the internal reinforcing bar, causing danger to other residents and blockages due to disposal of solid waste intothe system. In a separate part of the estate, the surrounding wall of the oxidation ponds has consistently been destroyed due to theft of the materials (blocks removedfrom the wall for building houses). A cast iron trunk sewer pipe crossing a small watercourse was also stolen resulting in raw sewage discharging directly into the environment. These issues have mostly been resolved with improved access and maintenance of the whole sewer system by the on-site team and several watchmen.

den Haring, (2022) observed that the CW serving the Mombasa housing estate has performed well since its construction in 2007 due to appropriate design and regular maintenance. However, several social, environmental, and operational factors identified at this location should be considered in future CW to make the implementation of CW more sustainable and appealing to private developers (den Haring, 2022).

A significant increase in the number of decentralized wastewater treatment systems in Kenya is critical to ensure "sanitation for all" as part of the Vision for Kenya 2030 and the targets of Sustainable Development Goal 6. Capital investment and operational costs for large centralized systems are often untenable for most Water Service Providers (WSPs) due to lack of funds, so smaller, decentralized systems such as CW (often for the private sector) are required. To achieve this, the enabling environment must be conducive to promote these systems and support the operators. Enabling factors should include all the following points (den Haring, 2022).

- Involvement from the outset of all stakeholders, especially the surrounding com-munity, in the planning process;
- Verification of qualified firms to build CW;
- Increased awareness and acceptance by environmental regulators of CW;
- Mechanisms to allow operators to charge fees to users or be given financial sup- port from the Government for their service (in lieu of sewerage rates from water utility) to cover construction, operation and maintenance costs of sewerage and wastewater treatment systems;
- Development of urban plans in low-income areas;
- Adherence to urban plans (where available) including restrictions on land use change;
- Assessment of life span of CW as part of the urban plan, and replacement with containerized systems or connected to sewer line when necessary and/or possible.

10.2.6 References

Bioseptic Sewerage Systems (2021) Cost of Septic Tank Construction. Available at http:// bioseptic.co.ke

Bodin, H., and Persson, J. (2012). Hydraulic performance of small free water surface constructed wetlands treating sugar factory effluent in western Kenya. *Hydrology Research*, 43(4), 476-488.

British Water, (2013). Flows and loads – 4 sizing criteria, treatment capacity for sewage treatment systems.

British Water, (2013). Flows and loads – 4 sizing criteria, treatment capacity for sewerage treatment systems.

Bundi, L. K., and Njeru, C. W. (2018). Use of vegetative wastewater treatment systems for counties' effluent management in Kenya. Rwanda *Journal of Engineering, Science, Technology and Environment*, 1(1).

Chakava, Y., Franceys, R., and Parker, A. (2014). Private boreholes for Nairobi's urban poor: The stop-gap or the solution?. *Habitat International*, 43, 108-116.

Climate-Data Mombasa (2021). Available at https://en.climate-data.org

den Haring, S. (2022). Constructed Wetlands in a Community Setting in Mombasa, Kenya. In Constructed Wetlands for Wastewater Treatment in Hot and Arid Climates (pp. 137-152). Cham: Springer International Publishing.

Garcia, J., Rousseau, D. P., Morato, J., Lesage, E. L. S., Matamoros, V., and Bayona, J. M. (2010). Contaminant removal processes in subsurface-flow constructed wetlands: a review. *Critical reviews in environmental science and technology*, 40(7), 561-661.

Gomes, A. C., Silva, L., Albuquerque, A., Simões, R., and Stefanakis, A. I. (2018). Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. *Chemosphere*, 207, 430-439.

Hinga, M. (2016). The Effect of Septic Tanks Sewage Disposal System Distances on Borehole Water Quality in Ongata Rongai, Kajiado County, Kenya (Doctoral dissertation, University of Nairobi).

JICA, (2015). Project for formulation of comprehensive development master plan in the Mombasa Gate City in the Republc of Kenya

Kayombo, S. T. S. A., Mbwette, T. S. A., Katima, J. H. Y., Ladegaard, N., and Jørgensen, S. E. (2005). Waste stabilization ponds and constructed wetlands design manual. UNEP-IETC with the Danish International Development Agency (Danida), 1-59.

Makopondo, R. O., Rotich, L. K., and Kamau, C. G. (2020). Potential use and challenges of constructed wetlands for wastewater treatment and conservation in game lodges and resorts in Kenya. T*he Scientific World Journal*, 2020.

Mara, D. D., Mills, S. W., Pearson, H. W., and Alabaster, G. P. (1992). Waste stabilization ponds: a viable alternative for small community treatment systems. *Water and Environment Journal*, 6(1), 72-78.

Matiru, V., Muthiga, N., and Waweru, S. (2002). Community Guide to Environmental Issues: and to the environmental management and co-ordination Act, 1999. Coast Province, Kenya. 56pp.

Mburu, N., Tebitendwa, S. M., Rousseau, D. P., Van Bruggen, J. J. A., and Lens, P. N. (2013). Performance evaluation of horizontal subsurface flow–constructed wetlands for the treatment of domestic wastewater in the tropics. *Journal of Environmental Engineering*, 139(3), 358-367.

McGill University. What is urban planning? Available at https://www.mcgill.ca/urbanplanning/planning

Munga, D., Mwangi, S., Ong'anda, H., Kitheka, J. U., Mwaguni, S. M., Mdoe, F., ... and Opello, G. (2006). Vulnerability and pollution of groundwater in Kisauni, Mombasa, Kenya. In Groundwater pollution in Africa (pp. 227-242). CRC Press.

Nzengy'a, D. M., and Wishitemi, B. L. (2001). The performance of constructed wetlands for, wastewater treatment: a case study of Splash wetland in Nairobi Kenya. *Hydrological processes*, 15(17), 3239-3247.

Oral, H. V., Radinja, M., Rizzo, A., Kearney, K., Andersen, T. R., Krzeminski, P., ... and Carvalho, P. N. (2021). Management of urban waters with nature-based solutions in circular cities—Exemplified through seven urban circularity challenges. *Water*, 13(23), 3334.

Ramírez, S., Torrealba, G., Lameda-Cuicas, E., Molina-Quintero, L., Stefanakis, A. I., and Pire-Sierra, M. C. (2019). Investigation of pilot-scale constructed wetlands treating simulated pre-treated tannery wastewater under tropical climate. C*hemosphere*, 234, 496-504.

Schultze-Nobre, L., Wiessner, A., Bartsch, C., Paschke, H., Stefanakis, A. I., Aylward, L. A., and Kuschk, P. (2017). Removal of dimethylphenols and ammonium in laboratory-scale horizontal subsurface flow constructed wetlands. *Engineering in Life Sciences*, 17(12), 1224-1233.

Stefanakis, A. I. (2019). The role of constructed wetlands as green infrastructure for sustainable urban water management. *Sustainability*, 11(24), 6981.

Stefanakis, A. I. (2020). Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. *Water*, 12(6), 1665.

Stefanakis, A. I. (2020). Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challenges and case studies in the Middle East. *Water*, 12(6), 1665.

Stefanakis, A. I. (2020). Constructed wetlands: description and benefits of an eco-tech water treatment system. In Waste management: concepts, methodologies, tools, and applications (pp. 503-525). IGI Global.

Stefanakis, A. I., Calheiros, C. S., and Nikolaou, I. (2021). Nature-based solutions as a tool in the new circular economic model for climate change adaptation. *Circular Economy and Sustainability*, 1, 303-318.

Von Sperling, M. (2007). Waste stabilisation ponds. IWA publishing.

WASREB, Impact Report 16, 2019/20

Zahui, F. M., Ouattara, J. M. P., Kamagaté, M., Coulibaly, L., and Stefanakis, A. I. (2021). Effect of plant species on the performance and bacteria density profile in vertical flow constructed wetlands for domestic wastewater treatment in a tropical climate. *Water*, 13(24), 3485.

10.3 Performance of a Constructed Wetland Treating Synthetic Greywater in Mauritius

ABSTRACT

The CW case for Mauritius is wholly based on the discussion presented in the research work by N. Nurmahomed *et al*., (2022), fairly new research findings published in the Bioresource Technology Reports Journal. Interestingly, this Mauritius case is presenting rather different CW treatment dimension focusing solely on greywater. The abstract of this case study is that the study aimed at providing design guidelines for a Horizontal sub surface flow constructed wetland treating greywater from single household in Tropical Island. The system was operated using synthetic greywater at variable operating conditions over a period of 41 weeks. The performance was assessed in terms of biological oxygen demand removal efficiency. The biological oxygen demand rate constant was determined using the first order plug flow model by fitting the observed values along the bed. A mean removal efficiency of 84 ± 3.5% (n = 32) was achieved for this system. The biological oxygen demand rate constant values ranging from 0.34–0.50 m/ d and averaging to 0.43 ± 0.06 m/d (n = 32) were obtained. Hence rate constants have been developed and can be used for sizing of beds treating greywater in tropical regions.

Keywords: Constructed wetland design, Biological oxygen demand, Rate constant, Plug flow model

10.3.1 Introduction and Rationale for Constructed Wetlands

The Nurmahomed *et al*., (2022) noted that the concept of greywater reuse is becoming a popular practice with rising concerns over the *availability* of fresh water (Prodanovic *et al*., 2017). Treated greywater is regarded as a source of water for water stressed countries (Arunbabu *et al*., 2015; Ragen, 2016). Maimon *et al*., (2014) and Ragen, (2016) stated that greywater reclamation acts as a water supply for non-drinkable purposes (Boddu *et al*., 2016) for instance (1) irrigating plants (2) flushing of toilet and (3) washing of clothes. Even though there are different greywater treatment systems that are in use (Li *et al*., 2008), constructed wetland is a viable solution to water shortage which favours positive socioeconomic, and environmental impact (Avery *et al*., 2007; Gharbia *et al*., 2016; Wang *et al*., 2017;).

Constructed wetland (CW) technology is recognized as an "Ecosystem reactor" which has the unique characteristics of removing all types of pollutants (Kadlec and Wallace, 2008; Bosma *et al*., 2017; Leguizamo *et al*., 2017). Hence, constructed wetland is regarded as a feasible wastewater treatment system treating many types of wastewaters (Vymazal, 2011). According to Pavlineri *et al*. (2017) and Machado *et al*., (2017), constructed wetland is an engineered system that mimics the water treatment processes that occur in natural wetland via biological, chemical, and physical means. The system consists of wetland vegetation, substrate, and an assemblage of microbes to treat wastewater in a controlled way (Zhang *et al.*, 2015; Ragen, 2016; Wang *et al.*, 2017).

Among the categories of CW, horizontal sub-surface flow constructed wetland (HSSFCW) which this study addresses, has gained increasing attention worldwide. HSSFCW provides advantages such as: (1) it is easy to operate, (2) uses less or no amount of energy, (3) can resist variations in high hydraulic and organic loading and (4) prevents mosquito breeding as water flow below the substrate (Saeed and Sun, 2012; Antonopoulou *et al.*, 2013; Vakil *et al.*, 2014; Arunbabu *et al.*, 2015; Osorio *et al.*, 2017 and Wang *et al.*, 2017) and concluded that greywater is deficient in nutrients. For this reason, the HSSFCW, which does not effectively remove nutrients, was selected in this study. Therefore, the removal of nutrients was not investigated, and the main focus was on organic matter removal.

The kBOD which is defined as the BOD rate constant, is a critical design factor used in the sizing of a HSSFCW. The kBOD indicates how fast BOD degradation occurs in the system. Inappropriate values selected will undeniably lead to an oversize or undersize system. The European Design and Operational Guidelines for Reed Bed Treatment Systems proposed a kBOD = 0.1 m/d for temperate regions (IWA (2001). Nevertheless, due to the absence of operational guidelines for tropical constructed wetland, Ragen (2016) has proved in his study that such value is un- suitable to be used due to the tropical climatic conditions prevailing in Mauritius. The author analysed a 2½-year old HSSFCW in Mauritius and suggested a range of kBOD values from 0.31–0.48 m/d and a mean of 0.39 ± 0.5 m/d. This clearly showed that the value obtained was 3–4 times greater than that proposed by the European Guidelines. Ragen (2016) proposed the following range of operating parameters, namely (1) Hydraulic loading rate (HLR) of 0.16–0.26 m/d, (2) water depth of 0.40–0.45 m, (3) Hydraulic retention time (HRT) of 17–29 h and (4) OSLR of 0.010–0.030 kgBOD/m^2·d. The main aims of this study were (1) to confirm/consolidate/refine these new designs and operating conditions by investigating a 2½ year old HSSFCW which treated synthetic greywater and (2) to investigate the bed performance in terms of BOD removal efficiency.

