Using eco-engineering systems to re-imagine an Integrated Water Resource Management Strategy

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Introduction and Background

As noted in the 2nd UN World Water Report, "key challenges of contemporary water management can only be understood within the very broad context of the world's socio-economic systems (UNESCO 2006:3). The report notes that changing demographics and population movements; shifts in geopolitics, with new country boundaries and alliances; fast developing information and communication technologies; plus the impacts of climate change and extreme weather conditions are all making the world "a more challenging place for decision-makers" (UNESCO 2006:3). It is against this background that water managers must administer what is becoming an "increasingly scarce and fluctuating resource" (UNESCO 2006:3). The report also argues that an Integrated Water Resources Management (IWRM) approach is required to consider all these factors and issues simultaneously in order to secure the equitable and sustainable management of freshwater (UNESCO 2006:3).

Water resources management must recognize the differing challenges presented by the type of human settlement: human settlements vary from the very low-density scattered single dwellings typically associated with rural development, through villages and small towns, to the higher densities associated with cities and ultimately mega-cities (UNESCO 2006:10). Half of the global population and most of the world's economic output is located in urban areas (UNESCO 2006:10). Very often these human settlements are not located in the optimal geographic location, for example, low-lying coastal areas or water-stressed areas. Johannesburg and Pretoria are cases in point: Johannesburg was developed as a consequence of the discovery of gold despite the city not having local and sustainable freshwater resources. Apart from being major consumers of freshwater resources, human settlements are also "the major polluters of water resources" (UNESCO 2006:10). Human settlements therefore provide a critical context for future water management.

State of the resource

It is stated that the water challenge is not about sufficient freshwater resource in the world but its uneven distribution (UNESCO 2006:11). This poses significant challenges to water managers especially where there is a mismatch between availability, distribution and human settlements. Within this high-level mismatch are lower level mismatches including increased water use, competition and pollution together with "highly inefficient water supply practices" (UNESCO 2006:12).

To sustainably manage freshwater resources requires an understanding of the solar-powered hydrological cycle (Figure 1). The hydrological cycles begins with evaporation of water from the earth's surfaces (land, lakes and oceans); the formation of clouds through the condensation of the moist air; the dispersion of this moisture around the globe; and its final return to the surface as precipitation (University of Illinois 2015; Environmental Science 2006:237). Once precipitation reaches the Earth's surface, some of it evaporates through transpiration; some of it seeps into the ground as subsurface flow where it may recharge aquifers or seep back into lakes, streams, rivers and ultimately the ocean, while the remaining balance is runoff which empties into lakes, streams and rivers and is ultimately carried back to the oceans where the cycle begins again (Environmental Science 2006:237).

