Limnological criteria for management of water quality in the southern hemisphere

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A Report of an International Workshop convened by the Committee for Inland Water Ecosystems, Wilderness, South Africa 1984

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PREFACE

The Southern Hemisphere contains many of the world's developing countries. Rampant population growth and industrial expansion, fuelled by modern technological capabilities to exploit rich natural resources, pose severe threats to the environment which eventually impinge upon aquatic ecosystems in one way or another. In the low and variable-rainfall expanses of Africa and Australia, water resources are particularly fragile. Provision of an assured supply of water of suitable quality for its intended use becomes tenuous and difficult to achieve. The limited availability of water in arid areas has, of necessity, focused greater attention on water quality and related environmental problems than has been the case in better-watered regions, such as South America for example. Nevertheless, the latter are not without water resource problems which have their origins in demographic development.

By and large, the difficulties experienced in the Southern Hemisphere do not differ radically from those which have confronted the First World countries in the north. But there are important departure points: the reduced availability of water and the increased variability in its supply; differences in the magnitude and seasonal timing of hydrological and limnological events; the thermal enhancement of metabolism of both individual aquatic organisms and entire ecosystems; and differences in the quality of natural waters, particularly the elevation of inorganic turbidity, are but some of the more obvious and pertinent in the context of water resource management.

Demands for water rise as populations expand. Improved living standards compound the problem by increasing *per capita* consumption. In certain countries, the Republic of South Africa being an excellent example, the availability of water promises to set a finite limit upon the size of population which can be supported at an acceptable standard. Anticipated demands for water are expected to match or exceed economically exploitable sources in this country within two or three decades. Water is thus poised to play a pivotal role in the future socio-economic development within this country as in many others in the Southern Hemisphere. Prevention of further deterioration in water quality, and in many instances a positive improvement in existing water quality, is desirable if not essential to preclude the strangulation of future economic development by present or future water-resource constraints.

Increasing the supply of water for industrial, agricultural or domestic use is principally an engineering function. In contrast to the singular engineering responsibility for such purely quantitative aspects, a mutually-supporting, interacting interface between engineers, limnologists and related water management disciplines is essential to tackle and resolve water quality and other environmental issues which arise as a result of the vicious self-fuelled spiral of demographic growth.

This interface is not always readily attained and consummated. The workshop at which this report was spawned and partially nurtured, was convened specifically to attempt to place into some perspective those limnological principles or concepts relevant to the management particularly of surface inland waters in poorly-watered regions of the Southern Hemisphere.

The Committee for Inland Water Ecosystems, under whose auspices the workshop was convened, aimed to stimulate, coordinate and integrate research and research findings which will provide decision makers with a better basis for the development and utilization of water resources in southern Africa. Cognisant of the valuable experience gained by researchers and managers in other parts of the Southern Hemisphere, the workshop organizers endeavoured to obtain as balanced a mix of contributors from the southern continents and the various disciplines as possible. There was nevertheless a predominance of southern African experience present which accounts for the fuller treatment of findings from this area.

The principal objectives of water resource management involve the provision of an assured supply of water of appropriate quality, and its optimal utilization. Progressive management additionally recognizes the need to meet these primary objectives with the minimum of environmental disturbance or damage possible at contemporary levels of understanding and within the logistic and practical constraints on operational requirements.

Impoundment and associated river regulation practices frequently represent the first step in acquiring and holding surface waters for subsequent use. The magnitude and extent of these operations is necessarily increased in regions which experience variable and largely unpredictable flows. The implications of such manipulation are not trivial. They are multi-faceted in nature and extent.

Various constraints to the attainment of the aforementioned management objectives exist. They are by no means peculiar or unique to the Southern Hemisphere, but their manifestation reflects the limnological and related environmental biases or characteristics of this region. Thus pollution, turbidity, salinization and eutrophication, considered in an arid, southern perspective comprise the chapters of the report, along with those on catchment management, stream regulation and fisheries. In all chapters, the intention was to provide an overview of appropriate limnological/ environmental principles and concepts, rather than a comprehensive review. During the workshop, access to literature was limited and accordingly the reference list is far from exhaustive.