10.3.2 System Description (size, type of CW, the design, and operating conditions)

10.3.2.1 Synthetic Greywater Preparation

Ramana (2015) investigated a HSSFCW treating real greywater which had a BOD concentration of 92–262 mg/l with a mean BOD of 166 ± 47 mg/L and COD concentration of 183–677 mg/L with a mean COD of 381 ± 178 mg/L. Ragen (2016) also operated a HSSFCW purifying real greywater of BOD and COD concentration of range of 46–150 mg/L with a mean of 89 ± 22 mg/L and 79–577 mg/L of mean of 176 ± 700 mg/L. Nevertheless, Ramana (2015) and Ragen (2016) used an oil trap just before their HSSFCW. For this study, synthetic greywater was prepared according to Weerakoon *et al.* (2013) method whereby 11.011 g of ammonium acetate, 3.462 g of $Na_2HPO_4{\cdot}7H_2O$ and 50 g of granular sugar were dissolved in 200 L of tap water so as to make sure that the BOD and COD concentration are within the range characterized by Ramana (2015) and Ragen (2016). In order to achieve a continuous flow, 400 L of synthetic greywater was prepared and fed into the system.

10.3.2.2 Set up of Experimental HSSFCW.

The HSSFCW used in this study was previously constructed and started up at the University of Mauritius, Reduit (20˚13'59.9"S 57˚29'57.5"E) by Phillipe (2015) according to the guidelines provided in USEPA (2000) and IWA (2001). The experimental system of dimensions 3.0 m × 0.5 m × 0.5 m, built with a slope of 1%, received synthetic influent which was prepared in a 400 L container. The HSSFCW consisted of inlet and outlet structures of length and width of 0.5 m and contained stones of 50–200 mm size. The bed consisted of washed 6 mm gravels (Phillipe, 2015) which have high hydraulic permeability (USEPA, 2000; IWA, 2001; Machado *et al.*, 2017). According to Manios *et al.* (2003), the best way to reduce clogging is by using fine gravels with enough gradients to keep the subsurface flow. Moreover, three perforated PVC pipes having diameter of 50 mm were implemented in the bed to 0.5 m in between each other in order to provide oxygen to the filter media and to collect samples for analysis (USEPA, 2000; Osorio *et al.*, 2017). Cattails (*Typha latifolia*) were planted in the system at a density of 8 plants/m^2, owing to their easy adaptation to wetland conditions and effectiveness in removing organic matter. Dornelas *et al.*, (2009) validated that *Typha latifolia* produced positive results for COD and BOD elimination. After the set-up of the system, the HSSFCW was flooded with synthetic greywater for two weeks to remove impurities from the gravels and stones. The influent line was fitted with ball valve to control the flow (HRT/HLR) of the system. The inlet structure provided a continuous flow in the bed. The depth of water was controlled by a T-perforated pipe which was fitted at the outlet structure. Figure 10.5 shows the experimental set up.

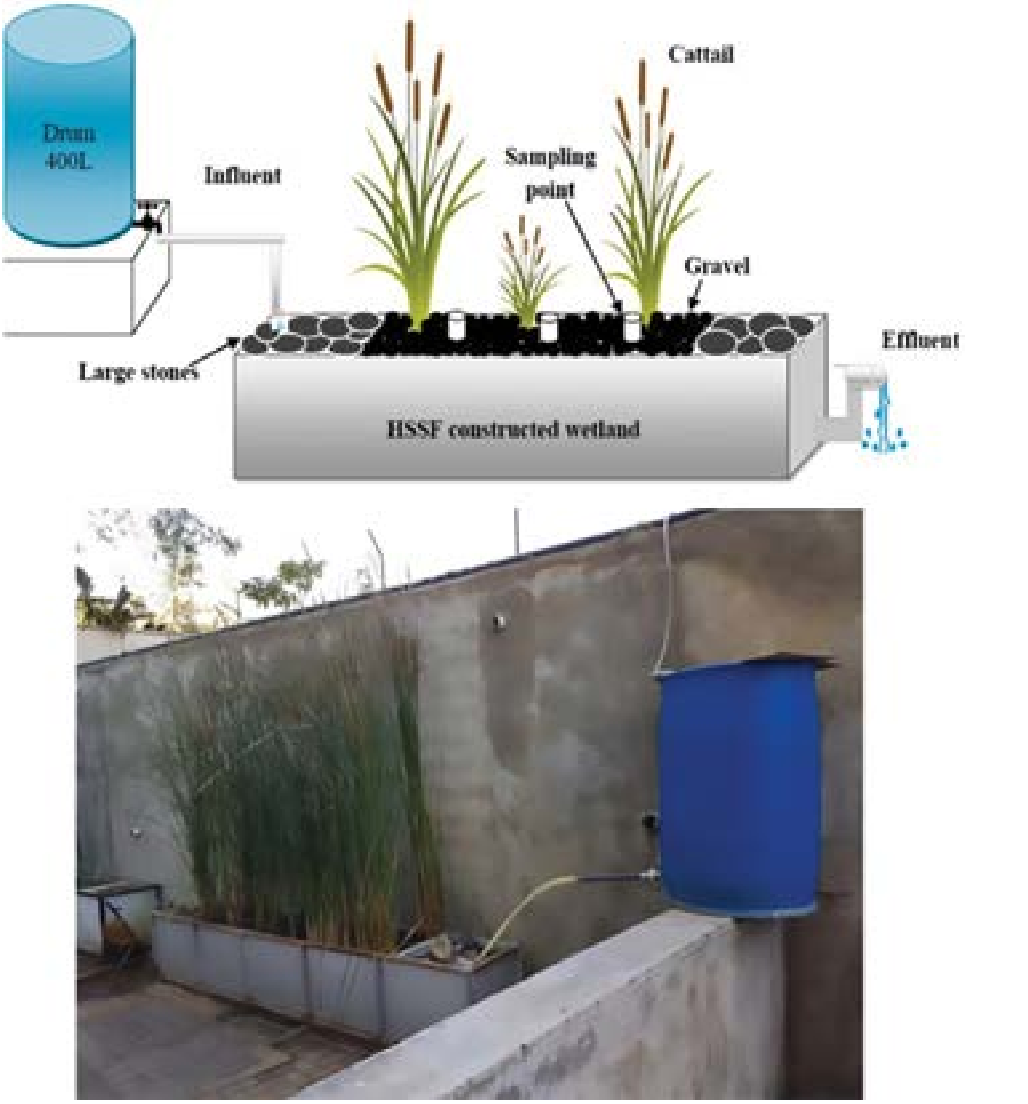


Figure 10.5: Set up of the experimental bed. (Nurmahomed et al., 2022)

10.3.2.3 Investigation of System Performance

Synthetic greywater was fed into the system continuously and run at different operating parameters. The experimental setup was initiated by Phillipe (2015) at an HRT of 24 h, with a water depth of 0.40 m, for a period of nine weeks, and at an OSLR ranging from 0.09 to 0.019 kg BOD/m^2·d. In this study, 32 runs were performed over 2½ year period and the system was operated at three HRTs *i.e.*, 24 h, 22 h and 20 h and at two water depths (0.40 and 0.45 m) with an OSLR ranging from 0.029–0.053 kgBOD/m^2·d as proposed by Ragen (2016). The bed performance was analysed s from its start-up in 2015 up to this study at varied operating variables. Samples were taken from the inlet, outlet and the three perforated pipes and were analysed for BOD and COD in accordance with APHA (1995). The analysis was done in duplicate for BOD and three times for COD.

10.3.2.4 First Order Plug Flow Model

The Kickuth (1977) equation as per Eq. (10.1) was originated from the K-C model also known as the first order plug flow model. This equation is identified as the most suitable equation describing the microbial removal of BOD along the system as stated by USEPA (2000), IWA (2001), Von Sperling and de Paoli (2013) and Ragen (2016)

$$A_h = Q\,(\ln C_o - \ln C_t)/kBOD \qquad (10.1)$$

where: -

A_h: bed surface area (m^2);

Q: influent flow rate (m^3/d);

C_o: average inlet BOD (mg/l);

C_t: average outlet BOD (mg/l);

kBOD: BOD rate constant (m/d).

The 1st order plug flow model can be represented by Eq. (10.2).

$$C_t = C_0 \text{ exp.-kt} \qquad (10.2)$$

where: -

C_t: final BOD (mg/l);

C_o: influent BOD (mg/l);

k: rate constant (/d);

t: degradation time (d).

The K-C model nevertheless was found unsuitable to be used due to some inconveniences such as (1) ideal conditions are considered which is absent in a HSSFCW, (2) an exponential BOD decrease is predicted following an asymptotic zero value and this does not exist in HSSFCW as stated by Von Sperling and de Paoli (2013). Hence, Kadlec and Knight (1996) reworked the K-C model to K-C* model which indicates a non-zero outlet BOD (Fonder and Xanthoulis, 2007; Akratos and Tsihrintzis, 2007). The lowest BOD value for the wastewater is represented by C* and does not go beyond 10 mg/l (Kadlec and Wallace, 2008). Eq. (10.3) illustrates the K-C* model.

$$C_t - C^* = (C_0 - C^*) \text{ exp.-kt} \qquad (10.3)$$

The kBOD is interrelated to k, which is the rate constant, as given in Eq. (10.4).

$$kBOD = kT\,dn \qquad (10.4)$$

where: -

kBOD: BOD rate constant (m/d).

k: rate constant (/d).

d: water depth (m);

n: porosity (dimensionless).

10.3.2.5 Operating Parameters

The performance of HSSFCW is affected mostly by operating parameters such as HRT, HLR and OSLR. The operating factors are given in Eqs. (10.5), (10.6) and (10.7).

$$HLR = Q/Ah \qquad (10.5)$$

where: -

HLR: hydraulic loading rate (m/d);

Q: flow rate (m^3/d);

Ah: bed surface area (m^2)

$$HLR = Lwd_n/Q \qquad (10.6)$$

where: -

HRT: hydraulic retention time (d);

L: bed length (m); w: bed width (m);

d: average water depth (m);

n: porosity of substrate within the bed (dimensionless).

Q = flow rate (m^3/d).

$$OSLR = QS_o/A_h \qquad (10.7)$$

where: -

OSLR: organic surface loading rate (kgBOD/m^2·d).

Q: flow rate (m^3/d); So: Inlet BOD (kg/m^3).

Ah: bed surface area (m^2).

Table 10.5: HLR effect on performance of the bed (Nurmahomed et al., 2022)

Reference	Change in HLR	Effect on performance
Calheiros *et al.* (2007)	0.006 to 0.18 m/d	With an influent COD averaged at 1598 mg/l, average effluent COD rose from 242 mg/l to 610 mg/l
Trang *et al.* (2010)	0.031 to 0.146 m/d	BOD removal efficiency reduced from 84% to 63%
Weerakoon *et al.* (2013)	0.08 to 0.30 m/d	A reduction in BOD removal efficiency from 90% to 80%
Ragen (2016)	0.474 to 0.863 m/d	A drop in BOD removal efficiency from 72.2 to 49.2%

HLR and HRT are operating parameters that are easy to regulate and are controlled by adjusting the flow rate. Ragen, (2016) mentioned that it is easier to vary HRT and HLR than OSLR as according to the Eq. (7) OSLR is dependent on the inlet BOD of the wastewater, which is extremely unpredictable. As flow is increased through the bed, HLR and OSLR are increased but cause a decrease in HRT. A reduction in HRT will eventually leads to more contact time between the microbes and the organic matter along the bed. Different studies were carried out to evaluate the effect of HLR on the performance of the bed, by increasing the HLR of the HSSFCW. Table 10.5 shows the studies that were conducted.

10.3.2.6 Statistical Analysis

The standard deviation values (STDEV) of (1) influent and outlet BOD and COD, (2) OSLR and (3) BOD removal efficiency was obtained using Excel Software to assess any deviation from their mean values. The IBM SPSS Software version 23.0 was used to conduct (1) paired sample t- test to assess the statistical significance at 5% significance level in the difference of the means of the inlet and outlet BOD and (2) Pearson, Kendall, and Spearman correlation tests to investigate the effect of selected operating variables on the bed performance in terms of the removal efficiency of BOD. The observed BOD values along the bed were fitted into both the K-C and K-C* models, to validate the data of this study. These results should fit well these two models because the bed was run under the plug flow model (Von Sperling and de Paoli, 2013).

10.3.3 CW System Pollutants Removal Performance

10.3.3.1 Characteristics of Synthetic Greywater

The synthetic greywater had a BOD and COD range of 114–262 mg/L and 219–460 mg/L, and a mean of 171 ± 39 mg/L (n = 32) and 349 ± 67 mg/Ll (n = 32), respectively. The temperature of the influent ranged from19 to 25˚C which was averaged to 22.5 ± 1.4 ˚C. (Friedler, (2004), Jefferson *et al.* (2004), Antonopoulou *et al.*, (2013), and Ragen, (2016)) stated that the greywater characteristics vary significantly due to different lifestyle, climatic conditions, household activities and avail- ability of water. The synthetic greywater of this study had a range of COD/BOD of 1.44–3.29 (n = 32) and a mean of 2.08 ± 0.34 (n = 32) showing the biodegradability of the synthetic greywater. Therefore, it is appropriate to treat the synthetic greywater in the HSSFCW.