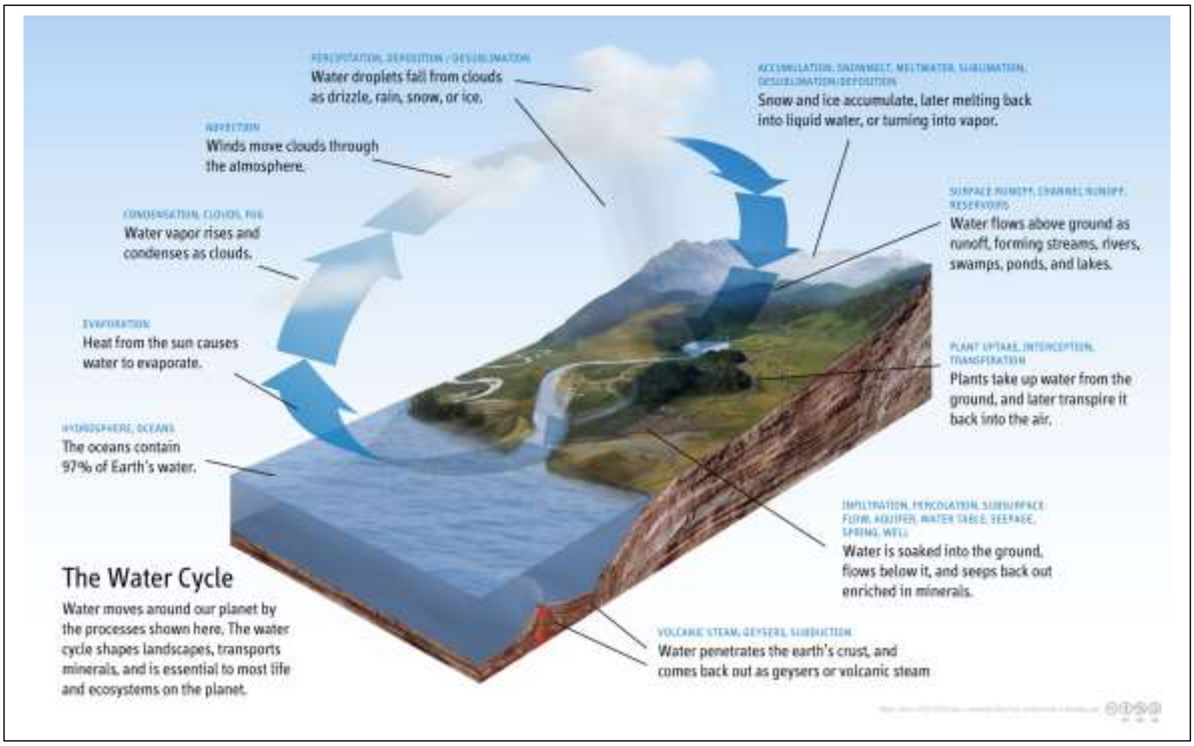

Figure 1: The Hydrological Cycle (Source: https://en.wikipedia.org/wiki/Water_cycle)

It can be observed that the 'unevenness of distribution' begins in the hydrological cycle: water evaporated from one geographical area may be discharged as precipitation to a different geographical area which may be many of thousands of kilometers away and even in another country. For example, Canada, which has only 0.5 per cent of the world's population, has one-fifth of the world's fresh water resource while China, which has one-fifth of the world's population, has only 7 per cent of the resource (Environmental Science 2006:237). In addition, water also goes through different phases – liquid, solid (ice) and gas (vapour) – within the hydrological cycle. Thus while the mass of water on Earth remains fairly constant over time, the state, dispersion and storage of this water into major reservoirs of ice, fresh water, saline water and atmospheric water is variable depending on a wide range of climatic variables (Environmental Science 2006:237). The glacial and interglacial cycles exercises a significant influence on the dispersion and storage pattern: during the last ice age glaciers covered almost one third of the Earth's land mass resulting in an increase in sea level decrease of about 122m (USGS 2008). On the other hand during the interglacial or warm period experienced about 125,000 years ago sea level increased by 5.5m (USGS 2008). It is thought that about three million years ago the oceans could have been up to 50m higher (USGS 2008). Scientific climate change projections suggest that the hydrological cycle will intensify over time with a reduction in precipitation in subtropical land areas (IPCC 2007). This drying out is projected to be strongest nearest the poleward margins of the subtropics, for example, the Mediterranean Basin, South Africa, southern Australia, and the South-western United States (IPCC 2007).

While 71 per cent of the world's surface is covered by water (Figure 2), only a small fraction of that, about 2.5 per cent is fresh water (Environmental Science 2006:238). This is due, in large part, to 78 per cent of global precipitation occurring over the oceans (NASA 2015). Of that amount, only 1.3 per cent (0.014 per cent of the total) is accessible fresh water distributed into lakes, biota, rivers, atmospheric water vapour, and soil moisture (Environmental Science 2006:238).