Two important prominent and recurrent limnological issues experienced in the Southern Hemisphere were not specifically addressed at the workshop. The first concerns the explosive and frequently nuisance growth of biota, particularly aquatic macrophytes. This often arises in indigenous organisms in response to an alteration of the aquatic regime - eg flood control, creation of new habitat, increased nutrient loading rate, or introduced exotic species released from the environmental and ecological constraints of their native localities. The second problem, linked to the above, concerns the introduction of alien species under vairous guises such as weed control, protein production, improved or favoured angling attributes, etc. The displacement of native species by these exotics represents a particularly insidious threat to aquatic ecosystems, especially since such introductions are widely undertaken with the best intentions, but in ignorance of their profound ecological effects.

Clearly complete treatment of subject matter was impractical during the workshop, but it is our hope that the contents of this report will assist in highlighting limnological issues and considerations which, from a management perspective, are the daily concern of water resource managers and those charged with environmental policy.

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ABSTRACT

The report presents the proceedings of an international workshop on the management of Southern Hemisphere inland waters held in Wilderness, South Africa, in July 1984. It includes an introduction and seven chapters dealing sequentially with catchment management, stream regulation, pollution, salinization, turbidity and suspensoids, eutrophication, and fisheries. Given that limnology is concerned with understanding that diverse array of intrinsic and extrinsic factors which together govern the physical, chemical and biological characteristics of lakes, reservoirs and rivers, each chapter attempts to assess the specific or general role it makes to the

holistic management of water quality in the Southern Hemisphere in general (excluding Antarctica and the sub-Antarctic islands) and the more arid latitudes in particular. In so doing, attention is drawn to the relevant use of terminology and definitions which, when used precisely, will materially decrease the semantic confusion which exists between the science of limnology and its application in the maintenance of surface water quality.

The chapters also represent a concensus of viewpoints between limnologists and managers in which a considerable amount of tedious descriptive detail has been very largely replaced by highlighting those processes considered essential not only in the implementation of modern limnological principles to water management practise, but also in drawing up research priorities.

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CHAPTER 1 CATCHMENT MANAGEMENT

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1.1 GENERAL STATEMENT OF A CATCHMENT AS A PHYSIOGRAPHIC AND HYDROLOGICAL UNIT

Although hydrologists have long recognized the close physical and chemical links between runoff and the terrestrial environment, the ecological and limnological links have only relatively recently been demonstrated factually. Hynes (1975) concluded that in every aspect the valley rules the stream and consequently the lake. Geology determines slope, the soil type and availability of ions. These and the climate determine the vegetation which in turn affects organic matter. This influences the soil and controls the release of water, particles and dissolved salts which in turn control aquatic ecosystem processes with which we as limnologists are concerned in this volume. Limnological problems are therefore essentially catchment problems so at this stage it may be useful to list some of the limnological problems we are to consider. We feel, however, that Hynes's view may be somewhat narrow. Although the valley rules the stream, regional climate and interactions of climate with catchment physiography (ie high relief resulting in rain shadow etc) and stream order also affect the stream. More recently, the concepts of interbasin transfers of water, dust and aerosols which result in acid rain, have complicated Hynes's view further. General problems, their source areas and causes in a whole catchment context are listed in Table 1.1.

TABLE 1.1 Limnological problems associated with catchment manipulation and development

Perceived problems	Source areas	Specific causes
Increasing runoff rather than storage or changes in runoff pattern	rural urban	reduced infiltration reduced infiltration
Decreasing water yield	forestry farming industry	evapotranspiration abstraction abstraction
Increase in turbidity	rural urban	poor farming poor forestry street runoff
Increasing salinity	rural urban	irrigation effluent disposal
Increasing nutrients	rural (forest and farm) urban	fertilizer application residential (streets) sewage waste dumps
Increasing toxicants	rural urban	herbicide pesticide hydrocarbons metals
Intercatchment transfers	-	-

TABLE 1.2 Weighted mean annual concentrations in atmospheric fallout (ie precipitation and dust fallout collected at weekly intervals over a number of years) in urban and mountain catchments (after Simpson and Kemp 1982 and Van Wyk 1984).