10.3.3.2 Bed Performance.

10.3.3.2.1 Inlet and Outlet BOD

Figure 10.6 illustrates the variations of inlet and outlet BOD and COD, respectively.

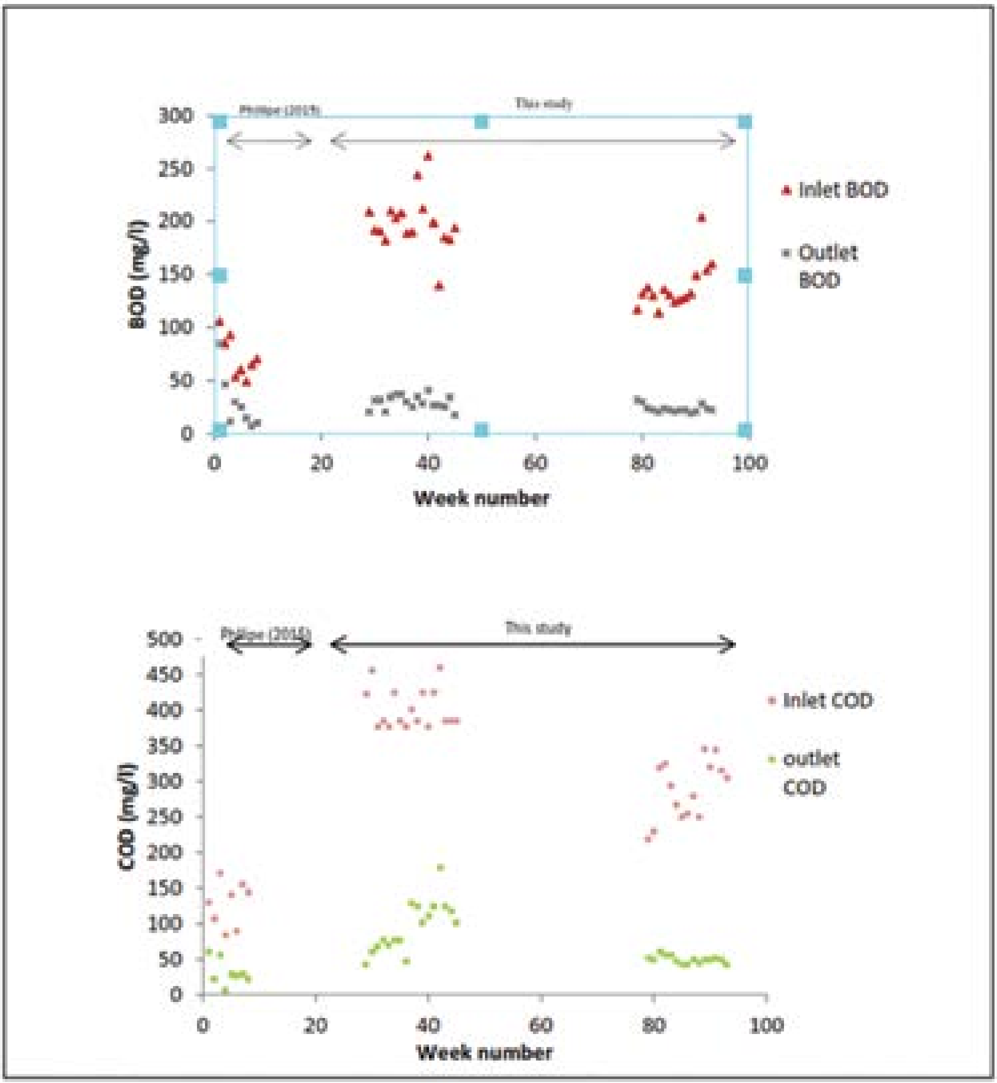


Figure 10.6: Inlet and outlet BOD and COD of the HSSFCW irrespective of the operating conditions (Nurmahomed et al., 2022)

Table 10.6 shows the average and STDEV of the inlet and outlet BOD, which is also illustrated in Fig. 10.6

Table 10.6: Comparison of inlet and outlet BOD and COD (Nurmahomed et al., 2022)

	Inlet (mg/l)		Outlet (mg/l)	
	BOD	COD	BOD	COD
Ramana (2015) (*n = 15*)	164 ± 47	381 ± 178	23 ± 4	37 ± 6
Ragen (2016) (*n = 61*)	89 ± 22	176 ± 70	18 ± 7	37 ± 13
This study (***n = 32***)	171 ± 39	349 ± 67	27 ± 6	75 ± 35

The average outlet BOD in this study was 27 ± 6 mg/L (n = 32). As shown in Table 10.7, the STDEV of the inlet BOD were systematically higher than that of the outlet. Same observation was obtained for the inlet and outlet COD as shown in Fig. 10.7. In this study, the average influent COD was 349 ± 67 mg/L (n = 32) and that of the outlet was 75 ± 35 mg/Ll (n = 32). Similar trends were observed by Ramana (2015) and Ragen (2016). A paired sample –t-test was carried out using the SPSS Software version 23.0. The p-value was lower than 0.05 and this proved that there was indeed a statistically significant (at 5% significance level) difference between the means of inlet and outlet BOD and COD. Thus, the null hypothesis was rejected, and this proved that the synthetic greywater was effectively treated by the experimental HSSFCW. Same statistical difference was also reported by (Vyzamal and Kropfelova (2011) and Ragen (2016)).

10.3.3.2.2 .BOD Removal Efficiency

Figure 10.7 shows the variation in the BOD removal efficiency of the bed since its start-up.

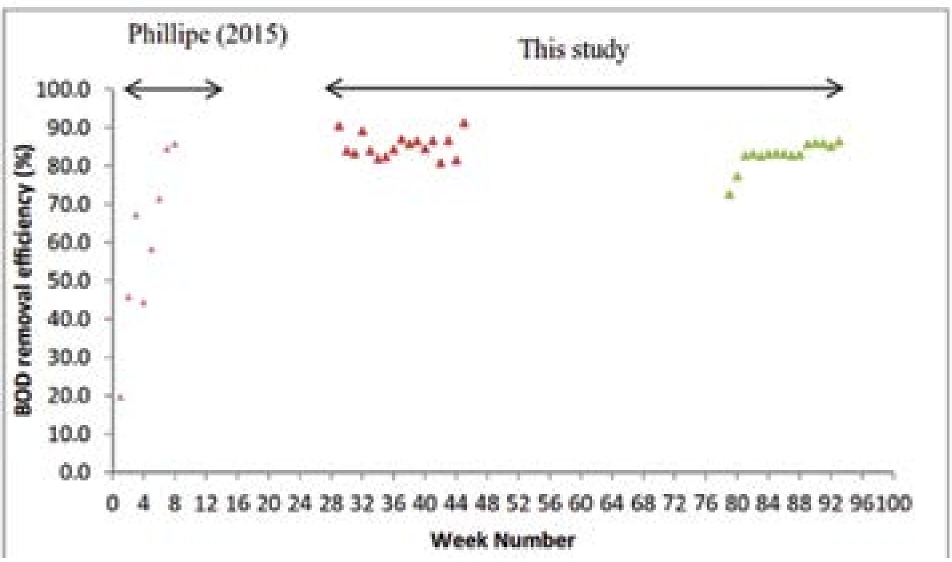


Figure 10.7: BOD removal efficiency of the bed since its start-up in 2015 (Nurmahomed et al., 2022)

During the start-up of the bed by Phillipe (2015) over a period 9 weeks, the BOD removal efficiency ranged from 19.8–85.9% and aver- aged at 59.7% ± 22.7 (n = 8). The BOD removal efficiency obtained by Phillipe (2015) result as illustrated in Figure 10.7 varied significantly. This was typical results of a start –up period during which the initial BOD removal efficiency of 19.8% (2nd week), increased to 67.3% (3rd week) and decreased to 44.4% (4th week). As from 6th week, the performance of the system increased above 80%. Phillipe (2015) thus concluded that the start-up period of the bed was around 9 week (63 days). Start-up period of constructed wetland as stated by Truu *et al*., (2009) may typically vary from 70 to 100 days. Ramana (2015) and Ragen (2016) took 10 weeks (70 days) to start up their systems. Afterward, the experimental bed was re-operated for 32 weeks at operating conditions as mentioned under Section 2.2. As illustrated in Fig. 10.7, BOD efficiency above 80% was obtained proving the system became stable. This study mentioned that the system performed effectively with high BOD removal efficiency in the range of 72.6–91.2% and a mean of 84.0 ± 3.5% (n = 32). A lower standard value was obtained by this study compared to that of Phillipe (2015) as the system already reached steady state. The low standard deviation value (3.5%; n = 32) showed that the HSSFCW had been well established.

10.3.3.3 Effect of Operating Parameters on the System Performance

The experimental bed was operated at two water depths and three different hydraulic retention time as mentioned in Section 10.3.2.3. The effect of HLR, HRT and OSLR on bed performance was investigated through the Pearson, Kendall, and Spearman correlations. Table 10.7 reproduced the results generated by the SPSS Software. The following can be concluded from Table 10.7.

- A strong correlation exists between HLR and HRT as all the coefficients (Pearson, Kendall and Spearman) are comparable and p <0.05. This is evident as per their definitions in Eqs. (10.5) and (10.6).
- The p-values for Pearson, Kendall and Spearman were less than 0.05 and this showed that there is strong impact of HLR and HRT on BOD removal efficiency.
- HRT had a positive correlation coefficient with BOD removal efficiency. It can be concluded that the BOD removal efficiency.
- increased when HRT was lengthened (flow is decreased).
- Negative coefficients were obtained for HLR showing an inverse relationship with BOD removal efficiency. This can be evidenced by their definitions given in Eq. (10.5). When flow is increased, HLR is increased. The higher the HLR, the lesser the time contact between the wastewater and the microorganisms. Also, the flow velocity will be quicker. The negative impact of HLR on bed performance can be explained in Table 10.7.

Table 10.7: Pearson, Kendall and Spearman correlation between HRT, HLR and OSLR on BOD removal efficiency (Nurmahomed et al., 2022)

		BOD removal efficiency		
		Pearson correlation	Kendall correlation	Spearman correlation
HRT	Correlation Sig. (2-tailed) N	0.485** 0.005 32	0.370** 0.010 32	0.444** 0.011 32
HLR	Correlation Sig. (2-tailed) N	32 -0.405* 0.010 32	-0.370* 0.010 32	-0.444* 0.011 32
OSLR	Correlation Sig. (2-tailed) N	32 -0.405* 0.021 32	-0.370* 0.004 32	-0.506* 0.003 32

** means that correlation is significant at the 0.01 level (2-tailed) and * means correlation is significant at the 0.05 level (2-tailed).

- The correlations mentioned above were also reported by Ragen (2016). The system was operated for 32 weeks at an HRT ranged from 20 to 22 h, HLR of 0.200 – 0.280 m/d at a water depth ranged from 0.40 – 0.45 m.

Kadlec and Wallace (2008) and Ragen (2016) proved that water depth impacted on the performance of the HSSFCW. Ragen (2016) studied the impact of water depth on COD, BOD as well as nitrate removal efficiency at three water depths of 0.35 m, 0.40 m and 0.45 m in his experimental bed treating real greywater. He suggested not to run a HSSFCW at a water depth of 0.35 m since the performance was significantly lower than at 0.40 m and 0.45 m. He proved that the optimum range for water depth ranged from 0.40 m–0.45 m. Similar observation was made by Kadlec and Wallace (2008). At deeper water depth, the HRT is longer and hence the removal efficiency is higher. Two water depths of 0.40 m and 0.45 m were investigated in this study at HRT of 24 h and 20 – 22 h. When the HRT was increased from 20 h to 24 h, the bed efficiency increased from 72.6 to 91.2%. Hence, the removal efficiency was higher for a water depth of 0.45 m compared to that of 0.40 m.

10.3.3.4 BOD Removal Reaction Rate Constant

According to von Sperling and de Paoli (2013), BOD degradation along a HSSFCW must follow a first order plug flow model when its aspect ratio ranges from 4:1 to 10:1. The HSSFCW of this study had an aspect ratio of 6:1. To validate the first order BOD degradation, the progression of the BOD removal along the bed was assessed. Figure 10.8 depicts the BOD degradation along the bed at HRT of 20 h, 22 h and 24 h, respectively. Fig. 10.8 illustrates the BOD observed at the different fractional distances from the inlet (where 0 and 1 represent the inlet and outlet, respectively).