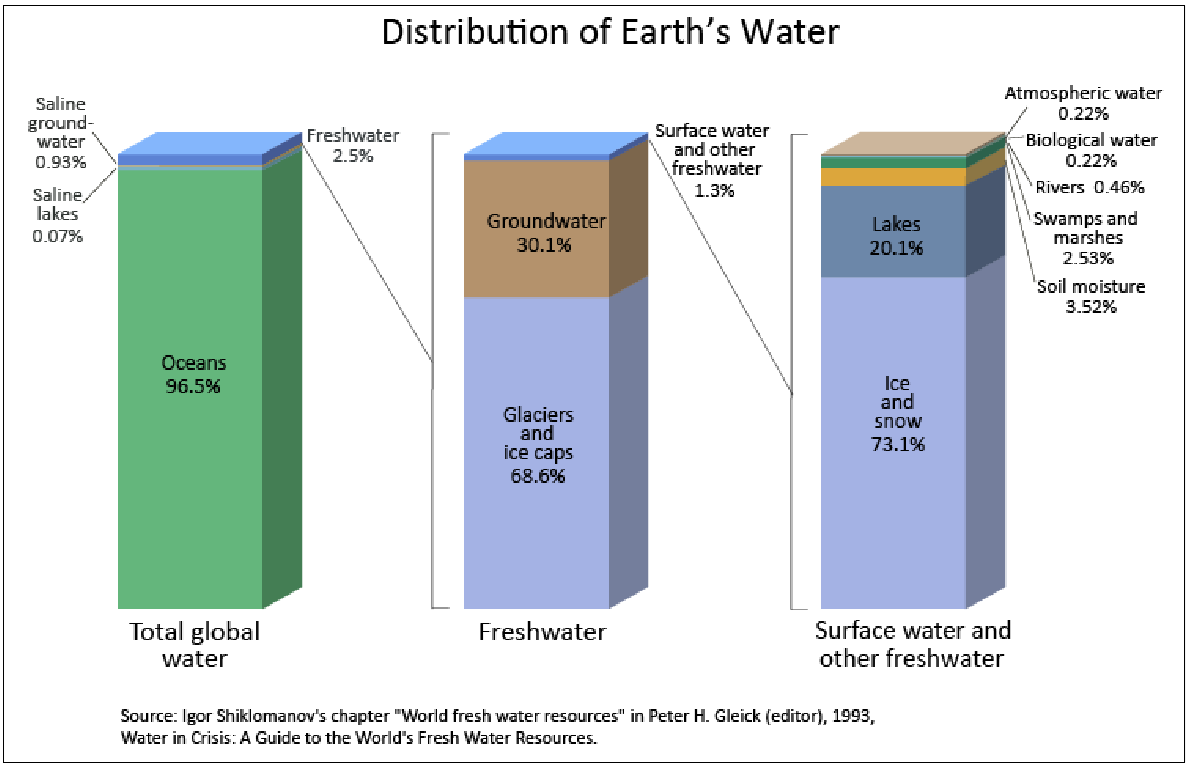

Figure 2: Distribution of the Earth's water.

This chapter focuses on the integrated management of runoff as, by definition, catchment deals with surface water and other fresh water runoff.

Defining catchments

A catchment, also known as a drainage basin, drainage area, river basin or water basin (Lambert 1998:130), is an area of land where surface water from rain, melting snow, or ice is collected by the natural landscape and converges to a single point where it joins another waterbody (Hunter Water 2015; Lambert 1998:130). Typically all rain and run-off water eventually flows to a stream, river, lake, ocean, dam, or groundwater system. Catchments drain into other catchment areas in a hierarchical pattern, i.e., smaller sub-catchment areas combine into larger catchment areas (University of Delaware 2008). As can be seen in Figure 2 above, surface water and other fresh water constitutes the water collected in catchment areas for storage and distribution. Catchment areas are therefore almost completely dependent on runoff.

The conventional approach to water catchment considers only natural features as identified above by Lambert (1998:130). Figure 3 below depicts a typical river basin, in this case the Steenbras River basin in the Western Cape of South Africa. Runoff collects and drains from the top right hand corner of the image towards the Steenbras Dam which comprises two dams; the upper and lower dam.

Excess water runs off toward the ocean, in this case False Bay which is part of the Atlantic Ocean, as shown in the lower left hand part of the figure. Other feeder dams are visible in the lower right hand of the figure. This configuration is typical of the dams of the Western Cape, and for South Africa.