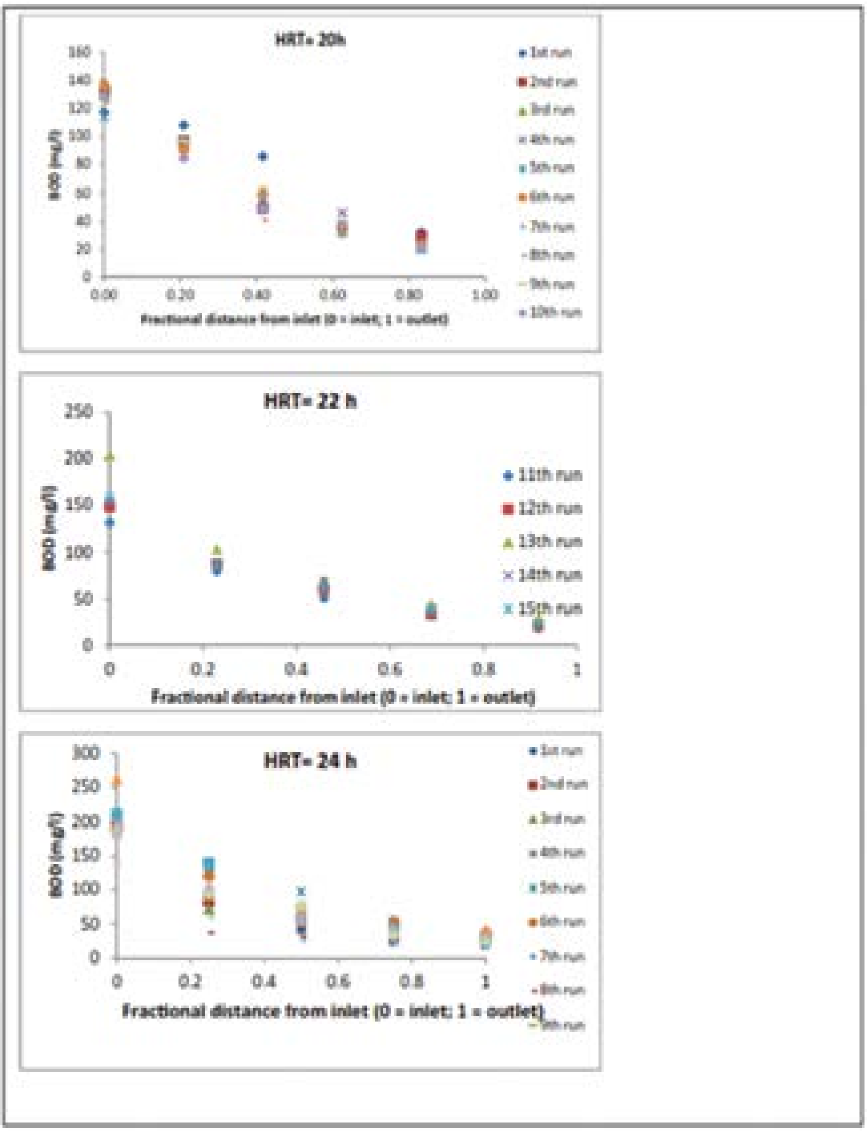


Figure 10.8: Progression of BOD at HRT 20 h (n = 10), HRT 22 h (n = 5) and 24 h (n = 17) (Nurmahomed et al., 2022)

Figure 10.8 illustrates the exponential decrease of BOD from the inlet to the outlet to a non-zero value, defined as the background BOD. Similar exponential decrease was obtained by Rousseau *et al*. (2004), Akratos and Tsihrintzis (2007), Fonder and Xanthoulis (2007), Von Sperling and de Paoli (2013), Ramana (2015) and Ragen (2016). The degradation of BOD at HRT of 24 h was more pronounced than at 22 h. Also, to fit the observed data in the first order plug flow model, the method of Von Sperling and de Paoli (2013) was carried out. The mean BOD was plotted against time. Afterward, an exponential trend line was drawn in the graph of the average BOD versus fractional HRT calculating the R^2-value using Excel software. Figure 10.9 depicts the exponential relationship between the averaged BOD progression along the system at a water depth of 0.40 and 0.45 m at HRT of 24 h, 22 h and 20 h respectively. High R^2-values were obtained at the three HRTs (0.967 at HRT = 24 h, 0.996 at HRT = 22 h and 0.994 at HRT = 20 h). This is illustrated in Figure 10.9. Hence, it can be concluded that the experimental data obtained in this study fitted well the 1st order plug flow model and therefore, the results obtained are validated. The BOD degradation along the experi- mental bed followed a 1st order plug flow model. Ramana (2015) investigated the treatment of real greywater in Mauritius with a HSSFCW of same size and under tropical climatic conditions. The model equation for K-C model in Table 10.8 at HRT 24 h was used to validate Ramana (2015) results. The outlet concentration of the calculated values was the same as the observed values. Hence, the model is thus validated. Rousseau *et al*. (2004), Kadlec and Wallace (2008) and Langergraber (2011) suggested that the K-C model may not be suitable for describing the kinetics of BOD removal in a HSSFCW because the effluent BOD would be zero at infinite HRT. However, in a HSSFCW this would never occur in practice. The K-C* model appears to be a better model since it shows a non-zero effluent BOD, denoted as C*, and it is defined in Eq. (10.3). C* represents the least outlet BOD value that is observed in a HSSFCW (Von Sperling and de Paoli, 2013). In this study, C* was found to be 17 mg/L. A C* value of no less than 10 mg/L was stated by Kadlec and Wallace (2008). The observed averaged BOD values at different fractional times minus C* were plugged into the K-C* model. This was done separately for the three HRTs. Fig. 10.10 illustrates the exponential decrease of the observed average BOD values minus C* at HRT of 20, 22 and 24 h, respectively. The derived expressions for both the K-C and K-C* models at the three HRTs investigated are given with their respective R^2-values in Table 10.8.

Table 10.8: Mathematical relationship derived for both K-C and K-C models and their respective R2 values at three HRTs (Nurmahomed et al., 2022)*

HRT (h)	Model	Correlation	R^2
20	K-C	$Ct = C_0e^{-2.07t}$	0.994
	K-C*	$Ct - C^* = (C_0 - C^*)e^{-3.90t}$	0.951
22	K-C	$Ct = C_0e^{-2.05t}$	0.996
	K-C*	$Ct - C^* = (C_0 - C^*)e^{-3.66t}$	0.948
24	K-C	$Ct = C_0e^{-1.93t}$	0.967
	K-C*	$Ct - C^* = (C_0 - C^*)e^{-2.73t}$	0.993

From Table 10.8 the BOD degradation at the three HRTs fitted well in both the K-C and K-C* models since the R^2 values > 0.95. The followings may be deduced from Table 10.8:

- The observed data in this study at all the three HRTs fitted well the K- C and K-C*.
- The first order BOD degradation rate coefficients (k) for the K-C model were lower than the K-C* model at different HRTs. The k- value for the K-C model at HRT of 20, 22 and 24 h were 2.07 day^{-1}, 2.05 day^{-1} and 1.93 day^{-1}, respectively whereas for the K-C* model it was 3.90 day^{-1}, 3.66 day^{-1} and 2.73 day^{-1}.

Moreover, the following remarks can be deduced from this study:

- The general exponential trend of the progression of the observed BOD along the bed conforms to literature value.
- The mean BOD observed value along the experimented HSS-FCW fitted well the 1st order plug flow K-C and K-C* models. This is accepted globally (von Sperling and de Paoli, 2013) and this validates the results of this study.
- The rate of BOD removal along the HSSFCW decreased with increasing HRT.

10.3.3.5 The Value of kBOD

Trang *et al.* (2010) mentioned that the method using directly the Kickuth (1977) design equation to estimate the kBOD value might be impacted by some parameters for instance system configuration and hydraulic loading. Thus, Kadlec (2003) came up with another technique in the estimation of kBOD values. This technique is less affected by these factors, and it consists of applying the Kickuth Equation, as defined in Eq. (10.1). Table 10.9 shows the kBOD values, as estimated from the K-C and K-C* models.

Table 10.9: Calculated kT and kBOD values by method of fitting in the K-C model (Nurmahomed et al., 2022)*

Flow (m^3/d)	HLR (m/d)	Mean OSLR $kg_{BOD}/m^2 \cdot d$	Water depth (m)	HRT (h)	Model	k_T (day^{-1})	k_{BOD} (m/d)
0.280	0.280	0.035±	0.45	20	K-C	2.07	0.48
		0.002			K-C*	3.90	0.90
0.250	0.250	0.040±	0.45	22	K-C	2.05	0.47
		0.007			K-C*	3.66	0.84
0.200	0.200	0.041±	0.40	24	K-C	1.93	0.40
		0.005			K-C*	2.73	0.56

Table 10.9 shows that at fixed depth of 0.45 m, there was an increase in the kBOD values when the HRT was decreased. The same trend was reported by Ragen, (2016) for HRT of 17.2–28.7 h and a depth of 0.45 m. Moreover, Kadlec and Wallace, (2008) reported by that the kBOD is hydraulic-dependent. Trang *et al.*, (2010) mentioned that the kBOD values calculated from the BOD profiles in the K-C* model is not appropriate for design as higher values are obtained due to parameters such as the growth of plant, climate, random fluctuations in input water characteristics. The removal rate constants as suggested by Kadlec, (2009) are calculated by applying the inlet and outlet BOD values from the HSSFCW. In this study, the observed kBOD were calculated using the results collected (inlet and BOD, flow rate and surface area). The observed kBOD were calculated using Eq. (10.1). The BOD rate constant for this study ranged from 0.34–0.50 m/d and averaged at 0.43 ± 0.06 m/ d (n = 32). Hence, it can be concluded that a kBOD value of 0.1 m/d is not appropriate for the sizing of HSSFCW treating greywater from single household level in Mauritius. Performance data for most HSSFCWs that are found in literature are from temperate regions (European countries). For tropical regions, pollutants removal is believed to be much higher since at a higher temperature microbial activity is more pronounced (high k-values). This was hypothesized in this study. A higher kBOD as shown in Table 10.9 were obtained for this study compared to those mentioned by Cooper (1990), Brix (1998), Kadlec and Knight (1996), Schierup *et al.*, (1990) and Kadlec *et al.*, (2000), and the reason is that kBOD is temperature dependent.

Moreover, even Trang *et al.*, (2010) who carried out their investigations under the tropical climatic conditions of Vietnam, obtained a lower kBOD value than this study. This is most probably due to the fact they applied river sand as substrate in their HSSFCW whereas in this study gravel was used. Therefore, the

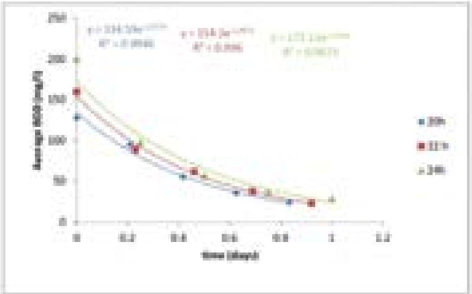


Figure 10.9: The K-C model of observed mean BOD progression along the bed at HRT 20-24 h (n=32) (Nurmahomed et al., 2022)

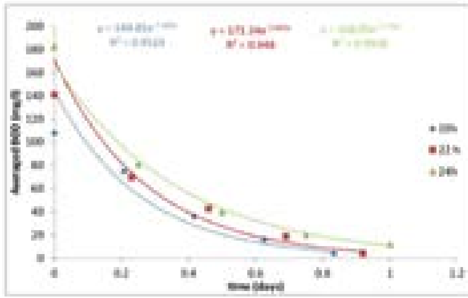


Figure 10.10: The K-C model of observed mean BOD at HRT of 20-24 h (n=32) (Nurmahomed et al., 2022)*

hydraulic loads decreased drastically due to lower porosity. This is in accordance with the statement made by von Sperling and de Paoli, (2013) that kBOD value may be impacted by types of substrates. The guidelines for design and operation suggested by Ragen, (2016) have been proved in this study. Hence, a new kBOD is required for designing a HSSFCW for the treatment of greywater in Mauritius.

10.3.3.6 Reuse of Treated Greywater

Another goal of this study was the recycling of treated greywater by the implementation of the HSSFCW treatment system. The treated effluent can be used for non-potable purposes such as:

- Gardening for household having a garden;
- Toilet flushing;
- General cleaning;
- Car washing.