Figure 3: Steenbras River Dam and Basin

The conventional approach to the planning and management of water resources assumes that the statistical properties of past water history remains unchanged over time and does not display any non-stochastic trends (Garcia, Matthews, Rodriguez, Wijen, DiFrancesco, and Ray 2014:vii). Garcia et al note that this assumption is widely referred to in the scientific and engineering literature as 'stationarity' meaning, the past is a good predictor for the future (2014:vii). However the hydrological cycle, as already addressed in this chapter, is "both extremely sensitive to climate shifts and very difficult to predict" (Garcia et al 2014:viii). This is critical as water resources will likely be the principal medium by which climate change impacts are felt and mitigated (UN Water 2010). In addition over time, the upstream runoff could be affected by land use changes including more intensive agriculture and urbanization. Garcia et al note (2014:4), the "assumption that streamflow was a stationary process facilitated the generation of a plausible 'future' sequences of stochastic inputs." The notion of 'stationarity' has been recently challenged by an opposing notion of 'non-stationarity' which has subsequently been further adapted through the recognition that time series are not simply stationary or non-stationary but may be stationary in some components and non-stationary in others (Garcia et al 2014:4). More critically, if decision-makers have overestimated their ability to reliably and predictably plan for the future, then a serious crisis arises as to how decisions in, inter alia, water supply and sanitation, are made (Garcia et al 2014:5). Ultimately Garcia et al (2014:5) quote Matthews, Wickel and Freeman (2011) who argue that "a sustainable vision of water resources management must encompass both ecological and engineering perspectives on non-stationary change." Garcia et al (2014:10) note that "traditionally, freshwater ecosystem management decisions have been *after* and *in response* to water infrastructure and management decisions” and that shifts in risk assessment may be used as an opportunity to “better integrate these perspectives through ‘eco-engineering’ systems that include more flexible environmental allocations – which can better balance operational, user, and environmental allocations – and that link dynamic ecological and engineering performance markers.”

Case study of catchment management in the Western Cape

Stationarity is clearly evident in the history of water catchment and dam construction in the Western Cape. There is a series of parallel ranges that form part of the Cape Fold Mountains of the Western Cape (Figure 4). The Cape Fold Belt is a fold and thrust belt of late Paleozoic age which affected the sequence of sedimentary rock layers of the Cape Supergroup in the Western Cape (Shone and Booth 2005). The rocks involved are generally shales, which persist in the valley floors, and the erosion resistant sandstones, which form the parallel ranges (Figure 5). The Cape Fold Belt extends from Cape Town in the southwest in a northerly direction to the Cederberg Mountains and in an easterly direction to Port Elizabeth.

Figure 4: The Cape Fold Belt (Source: https://en.wikipedia.org/wiki/Cape_Fold_Belt)

The portions of the Cape Fold Belt that are used as catchment for the Greater Cape Town Metropolitan Area are shown in Figure 5. Dam construction commenced very early in the history of colonial settlement in Cape Town (Table 1 tabulates the history of dam construction in the metropolitan area). From Table 1 it is clear that most of the dam construction in the 18th and 19th century took place on the Table Mountain range shown circled on the left of Figure 5. Once these catchments were exhausted, development shifted to the area circled on the right of Figure 5, commencing with the construction of Steenbras River Dam in 1921 (see also Figure 3) and progressive development of catchments extending to the north and east. These opportunities are practically exhausted and future water management strategies are based on water augmentation schemes (City of Cape Town 2005:12).

Figure 5: Catchment areas serving the Greater Cape Town Metropolitan Area

The sustainability of this approach is questionable: from Table 1 it can be seen that the response to meeting increasing demand has been to build more dams.

Table 1: Chronology of dam building in the Greater Cape Town Metropolitan Area

Date	Dam/Reservoir	Location	Capacity (Ml)
1663	Waggenaar	City Bowl	1
1852	Molteno One	City Bowl	9.4
1856	Molteno Two	City Bowl	45.4
1881	Molteno Three	City Bowl	200
1895	Victoria	Table Mountain	128
1890-1897	Woodhead	Table Mountain	955
1898	Hely-Hutchinson	Table Mountain	927
1898	Silvermine	Table Mountain	No data
1903	Alexandra	Table Mountain	126
1903	De Villiers	Table Mountain	243
1921	Steenbras	Hottentots-Holland Mountain	33,897
1954	Keerom	Nuy River, Worcester	10,400
1955	Stettynskloof	Stettenskloof River, Worcester	14,700
1957	Wemmershoek	Wemmers River, Franschoek	58,700
1969	Oudebaaskraal	Tankwa River, Ceres	34,000
1971	Voelvlei	Voelvlei River, Gouda	158,600
1974	Lakenvallei	Sanddrifskloof River, Ceres	10,300
1975	Kwaggaskloof	Part of Brandvlei Dam	173,900
1976	Elandskloof	Elands River, Villiersdorp	11,017
1977	Eikenhof	Palmiet River, Grabouw	28,900
1977	Steenbras Upper	Hottentots-Holland Mountain	32,483

1978	Theewaterskloof	Riviersonderend River, Villiersdorp	480,200
1986	Rockview	Palmiet River, Grabouw	16,400
1986	Kogelberg	Palmiet River Grabouw	19,000
1989	Greater Brandvlei	Breede River, Worcester	474,046
1997	Kruismanskraal	Kruismans River	637,900
2007	Berg River	Berg River, Franschoek	127,100

In many ways, dam construction is a proxy for urban growth: the dates in Table 1 reflect population growth in Cape Town driven by the influx of settlers post-1820; preparation for and post-war settlement during and after the South African War of 1899-1903; post First World War settlement after 1918; post Second World War settlement after 1945; and rapid urbanization from the 1950s onwards.

Exploiting eco-engineering solutions

With traditional catchment areas exploited, new solutions have to be found to ensure a sustainable freshwater supply to the Greater Cape Town Metropolitan Area. Eco-engineering provides at least two opportunities.

Aquifers

As stated earlier, the geological formation of the Cape Peninsula indicates that the ancient landscape after the formation of the Cape Fold Belt Mountains was at a much higher elevation than its current elevation as shown in Figure 6 (Compton 2004:24). Subsequent erosion of the softer rocks resulted in the lowering of the elevation to its current status stopped only by the harder and erosion-resistant basement rock layers comprised of shales and granite as shown in Figure 6 (Compton 2004:24). The softer rocks weathered into a 50 km wide sandy plain known locally as the 'Cape Flats' (Compton 2004:24). While early colonial settlers believed that the Cape Flats was a sand bar extending between the Atlantic Ocean to the north and the Indian Ocean to the south, our current knowledge indicates that the sand is a thin layer of decomposed soft rocks overlain on erosion-resistant shales and granites (Compton 2004:24; Maclear 1995).