This is achieved by carrying out analysis and comparing the quality of treated wastewater with the standards for the use of effluent in irrigation purposes in Mauritius. The Standards for Effluent for Use in Irrigation Regulation 2003, the limit of BOD is 40 mg/L and that of COD is 120 mg/L. The characteristics of the influent and treated effluent are compared with the standards. Elements such as heavy metals and pesticides are not applicable due to its absence in greywater. The influent BOD (114–262 mg/L; mean 171 ± 39 mg/L) and COD (219–460 mg/L; mean 349 ± 67 mg/L) were higher compared to the norms and this value was decreased by the HSSFCW below the applicable standards for effluent use as irrigation purposes. The effluent BOD ranged from 17 to 41 mg/L having mean of 27 ± 6 mg/L and COD ranged from 42 to 178 (75 ± 35 mg/L). Hence, treated wastewater from the HSSFCW conformed to the norms in terms of BOD and COD. This proved that the treated greywater can be reuses for purposes that were mentioned before. Nevertheless, Ragen (2016) recommended that UV disinfection should be used to deactivate any pathogen that are present when real greywater is treated by HSSFCW so as the treated effluent can be used safely. Friedler and Gilboa (2010) stated that by using UV light, total inactivation of ***E. coli*** occurs and confirmed that the treat greywater could be utilized for flushing of toilet without any health issues.

10.3.4 Conclusion

Finally, it can be concluded from this study that HSSFCW is an appropriate treatment system treating synthetic greywater. It was proven in this study that the operating parameters such as water depth, HRT, HLR and OSLR impacted on the performance of the HSSFCW The performance in terms of BOD removal of the HSSFCW can reach more than 85% if the system is designed properly and operates under the required conditions, thus producing effluent having a low BOD which conforms to norms and can be reuse.

10.3.5 References

Akratos, C. S., and Tsihrintzis, V. A. (2007). Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecological engineering*, 29(2), 173-191.

American Public Health Association, Washington, DC.

Antonopoulou, G., Kirkou, A., and Stasinakis, A. S. (2013). Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods. *Science of the Total Environment*, 454, 426-432.

APHA. (1995). Standards Methods for the Examination of Water and Wastewater, 19th ed.

Arunbabu, V., Sruthy, S., Antony, I., and Ramasamy, E. V. (2015). Sustainable greywater management with Axonopus compressus (broadleaf carpet grass) planted in sub surface flow constructed wetlands. *Journal of Water Process Engineering*, 7, 153-160.

Avery, L. M., Frazer-Williams, R. A., Winward, G., Shirley-Smith, C., Liu, S., Memon, F. A., and Jefferson, B. (2007). Constructed wetlands for grey water treatment. *Ecohydrology & Hydrobiology*, 7(3-4), 191-200.

beds in Denmark-state of the art. In: Cooper, P.F., Findlater, B.C. (Eds.), Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control, Cambridge, UK, 24–28 September (1990), pp. 495–504.

Boddu, V. M., Paul, T., Page, M. A., Byl, C., Ward, L., and Ruan, J. (2016). Gray water recycle: Effect of pretreatment technologies on low pressure reverse osmosis treatment. *Journal of Environmental Chemical Engineering*, 4(4), 4435-4443.

Bosma, C., Glenk, K., and Novo, P. (2017). How do individuals and groups perceive wetland functioning? Fuzzy cognitive mapping of wetland perceptions in Uganda. *Land Use Policy*, 60, 181-196.

Brix, H. (1998). In: Vymazal, J., Brix, H., Cooper, P.F., Green, M.B., Haberl, R. (Eds.),

Calheiros, C. S., Rangel, A. O., and Castro, P. M. (2007). Constructed wetland systems vegetated with different plants applied to the treatment of tannery wastewater. *Water research*, 41(8), 1790-1798.

Caselles-Osorio, A., Vega, H., Lancheros, J. C., Casierra-Martínez, H. A., and Mosquera, J. E. (2017). Horizontal subsurface-flow constructed wetland removal efficiency using Cyperus articulatus L. *Ecological Engineering*, 99, 479-485.

Constructed Wetlands for Wastewater Treatment in Europe, (1998). Backhuys Publishers, Leiden, pp. 123–152.

Cooper, P.F. (1990). European design and operation guidelines for reed bed treatment systems, prepared by EC/EWPCA Emergent Hydrophyte Treatment Systems Expert Contact Group. In: *Journal of Water Research Centre*, Swindon, UK.

De Paoli, A. C., and von Sperling, M. (2013). Evaluation of clogging in planted and unplanted horizontal subsurface flow constructed wetlands: solids accumulation and hydraulic conductivity reduction. *Water Science and Technology*, 67(6), 1345-1352.

Dornelas, F. L., Machado, M. B., and von Sperling, M. (2009). Performance evaluation of planted and unplanted subsurface-flow constructed wetlands for the post-treatment of UASB reactor effluents. *Water Science and Technology*, 60(12), 3025-3033.

Fonder, N., and Xanthoulis, D. (2007). Removal processes and their distribution inside a subsurface horizontal flow constructed wetland. In Proceedings of the International Conference on Multiple Roles of Wetlands, multi-functions of wetland systems.

Friedler, E. (2004). Quality of individual domestic greywater streams and its implication for on-site treatment and reuse possibilities. *Environmental technology*, 25(9), 997-1008.

Friedler, E., and Gilboa, Y. (2010). Performance of UV disinfection and the microbial quality of greywater effluent along a reuse system for toilet flushing. *Science of the total environment*, 408(9), 2109-2117.

Gharbia, S. S., Aish, A., Abushbak, T., Qishawi, G., Al-Shawa, I., Gharbia, A., ... and Pilla, F. (2016). Evaluation of wastewater post-treatment options for reuse purposes in the agricultural sector under rural development conditions. *Journal of Water Process Engineering*, 9, 111-122.

IWA (International Water Association). (2001). Constructed wetlands for pollution control:

Jefferson, B., Palmer, A., Jeffrey, P., Stuetz, R., and Judd, S. (2004). Grey water characterisation and its impact on the selection and operation of technologies for urban reuse. *Water science and technology*, 50(2), 157-164.

Kadlec, R. H., and Wallace, S. (2008). Treatment wetlands. CRC press.

Kadlec, R., Knight, R., Vymazal, J., Brix, H., Cooper, P., and Haberl, R. (2000). Constructed wetlands for pollution control: processes, performance, design and operation. IWA publishing.

Kadlec, R.H. (2009). Comparison of free water and horizontal subsurface treatment wetlands. *Ecol. Eng.* 35 (2), 159–174.

Kadlec, R.H., and Knight, R.L. (1996). Treatment Wetlands. In: CRC Press, Boca Raton, FL, p. 893.

Kickuth, R. (1977). Degradation and incorporation of nutrients from rural wastewaters by plant rhizosphere under limnic conditions. Utilization of manure by land spreading, 335-343.

Langergraber, G. (2011). Numerical modelling: a tool for better constructed wetland design?. *Water Science and Technology*, 64(1), 14-21.

Leguizamo, M. A. O., Gómez, W. D. F., and Sarmiento, M. C. G. (2017). Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands—a review. *Chemosphere*, 168, 1230-1247.

Li, L., Li, Y., Biswas, D. K., Nian, Y., and Jiang, G. (2008). Potential of constructed wetlands in treating the eutrophic water: evidence from Taihu Lake of China. *Bioresource technology*, 99(6), 1656-1663.

Machado, A. I., Beretta, M., Fragoso, R., and Duarte, E. D. C. N. F. D. A. (2017). Overview of the state of the art of constructed wetlands for decentralized wastewater management in Brazil. *Journal of environmental management*, 187, 560-570.

Maimon, A., Friedler, E., and Gross, A. (2014). Parameters affecting greywater quality and its safety for reuse. *Science of the Total Environment*, 487, 20-25.

Manios, T., Stentiford, E. I., and Millner, P. (2003). The Removal of Chemical Oxygen Demand from Primary-Treated Domestic Wastewater in Subsurface-Flow Reed Beds Using Different Substrates. *Water environment research*, 75(4), 336-341.

Nurmahomed, N., Sobhun, T., Ragen, A. K., and Sheridan, C. M. (2022). Performance of a constructed wetland treating synthetic greywater. *Bioresource Technology Reports*, 17, 100930.

Pavlineri, N., Skoulikidis, N. T., and Tsihrintzis, V. A. (2017). Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. *Chemical Engineering Journal*, 308, 1120-1132.

Phillipe, J.M.S. (2015). Start Up of a Horizontal Sub Surface Flow Constructed Wetland Treating Synthetic Greywater. Faculty of Engineering, University of Mauritius. BEng (Hons.) Dissertation.

processes, performance, design and operation. In: Scientific and Technical Report No. 8. IWA Publishing, London, UK.

Prodanovic, V., Hatt, B., McCarthy, D., Zhang, K., and Deletic, A. (2017). Green walls for greywater reuse: Understanding the role of media on pollutant removal. *Ecological Engineering*, 102, 625-635.

Ragen, A.K. (2016). Design and operational criteria for tropical constructed wetland: a Mauritian case study. Ph.D Thesis Faculty of. Engineering University of Mauritius.

Ramana, A.D. (2015). Horizontal sub surface flow constructed wetland. BEng (Hons.) Dissertation, Faculty of Engineering. University of Mauritius.

Rousseau, D. P., Vanrolleghem, P. A., and De Pauw, N. (2004). Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. *Water research*, 38(6), 1484-1493.

Saeed, T., and Sun, G. (2012). A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: dependency on environmental parameters, operating conditions and supporting media. *Journal of environmental management*, 112, 429-448.

Schierup, H.H., Brix, H., Lorenzen, B. (1990). Wastewater treatment in constructed reed

Trang, N. T. D., Konnerup, D., Schierup, H. H., Chiem, N. H., and Brix, H. (2010). Kinetics of pollutant removal from domestic wastewater in a tropical horizontal subsurface flow constructed wetland system: effects of hydraulic loading rate. *Ecological engineering*, 36(4), 527-535.

Truu, M., Juhanson, J., and Truu, J. (2009). Microbial biomass, activity and community composition in constructed wetlands. *Science of the total environment*, 407(13), 3958-3971.

USEPA, 2000. In: Constructed Wetlands Treatment of Municipal Wastewaters. United States Environmental Protection Agency, p. 154.

Vakil, K. A., Sharma, M. K., Bhatia, A., Kazmi, A. A., and Sarkar, S. (2014). Characterization of greywater in an Indian middle-class household and investigation of physicochemical treatment using electrocoagulation. *Separation and Purification technology*, 130, 160-166.

Von Sperling, M., and de Paoli, A. C. (2013). First-order COD decay coefficients associated with different hydraulic models applied to planted and unplanted horizontal subsurface-flow constructed wetlands. *Ecological Engineering*, 57, 205-209.

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: five decades of experience. *Environmental science & technology*, 45(1), 61-69.

Vymazal, J., and Kröpfelová, L. (2011). A three-stage experimental constructed wetland for treatment of domestic sewage: first 2 years of operation. *Ecological Engineering*, 37(1), 90-98.

Wang, Z., Huang, M., Qi, R., Fan, S., Wang, Y., and Fan, T. (2017). Enhanced nitrogen removal and associated microbial characteristics in a modified single-stage tidal flow constructed wetland with step-feeding. *Chemical Engineering Journal*, 314, 291-300.

Weerakoon, G. M. P. R., Jinadasa, K. B. S. N., Herath, G. B. B., Mowjood, M. I. M., and Van Bruggen, J. J. A. (2013). Impact of the hydraulic loading rate on pollutants removal in tropical horizontal subsurface flow constructed wetlands. *Ecological Engineering*, 61, 154-160.

Zhang, D. Q., Jinadasa, K. B. S. N., Gersberg, R. M., Liu, Y., Tan, S. K., and Ng, W. J. (2015). Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000–2013). *Journal of Environmental Sciences*, 30, 30-46.