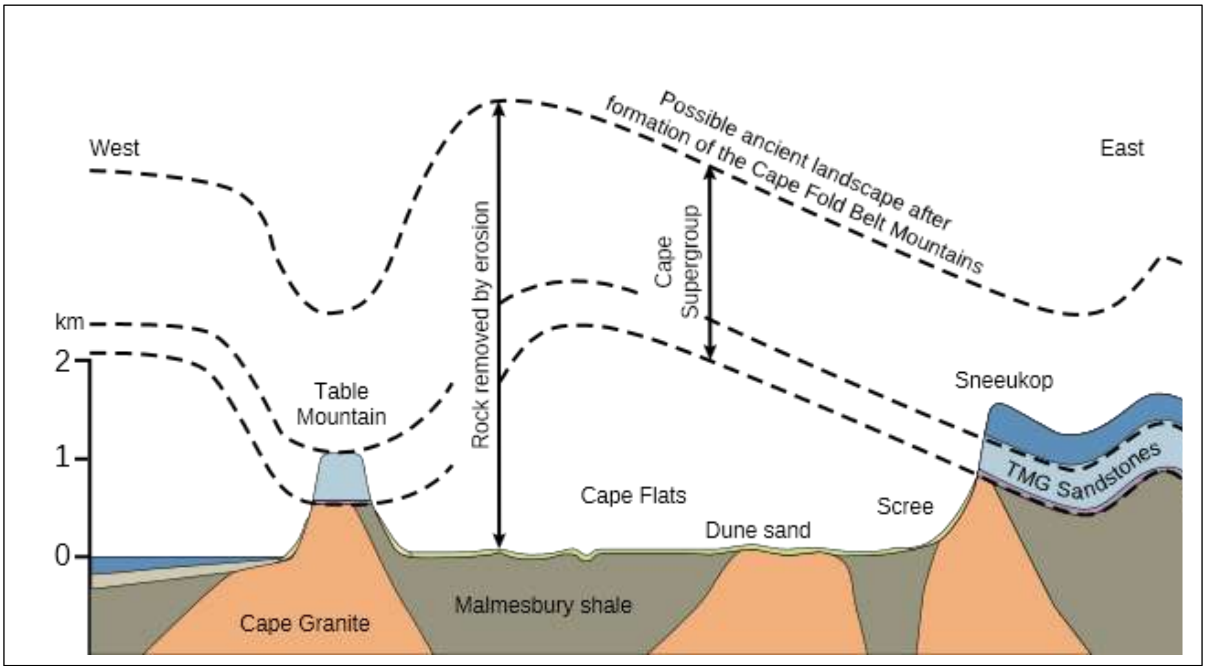

Figure 6: Figure 5: Geological cross section through Table Mountain on the Cape Peninsula. (Source: https://en.wikipedia.org/wiki/Cape_Fold_Belt)

Because geological rock formation is uneven, it is highly likely that the basement surface is uneven as well, resulting in peaks and valleys. Each valley is therefore potentially an aquifer. The potential of this aquifer or aquifers known as the Cape Flats Aquifer Unit (CFAU) was recognized by Maclear (1995:1): he notes that the generally shallow water table – 3.75m below the surface on average – and medium- to coarse-grained nature of the saturated sands "result in a primary aquifer of significant exploitation potential" (Maclear 1995:2). Other known aquifers are shown in Figure 7 and include Albion Spring, Atlantis Aquifer (comprising two aquifers namely Witzands and Silwerstroom), Newlands Aquifer and the Table Mountain Group Aquifer (City of Cape Town 2006:3)

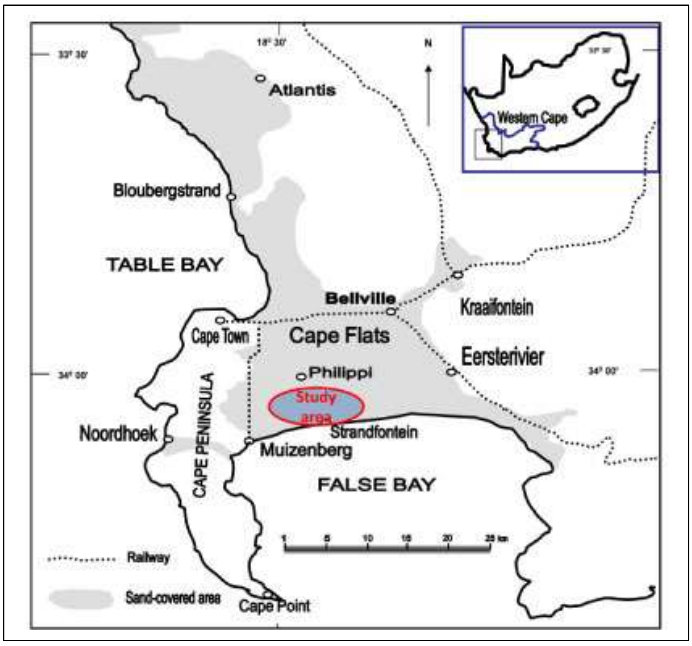

Figure 7: Aquifers in the Greater Cape Town Metropolitan Area (Source: https://www.google.co.za/search?q=cape+flats+aquifer&rlz=1T4PLXB_enZA655ZA656&tbm=isch&tbo=u&source=univ&sa=X&ved=0CDIQsARqFQoTCL7q_cuVtcgCFUzpFAodgyEFBw&biw=1920&bih=931#imgrc=BbJqvSx7X-AdlM%3A)

In addition, Maclear (1995:2) classifies the quality of the groundwater as 'fresh' due its salinity range of 300-1000mg/l total dissolvable solids TDS i.e. falling within the acceptable limits for drinking water. Maclear argues for the exploitation of the aquifer for its water-supply potential. Estimations of the capacity of the CFAU varies: Maclear conservatively calculated at 53.4Mm^3/yr, or the equivalence of 20 per cent of the total water supply to the Greater Cape Town Metropolitan Area (1995:3). Table 2 indicates the water supply potential of the CFAU as calculated by Maclear (1995:3).

Table 2: Water supply and population statistics for the GCTMA and CFAU area (1995).

	Total GCTMA	CFAU area	CFAU % of Total
Water supply (m^3/yr)	267 152 550	162 891 711	61
Population	2 220 856	1 561 473	70

Maclear (1995:3) calculates the water supply of the CFAU using annual rainfall: however the recharge rate assumes that all available rainfall is absorbed as groundwater whereas increasingly runoff in urbanized areas is collected through an elaborate storm water system and discharged to the sea. The sustainable management of the CFAU would require eco-engineering solutions where rainfall is not diverted to a storm water system but is carefully managed and treated to recharge aquifers. In addition, eco-engineering solutions could include other strategies such as Sustainable Urban Drainage Systems (SUDS) described elsewhere in this handbook in a separate chapter. This would include, inter alia, greywater absorption. Maclear argues that the "localised use of the CFAU can provide sufficient groundwater for small-scale use such as garden irrigation" (1995:3) but eco-engineered solutions would enable its use for human consumption. Adelana and Xu, on the other hand, estimates the water supply volume as 18 billion litres per year and suggest that this could meet more than two-thirds of the basic water needs of the population in the GCTMA (UNEP 2006:265-278). A City of Cape Town report estimates the capacity of the CFAU as 128 Mm^3 (million cubic meters) and the recharge rate at only 18 Mm/annum (2005:3).

The above calculations also assume a single usage i.e. aquifers are recharged, water is extracted, and disposed of and the cycle starts again. Clearly this is not sustainable: urban sprawl severely restricts the ability to recharge aquifers even as it increases demand. Three strategies are required: firstly, the precipitation loop must be closed by minimizing disposal of surface water to the sea; secondly, multiple use must be made of available water through recycling and reuse; and thirdly, demand must be reduced through the application of water-efficient and water-free fixtures, including sanitation systems.

Rainwater harvesting

Rainwater harvesting is an eco-engineering technology used for collecting and storing rainwater collected from rooftops, the land surface or rock catchments. Rainwater harvesting systems consist of three principal components namely, the catchment area, the collection device, and the conveyance system (GDRC 2015). For purposes of this chapter emphasis is placed on rooftop capture.