10.4 Application of Municipal Wastewater Technology to Semi- arid Regions: "A Pilot Study using a Constructed Wetland in Toliara city, Madagascar"

ABSTRACT

The CW case study for Madagascar s based on Doctoral thesis titled Application of Municipal Wastewater Technology to Semi- arid Regions: A Pilot Study using a Constructed Wetland in Toliara city, Madagascar of Solphi Joli Hamelo who successfully defended his work on 2011. The interesting chapter of his thesis relevant to this work was chapter 4 which reported on Performance of Constructed Wetland System Used in the Hot Climate of Post Treatment of Anaerobic Effluent at Jardin De La Mer Toliara City. Joli abstract started by discussing that the municipality of Toliara in South-west of Madagascar, having population of 203, 061, generates approximately 8,250 m^3/d of wastewater produced daily. At present, about 10 % of the total wastewater is being collected by Toliara central and the remaining 90 % of the wastewater is being disposed of into open drains or haphazardly disposed into the open environment. Under such conditions wastewater management is challenging and daunting task to realize in a city which such a poor sanitation infrastructure system. In this study, the current situation for wastewater management has been investigated and possible solution discussed. Included in this has been collecting and characterizing wastewater from different areas of the city, application of mathematical models for design of a constructed wetland for treatment of wastewater from the city and a 14 months pilot experiment on wastewater treatment with a constructed wetland in Toliara city. The Toliara wastewater composition included the analysis of oxygen, pH, temperature, BOD, TSS and nutrients. Most of the wastewater was anaerobic or had low oxygen levels of 0.08 – 3.43 mg/L), the pH value was in the range 7-7.5 and the wastewater temperature about 30-32 °C prevailed. The BOD and TSS were ranged 179-220 mg/L and 51–159 mg/L. These results were applied to a model developed for a constructed wetland (CW), which was used for design of a constructed wetland for the city of Toliara. The design was done at various temperatures experienced in Toliara, for different reactor types and with and without pretreatment (septic tank). A pilot scale subsurface CW system was designed to treat the septic tank effluent (public toilet used by 70-250 persons). The CW consists of two parallel modules for comparative studies and some of the cells were filled with different media (with sand or gravel). The CW systems were operated at three different modifications in three phases (experimental phase I, II and III). The hydraulic loading rate applied during the different experimental phases varied between the phases. The experimental results showed higher removal efficiencies of BOD and TSS from phase I to phase II and to phase III. The main reason for this was modifications to enhance the oxygen supply in the wetland. The maximum BOD and TSS removal reached 62 and 45 %, respectively, in pond G, and 45 and 53 %; respectively, in the reference pond

D. As the removal efficiency for BOD and TSS increased, so did the removal of nutrients; NH_4-N (40-50%), NO_3-N (25-50%) and PO_4-P(30-40%).These results show the high potential for the application of CW for the treatment of wastewater in Toliara city. Further studies on modification and optimizations are thus recommended.

Key Words: municipality, wastewater, management, design, wetland, temperature and BOD removal.

10.4.1 Introduction and Rationale for CW

Septic tank is pretreatment of domestic wastewater from individual household and private. It is the first process in the onsite sewage system. Most of the pre-treatment process will be anaerobic. Septic tank effluent has reported to contain biological oxygen demand, chemical oxygen demand, nutrients and pathogen microorganisms at concentration levels which are far higher than the recommended standard for effluent disposal (Kaseva, 2004). Inadequate treatment of domestic wastewater contributes to pollution of surface water and might led to ground water problems. A simplified technology for sanitation should be included in the process of treatment. According to the literature review, sanitation services level and conditions is still largely low and poorly provided in developing countries, there is a need for simplified systems of collecting and treating effluents using the appropriately low cost domestic wastewater treatment to improve the septic tank system effluents. Constructed wetlands are attractive options for the post-treatment of effluent from anaerobic septic tanks. These advantages include the low cost of installation and easy operation (UNEP *et al*., 2004). The subsurface flow constructed wetland has been studied for the treatment of high strength effluent domestic in particular areas.

This study chose the septic tank effluent from a public toilet in the city. The aim of this study was design of constructed wetland systems for using a post-treatment and assessment of the performance of the subsurface wetland in the hot climate. The system was evaluated in the performance of the removal of organic matter, suspended solid and nutrients. The removal of pollutant in wetland is effected by factors inflow, pollutant loading rate, HRT, HRL, climatic condition such as temperature, pH, DO availability, surface area for biofilm growth and wetland design flow.

The main objective of this study was to demonstrate a small scale constructed wetland for wastewater treatment. Also local authorities were involved in using the simple technology to treat municipal wastewater. The specific objectives were:

- to determine the treatment of septic tank wastewater using a small scale constructed wetland in hot climate conditions;
- to assess ways of improving the design criteria of the system to be guideline in the hot climate areas;
- to raise the awareness of the simple technology as a relevant method for wastewater treatment.

10.4.2 CW System Description (size, type of CW, the design and operating conditions)

In this research, the Institut Halieutique et des Sciences Marines (IH.SM) has established a small scale constructed wetland at Jardin de la Mer, Toliara city. The constructed wetland system was built for post treatment of septic tank effluent. The small pilot constructed wetland is located at 23°21'30.36"S of latitude and 43°40'.0.90"N of longitude at the Toliara city (Figure 10.11). It was behind the public toilet and guardian house. The primary treatment consists of a prefabricated septic tank. The secondary treatment includes the wetland. Figure 10.12 shows the septic tank system.

Figure 10.11: The site of the pilot study of small scale of constructed wetland (Hamelo, 2011)

Figure 10.12: Septic tank system (pretreatment) (Hamelo, 2011)

The wetland selected was the subsurface flow for treating the septic tank effluent. It is good for removal of BOD, TSS and nutrients (nitrogen and phosphorus). Also it minimizes odor and vector problems, simple to construct, maintenance and operational costs are low compared to vertical subsurface flow systems (Brix, 1987; Cooper *et al*., 1996). It is simple technology, solar driven systems that is user friendly and does not require highly trained and skilled operators compared to conventional systems. Selection of the type of constructed wetland is based on the treatment objectives required and available site.

The criteria of the wetland units were based on the BOD concentration loading rate. BOD, TSS, nitrogen (NH4-N and NO3-N) compounds and phosphorous (PO3-P) compounds are treated by the constructed wetland. The removal of soluble pollutants in the CW is due to bacteria and algae growth attached to the substrates. Some modification was made with respect to the growth of algae and dissolved oxygen variation at high temperatures that prevail in this study.

The summarized of calculation of design criteria used were:

- 79 - 250 per day of the number of persons censured using of the public toilet (WC, bathroom and Urinal);
- Flow rate variable and hydraulic retention time in three phases (Table 10.10);
- BOD concentration influent from head tank maximum 51-160 mg/L;
  - BOD concentration effluent of 25 mg/L (EU standard).
  - Temperature at 20°C

Construction of the wetland cell

During the design of the landscape, the water table was difficult to manage because it was easy to get water from the groundwater in this area (Figure 10.13). The material of construction for the wetland cells was cement, gravel and sand, and iron. The wetland system was constructed using the bed slop of 1% with dimension of length 4 m and 1.50 m wide. The bottom and walls of the pond was made of concrete cement which composed the sikalite to protect from water coming in and out.

Figure 10.13: The territorial landscape (Hamelo, 2011)

Both the pond D and pond G were divided to 3 wetland cells. Each wetland cell had length of 1.25 m and 0.715 m wide. In addition, the wetland cells 1, 2 and 3 had depth of 0.35 m, 0.37m and 0.39 m, respectively (Figure 10.14).

Figure 10.14: A constructed wetland with 3 parallel cells (Hamelo, 2011)

All corners and above of the pond was fixed by iron of 8 mm diameters. A PVC pipe of 100 mm led septic tank effluent from the head tank into the first compartment. The inlet of the pond was used and reduced the PVC pipe of 50 mm of the diameter. A PVC pipe with a diameter of 40 mm connected the first, second and third wetland cells.

Experiment Start Up and Operational System

In this study, pilot scale subsurface flow constructed wetland has been constructed. The two pond systems comprise of one pond G system with gravel and one pond D system (control). The substrate gravel used was of limestone type in the system. The type and size of gravel ranged from 10 to 25 mm diameter. Also, it was added and mixed with fine sand. The head tank accumulated septic tank sludge. It was cleaned once a month because it provoked clogging of the PVC inlet pipe. The flow rate of the wastewater at the inlet of each pond D and G was measured by using a graduated cylinder and stopwatch. The experiments were conducted in two equal parallel units each of 3 wetland cells. The cells were connected in series. The experiments were carried out in three different phases. Septic tank effluent was discharged by gravity of PVC 100 mm pipe of diameter from the head tank and was reduced to PVC of 50 mm pipe to the pond D and G.

Table 10.10: Volumetric loadings and operational data applied (Hamelo, 2011)

Phase	Flow rate	Hydraulic retention time	Organic loading rate
	(m^3/d)	(d)	g BOD/L/d
	4.2	0.45	0.32
Phase I	3.6	0.52	0.28
	3	0.62	0.23
	2.7	0.69	0.21
	2.5	0.75	0.19
Phase II	2.4	0.78	0.18
	2.3	0.81	0.18
	2.1	0.89	0.16
	2	0.93	0.15
Phase III	1.9	0.98	0.15
	1.8	1.04	0.14
	1.8	1.04	0.14

The pond system and operation characteristics are summarized in Table 10.10 and Table 10.11. The pond D and G system was modified in the different phases. The modification was done to improve the oxygen production and it will optimize the wetland removal efficiency.

Table 10.11: Pond D and pond G systems characteristics (Hamelo, 2011)

Phase I			Phase II		Phase III	
Wetland	**Pond D**	**Pond G**	**Pond D**	**Pond G**	**Pond D**	**Pond G**
(Pond)						
Cell 1	Open	Open	Open	Open	Open	open
Cell 2	Open	Open	Gravel + sand	Gravel + sand	Rearranged to gravel dam form	Rearranged to gravel dam form
Cell 3	Open	Gravel + sand	Open	Gravel + sand	Open	Rearranged gravel dam

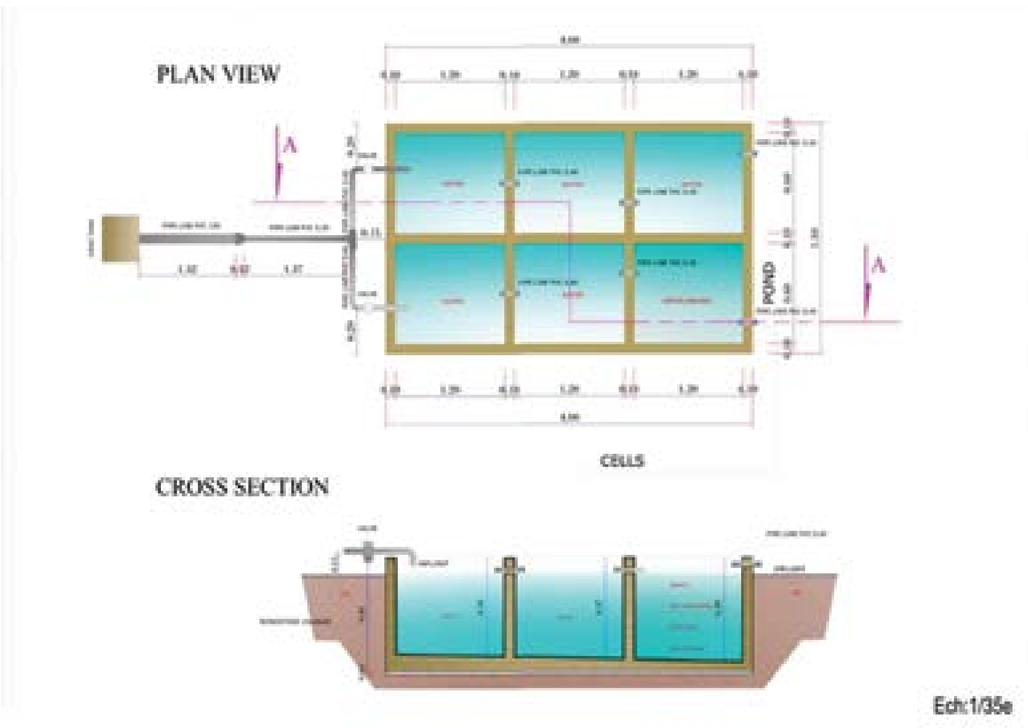


Figure 10.15: Schema of constructed wetland in the phase I period (Hamelo, 2011)

Procedures Sample Collection and Analysing

In phase I, II and III, the samples were usually analysed according to the standard methods and water and wastewater analysis. The standard methods were referred to for analysis of samples. In the site, the key environmental (dissolved oxygen, pH and temperature) parameters were recorded. Parameters such as dissolved oxygen, pH and temperature in the septic tank effluent and pond D and G effluent were analysed with Multi parametric portable probes (Multi 340i WTW). Samples analyses were carried out at the IH.SM laboratory. To monitor the fluctuation of the flow rate, it was determined three times a day in the pond at Jardin de la Mer. The flow rate varied during the different phases. The running of this experiment was for 14 months, the sampling points were placed the inlet and outlet of wetland. In the different cells, the variation of the environmental parameters was sometimes measured in the middle of cell in the pond D and G. All water samples collected by the students and technicians were stored in the ice cooler box and were transported from the site to IH.SM laboratory for analysis. Sampling was carried out three times a week in all the points. The sampling was changed when the system had a problem and modified. The sampler could provide refrigeration while the sample is being collected and stored inside. The sampling was normally done between 9 a.m. and 17 p.m. Usually, it was used a bottle 250 mL taking a sample from septic tank effluent (inlet) and also 2*250 mg/L from pond D and pond G effluent.