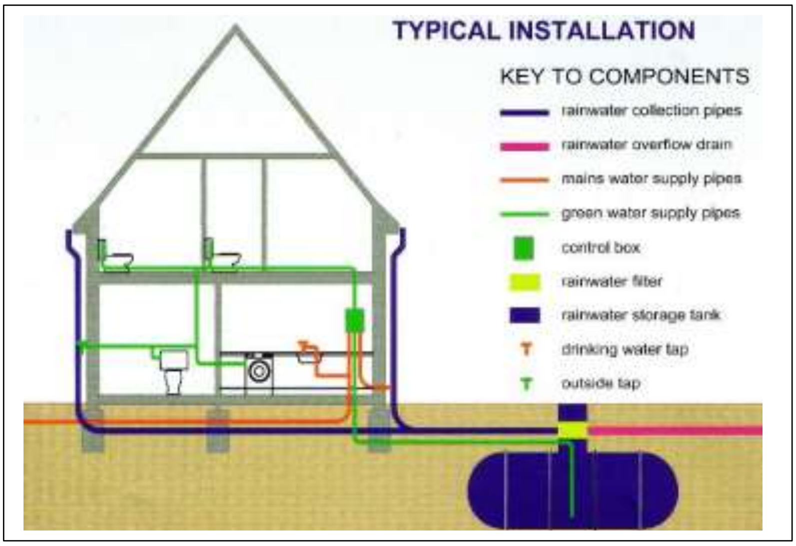

Figure 8: Typical rainwater installation

(Source:
https://www.google.co.za/search?q=rainwater+harvesting&rlz=1T4PLXB_enZA655ZA656&source=lnms&tbm=isch&sa=X&ved=0CAcQ_AUoAWoVChMI9JHKx5fWyAIVxboaCh3LtQhG&biw=1920&bih=931#imgrc=IEqm_1yDhsFd9M%3A)

In the most elementary form of this technology, rainwater is collected in simple storage tanks located at the edge of the rooftop. Further sophistication sees the installation of a conveyance system such as a gutter to convey the water to a more convenient collection point through the use of a downpipe. More recent sophistication places a filter at the gutter and downpipe joint to capture and remove organic and inorganic material before entering the storage tank. As the rooftop is the main catchment area, the amount and quality of rainwater collected depends on the climatic conditions of the location (annual precipitation and wind speed), the area of the rooftop, and the type of roofing material used (GRDC 2015). The collection device could be a cistern or water tank located either above or below ground.

The significance of recognizing rooftops as catchment areas is that it extends the conventional application of catchment areas as described in Figures 3 and 5 to include urbanized areas. Thus, water capture and storage is delinked from the traditional development of mountain catchment as reflected in Table 1.

In addition, rainwater harvesting technologies are simple to install and operate and can be undertaken and managed by the local community with local materials. Rainwater harvesting is convenient as water is stored at the point of use with the owner of the system having full control of how and when it gets used thereby reducing operation and maintenance costs. The range of collection devices has a lower environmental impact than the traditional collection devices such as dams and reservoirs. Rainwater harvesting can provide a continuous source of water supply especially for the poor and rural populations as water collection and storage capacity can be adjusted to suit the local climatic conditions and programmatic requirements.

Conclusion

As noted in the beginning of this chapter, water managers must administer what is becoming an "increasingly scarce and fluctuating resource" (UNESCO 2006:3). The chapter notes that an Integrated Water Resources Management (IWRM) approach is required to consider all these factors and issues simultaneously in order to secure the equitable and sustainable management of freshwater.

The chapter also notes that such IWRM must recognize the differing challenges presented by the type of human settlement, including the supply and demand nexus and the polluting impacts of human settlements. The chapter also observes the 'unevenness of distribution' which begins in the hydrological cycle: water evaporated from one geographical area may be discharged as precipitation to a different geographical area which may be many of thousands of miles away and even in another country, placing additional stresses on water security.

The chapter notes that surface water and other fresh water constitutes the water collected in catchment areas for storage and distribution and that catchment areas are therefore almost completely dependent on runoff. More specifically, the chapter observes that the conventional approach to water catchment considers only natural features.

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The chapter describes the stationarity approach manifest in traditional freshwater supply management making use of water management history in the Cape Peninsula. It then argues that the adoption of eco-engineering systems, such as aquifer management and rainwater harvesting, can better balance operational, user, and environmental allocations.

More critically, the chapter argues that redefining catchment to include aquifers and rooftops recognizing rooftops extends the conventional application of catchment areas as described in Figures 3 and 5 to include urbanized areas. Thus, water capture and storage is delinked from the traditional development of mountain catchment as reflected in Table 1. Essentially, every building, street, parking area, and garden becomes a catchment area, a collection device, and a conveyance system.

The chapter argues that adopting this approach, i.e., making what was once considered to be part of the problem part of the solution, into an Integrated Water Resources Management (IWRM) strategy will contribute to securing the equitable and sustainable management of freshwater.

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