Modeling Wetland BOD Data as a Tank in Series System (phase III)

The results from the wetland can be used for determining rate coefficients for the limiting parameter. Most current models assume dissolved BOD as limiting parameter. In some systems dissolved oxygen may limit the BOD removal rate, depending on the relative loading of BOD and supply of oxygen. It can be assumed BOD limitation when an excess of oxygen is measured in the effluent; more than 2 mg/L. In the systems investigated in this study, effluent oxygen varied and based on the results the limitation may have been due to oxygen for some periods and limited by BOD for some periods. Thus, the structure of the model incorporates BOD as the limiting parameter and will be used in this application. The pilot plant consisted of three compartments for each module (D and G) and a tank in series (TIS) type of model was applied. The solution for the TIS was found as equation (10.8):

$$Ce = \frac{Ci}{\left(1 + k * \frac{v}{(n*Q)}\right)^{n}} \qquad (10.8)$$

where;

$n = 3$,

$t_h = V/Q$

This is expression yields:

$$th=[\left(\frac{C_i}{C_e}\right)^n-1](\frac{n}{k} \qquad (10.9)$$
(Metcalf and Eddy, 2003)

By inverting and linearizing it can be solved graphically and the reaction rate can be determined based on the data from the pilot with 3 tanks in series:

This is expression yields:

$$\frac{1}{th}=\left[\left(\frac{Ci}{Ce}\right)^3-1\right]*\left(\frac{\frac{1}{3}}{k}\right) \qquad (10.10)$$
(Metcalf and Eddy, 2003)

The slope of the graph represents $(k/3)$ so then the rate can be determined (Figure 10.16).

Pond D: Slope = $0.1425 = k/3 \Rightarrow k = 0.43\ d^{-1}$

Pond G: Slope = $0.1292 = k/3 \Rightarrow k = 0.39\ d^{-1}$

There is some uncertainty associated with the results, as can be seen by the low correlation factor for the trend lines (r^2). So, to complete the evaluation of the actual reaction rate it is recommended more measurements to verify the values found here.

Data Analysis

In this study used the Excel Microsoft 2010 to arrange the data set and XL-STAT 2009 software for the statistical analysis. Statistical analysis of results was carried out through the correlation test by Pearson-test between two mean comparisons. t-student was required for variance comparison to select the equal or different variances. Trends and plots have been used when required to show differences in both mean values and dispersion.

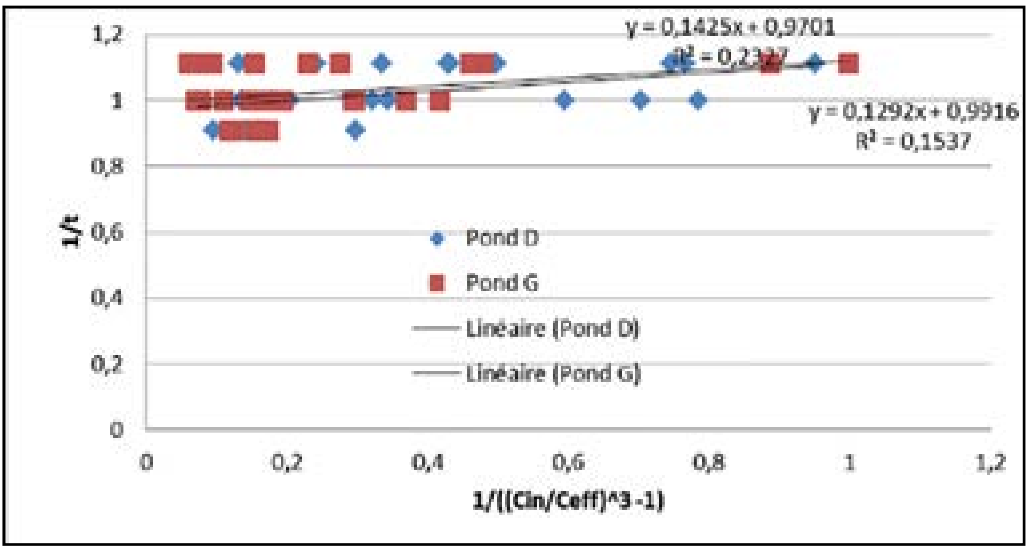


Figure 10.16: Linearized BOD data for determination of reaction rates (k) (Hamelo, 2011)

10.4.2.1 CW System Pollutants Removal Performance

pH

The dissolved oxygen, temperature, and pH ranges for the three phases are given in Table 10.12. In the time of experimentation, the pH increased in pond D (Figure 10.17). The pH values from the septic tank effluent, pond D and pond G was uniform throughout the serial of experiment (phase I, II and III). It ranged from 6.97 to 8 which is close neutral and was increasing during the experiment. During the experiment, the pond was completely covered with bloom algae on the surface and in the bottom. The growth of algae correlates with the light that stimulates the photosynthesis mechanism. pH of the pond D effluent and pond G effluent increased in the wetland as dissolved oxygen also increased. Then, BOD removal requires DO supply in wetland.

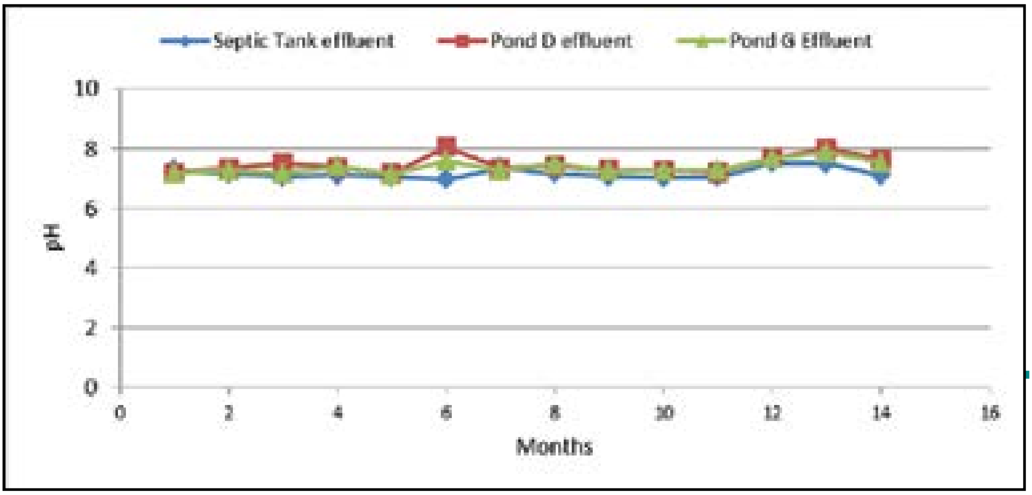


Figure 10.17: pH values in the septic tank effluent and effluent from the wetland (pond D and pond G) (July 2010-August 2011)

Table 10.12: Data ranged of the environmental parameters measured from July 2010 to August 2011, from the septic tank effluent, pond D and pond G effluent (Hamelo, 2011)

	Parameters	pH	Temperature (°C)	Dissolved oxygen (mg/L)
Phase I	Septic tank effluent	6.97-7.29	22.3 – 31.5	0.66- 1.11
	Pond D effluent (control)	7.17- 8.07	20.9 – 32.4	0.39- 3.16
	Pond G effluent	7.14 – 7.60	20.1 – 31.6	0.40 – 4.52
	Septic tank effluent	7.03-7.36	26.5 – 30	0.83- 2.61
Phase II	Pond D effluent (control)	7.23 – 7.43	26.62 - 30.3	0.66- 2.37
	Pond G effluent	7.24-7.49	26.7 – 30.2	0.89 – 2.42
	Septic tank effluent	7.11- 7.52	19.3 – 20.6	0.61 – 0.7
Phase III	Pond D effluent (control)	7.65 – 8	17.7 – 20.3	0.96 – 3.09
	Pond G effluent	7.54 – 7.89	18.1 – 20.4	0.93

Wastewater temperature

The water temperature was influenced by the season (summer and winter).

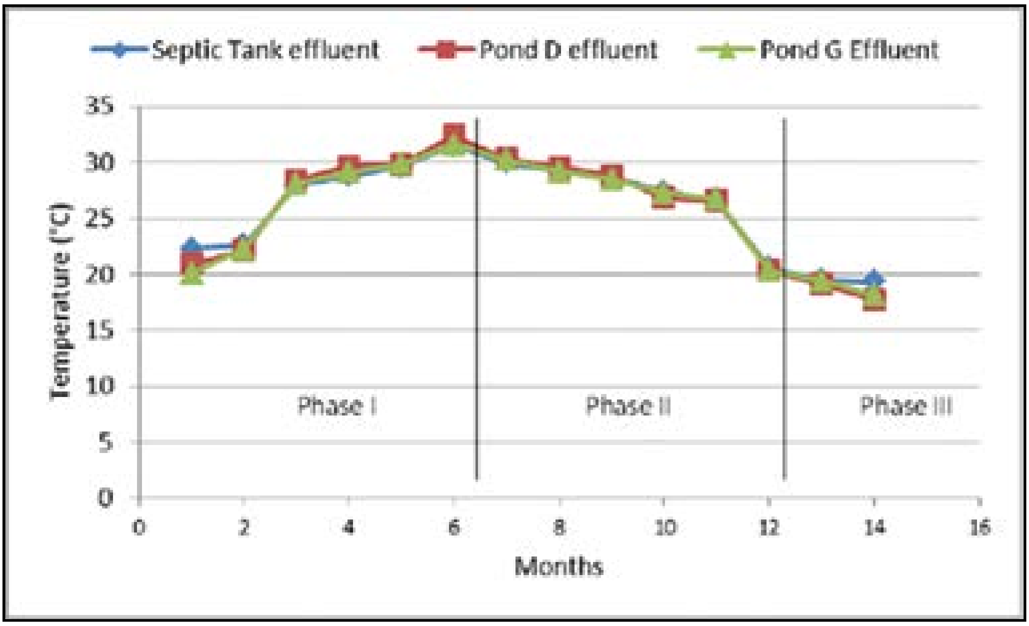


Figure 10.18: Variation of temperature (°C) from the septic tank effluent and effluent from the pond D and pond G (phase I, II and III, July 2010 – August 2011) (Hamelo, 2011)

During the experiment, the fluctuation of temperature was high temperature in the influent (septic tank effluent) and effluent (pond D and G) in November 2010, December 2010, January 2011, February 2011, and Marsh 2011. The temperature from the influent and in the effluent remained relatively steady and uniform during this study (Figure 10.18). The water temperatures at Toliara city were not subject to seasonal variability like in the case of temperature wetland. The water temperature was expected to have been nearly steady all year around from influent to effluent during all phases.

Dissolved oxygen (DO)

Variation of dissolved oxygen was measured in the influent and effluent during this experiment (Table 10.10). The dissolved oxygen concentration was not constant in the influent and effluent during this study in Figure 10.19. The septic tank effluent came from an anaerobic system and was low in DO while pond D and G effluent was from an aerobic system. These results were affected by modifications of the system in the next phase. The target of the modification was to improve the oxygen supply in the wetland and at later stage when algal blooms prevailed in the open zone ponds. High DO is required for BOD removal in the wetland.

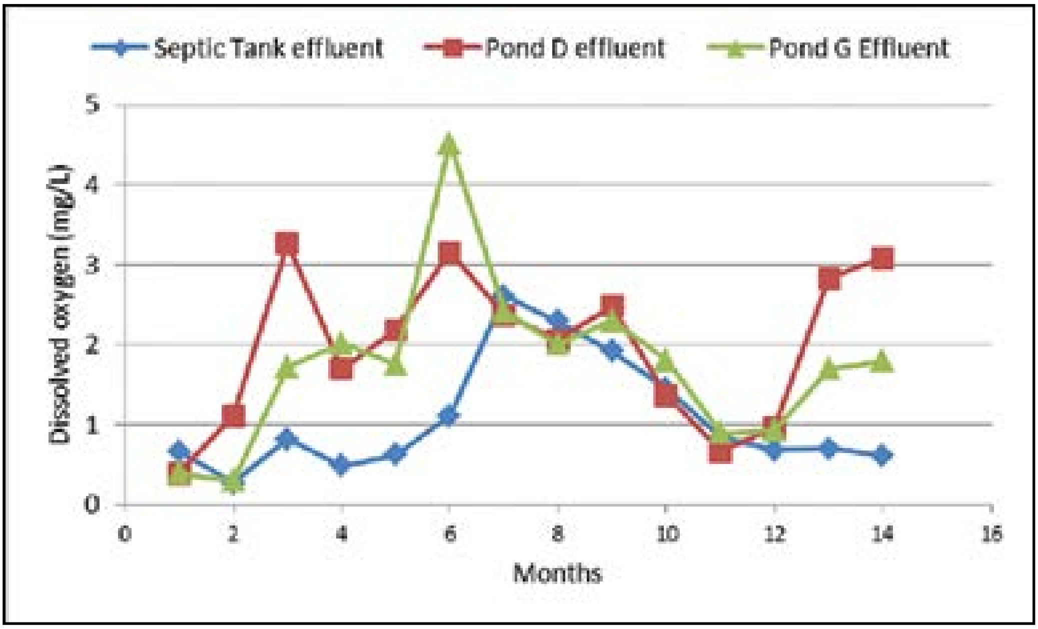


Figure 10.19: Dissolved oxygen concentration profiles in the phase I, II and III from the septic tank effluent (influent to wetland) and from effluent of pond D and pond G (July 2010 – August 2011) (Hamelo, 2011)

Removal of pollutants

Biochemical oxygen demand and Total suspended solid

Concentration trends

In phase I, the BOD and TSS concentration trends in the wetland system was decreasing values. The means of BOD and TSS concentration from the septic tank effluent and from the pond D and pond G effluent recorded 72.7 mg/L, 62.5 mg/L and 53.1 mg/L respectively (Figure 10.20) and the means of TSS concentration from septic tank effluent and from pond D control system and pond G were 27.5 mg/L, 22.8 mg/L and 20.2 mg/L respectively in Figure 10.21. In Figure 10.20 the BOD concentrations in pond D and G effluent were lower than the values from the septic tank throughout the time on the study. Maximum BOD reduction in the pond D (control) and G were obtained at the longest hydraulic retention time.

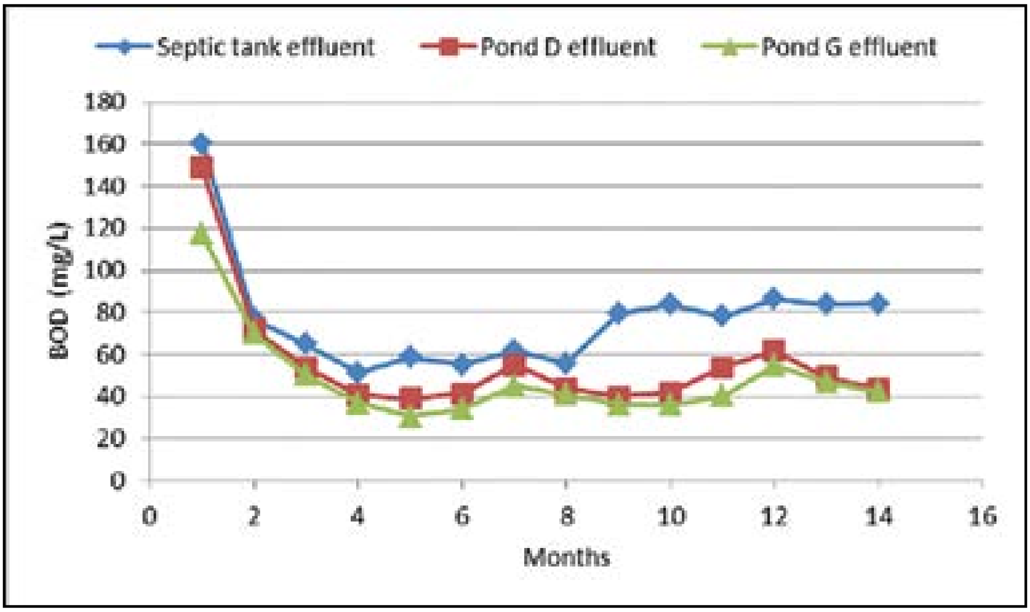


Figure 10.20: Concentration trend of BOD from septic tank effluent and from pond D and pond G (as measured from July 2010 to August 2011). (Hamelo, 2011)

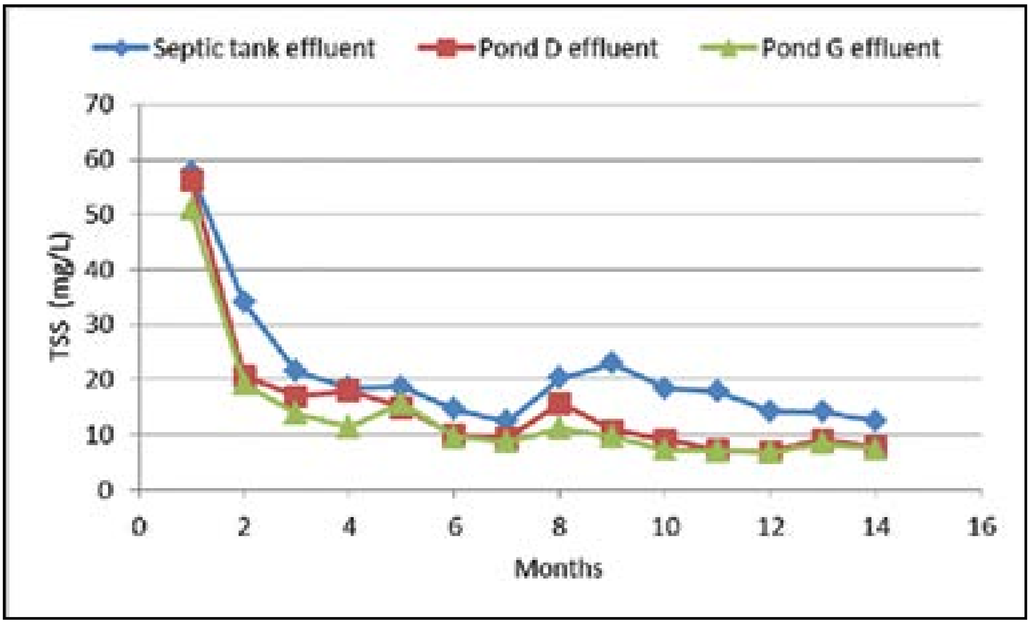


Figure 10.21: Concentration trend of TSS from septic tank effluent and from pond D and pond G (as measured from July 2010 to August 2011). (Hamelo, 2011)

The hydraulic loading rate influenced the corresponding mass reduction of BOD in the septic tank effluent. The volumetric loading rate into the wetland system was modified 3 times (Table 10.10).

In phase III, the BOD removal increased and could be a result of the modification for improved DO supply. Also improved TSS removal could be due to filtration in the gravel dams.

10.4.2.2 Removal Efficiency

The average concentrations of BOD and TSS from the septic tank effluent (influent to the wetland units) and the effluent from the pond G are given in the Table 10.13 Also, the percentage removal efficiency calculated based on concentrations for each parameter during the experiment (phase I, II and III) is shown in the Table 10.13.

Table 10.13: Summary of BOD, TSS, NH_4-N, NO_3-N and PO_4-P concentrations in the influent (septic tank effluent) and effluent (pond D and G) per month and removal efficiency during the phase I, II and III; (Hamelo, 2011)

	Parameters	Septic tank Effluent (mg/L)	Effluent pond D (mg/L)	Effluent pond G (mg/L)	Pond D Removal Efficiency (%)	Pond G Removal Efficiency (%)
	BOD	72.7	62.5	53.1	16.4	29.7
	TSS	27.5	22.8	20.2	19.6	29.7
Phase I	NH_4-N	96.1	56.2	52.5	40.1	48.1
	NO_3-N	1.4	0.9	1	33.8	36.8
	PO_4-P	10.8	10.9	5.8	15.5	39.4
	BOD	71.7	46.8	41.5	32.8	39.6
	TSS	20.4	10.5	8.8	44.8	53.2
Phase II	NH_4-N	65.6	37	33.8	42.6	47.8
	NO_3-N	2.8	2.1	2	24.8	32.5
	PO_4-P	20.1	11.4	10.5	38.5	41.7
	BOD	84.7	51.4	32	39.4	62
	TSS	13.6	8	7	43.4	46.1
Phase III	NH_4-N	29.2	1.4	14.4	44.5	52
	NO_3-N	1.1	0.7	0.6	37.8	47.7
	PO_4-P	16.9	10.3	9.4	36.3	41.9

Dissolved oxygen was required for reducing the BOD and TSS concentrations through pond D and pond G system. When the DO increased, the BOD and TSS removal efficiency increased throughout the time of the experiment in the phase III. However, the concentration of these parameters remained steadily lower than the influent regardless of the fluctuation in the septic tank effluent. The BOD and TSS reduction in pond G (Table 10.13) were improved from the phase I to phase II and III.

10.4.3 Lessons Learnt (Worst Case and Best-Case Scenarios)

The septic tank and wetland combination was suitable for treatment of the wastewater from the public toilet. According to the results, the pond G system with most gravel has higher removal efficiency compared pond D system (control). These findings also show the suitability of limestone gravel to be used in constructed wetland to treat septic tank effluent. Increasing the dissolved oxygen in the wetland, improved the BOD removal in different phases. In the pond D system, the BOD was recorded 16.4 %, 32.8% and 39.4% in the phase I, II and III, respectively. The BOD removal efficiency in pond G was higher than in the pond D, 33.6%, 56.3% and 60.7% for phase, I, II and II, respectively. The presences of the nutrients (NH_4-N, NO_3-N and PO_4-P) in the wetland stimulated algae growth on the gravel surface with corresponding uptake of nutrients and contribution to oxygen supply. The highest efficiency of the pond G systems, in term of nutrients removal was recorded at, 47.6% and 52% for NH_3-N, 36.8%, 32.5% and 47.7% for NO_3-N and 39.4%, 41.7 and 41.9 % for PO_4-P, in the phase I, II and III, respectively. These results were generally higher that the reference pond D (Table 10.13) As a conclusion, pond G system had higher removal efficiency compared to pond D. The removal efficiencies obtained in this study suggests a need for further research to show that this system can produce final effluent, which can meet the required standards (5 mg/L to 25 mg/L of BOD effluent, Madagascar standard) recommended for effluent disposal in receiving water bodies in Toliara city.

10.4.4 References

Brix, H. (1987). Treatment of wastewater in the rhizosphere of wetland plants–the root-zone method. *Water Science and Technology*, 19(1-2), 107-118.

Cooper, P. F., Job, G. D., Green, M. B., and Shutes, R. B. E. (1996): Reedbeds and Constructed wetland for wastewater treatment WRc Swinden.

Kaseva, M. E. (2004). Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater—a tropical case study. *Water research*, 38(3), 681-687.

UNEP, GPA and WIOMSA. (2004). Regional overview of the physical alteration and destruction of habitat (PADH) in the Western Indian Ocean region. United Nations Environment Programme.73 pp.

About the University of Dar es Salaam (UDSM)

Established on 25th October 1961, UDSM stands as Tanzania's oldest and largest public university in Tanzania. Nestled on Observation Hill just 13 kilometres west of Dar es Salaam's city centre, its expansive 1,625-acre campus is a beacon of academic excellence and innovation.

Guided by a bold vision to become a leading Centre of Intellectual Wealth, UDSM is committed to driving sustainable and inclusive development. Through world-class teaching, pioneering research, and dynamic knowledge exchange, the university plays a transformative role in shaping Tanzania's economic, social, and technological future—and extending its impact far beyond.

www.udsm.ac.tz

About WIOMSA

WIOMSA – Western Indian Ocean Marine Science Association, founded in 1993, is a non-governmental organization representing a membership that includes individuals, associates, students, institutional and corporate members. WIOMSA is dedicated to promoting the educational, scientific and technological development of all aspects of marine sciences in the Western Indian Ocean (WIO) region. Even in those early days, its establishment was a recognition that marine and coastal science require a regional and interdisciplinary approach and that there was added value in combining these two aspects. Over time, WIOMSA's role has evolved significantly, although its primary focus on working with its members to address key areas of regional interdisciplinary marine and coastal science remains the same. WIOMSA has established itself as the leading non-governmental organization to support and coordinate regional research in marine and coastal management. The Association has become the institution of choice for representing WIO issues and science in many regional and international policy fora.

Learn more about WIOMSA here: **www.wiomsa.org**

About Nairobi Convention

Back in 1985, when the Western Indian Ocean (WIO) was still pristine, already leaders of the region together with a number of partners had the foresight to create a mechanism for regional cooperation, coordination and collaborative actions to enable better management of their shared marine space. This coming together was an important step in getting countries of the region to address common priorities through a mechanism that was legally binding with the aim of achieving long term sustainable measures.

The United Nations Environment Programme hosted the 1985 conference of plenipotentiaries for the Nairobi Convention for the Protection, Management and Development of Coastal and Marine Environment of the Western Indian Ocean (WIO) region had a great vision of a prosperous Western Indian Ocean region with healthy rivers, coasts and oceans. To realise the vision, the Convention aimed at increasing the capacity of the Western Indian Ocean nations to protect, manage, and develop their coastal and marine environment.

Member States and Parties to the Nairobi Convention undertake the implementation and enforcement of priority activities identified in the Nairobi Convention as well as Decisions made at the Conference of Parties (COP), both nationally and regionally. Each Member State or party has an obligation to designate an appropriate government authority known as the National Focal Point (NFP) for the purpose of communications with the Secretariat as well as for monitoring the national implementation of the Convention.

ISBN 978-9976-56195-1

FIRST EDITION

WIOMSA
Coasts Ocean and People