Parameter	Urban	Mountain
Suspended solids mg l^{-1}	25-50	-
Orthophosphate-P mg l^{-1}	0,007-0,026	0,006
Soluble-P mg l^{-1}	0,009-0,032	-
Total-P mg l^{-1}	0,047-0,103	0,019
Nitrate-N mg l^{-1}	0,184-0,438	0,091
Ammonia-N mg l^{-1}	0,207-0,434	0,093
Soluble Organic-N mg l^{-1}	0,151-0,247	-
Total Kjeldahl-N mg l^{-1}	0,562-1,096	0,204
Chloride mg l^{-1}	5,0-5,7	5,1
Sulphate mg l^{-1}	3,5-5,9	6,5
Fluoride mg l^{-1}	-	0,02
Sodium mg l^{-1}	-	2,8
Potassium mg l^{-1}	-	0,2
Calcium mg l^{-1}	-	0,4
Magnesium mg l^{-1}	-	0,2
Bicarbonate (HCO_3) mg l^{-1}	-	5,6
Conductivity mSm^{-1}	7,4-9,1	-

Certain of these problems are specifically addressed in subsequent chapters on pollution, salinization, turbidity and eutrophication (Chapters 3 to 6, respectively).

1.2 IMPORT OF WATER TO THE CATCHMENT

This section deals only with the quality of precipitation. We recognize that the quantity of precipitation can be altered by techniques such as cloud seeding but these are outside the scope of this document. Water can also be introduced via intercatchment transfers.

1.2.1 STATISTICS REGARDING MEAN, MEDIAN AND VARIABILITY OF PRECIPITATION QUALITY

Table 1.2 gives an impression of the levels of various particulate and dissolved compounds in rainfall in South Africa. Note the high levels of nitrogen, sulphur and phosphorus compounds.

1.2.2 THE EFFECT OF MAN ON THESE VALUES

Man affects the quality of precipitation in a number of ways:

- Atmospheric dust can be increased following extensive ploughing or overgrazing.

- Smoke (organic and inorganic particulate matter) is generated by burning vegetation or solid fuels.

- Farming practices in heavily fertilized catchments (eg in New Zealand) where widespread use of urea and ammonium salts occurs, can result in volatilization of these compounds.

- Industrial development often produces sulphur, phosphorus and nitrogen oxides which can markedly affect atmospheric conditions and provide an atmospheric source for these elements.

1.2.3 LIMNOLOGICAL CONSEQUENCES

The limnological consequences of nutrients in dust and smoke are probably of little significance. Interpretation of nutrient levels in precipitation should be done with caution. For instance, the phosphorus content in the rain over remote Lake George in Uganda is similar to that over the industrialized South African Witwatersrand. The limnological consequences of volatilized nitrogen compounds from vegetation (agriculture and forestry) is not well known. However, in some parts of the world (New Zealand and Japan) dissolved organic nitrogen compounds originating from catchments can be a major source of nitrogen in precipitation, and can be a significant contributing factor to the nitrogen inputs in some inland waters.

TABLE 1.3 River basin potential evaporation, precipitation and runoff for representative catchments in South Africa (W J R Alexander, unpublished)

Site	Gross evaporation mm	Precipitation mm	Runoff mm	Percentage runoff	Statistical properties of annual runoff			
					mean 10^6m^3	median 10^6m^3	coefficient of variation	skewness coefficient
Steenbras Dam	1 410	1 230	670	54	45	43	0,32	0,69
Churchill Dam	1 390	1 150	200	17	72	48	1,04	2,73
Woodstock Dam	1 300	1 490	480	32	548	499	0,44	0,75
Midmar Dam	1 390	970	180	18	164	135	0,56	1,80
Vaal Dam	1 700	750	50	6,7	1 933	1 315	0,76	1,41
Kalkfontein	1 880	450	15	3,3	155	71	1,48	3,55
Kamanassie Dam	1 700	460	24	5,2	37	22	1,10	2,81
Rooiberg Dam	2 740	150	1	0,7	75	20	2,55	4,07

The limnological consequences of the industrial sources of atmospheric nitrogen, phosphorus, and sulphur compounds can be severe. The formation of acid rain, for instance, is a major issue in industrial catchments in the Northern Hemisphere, but has not been identified as important in the Southern Hemisphere.

1.2.4 POINTS FOR PLANNERS AND MANAGERS TO CONSIDER

In heavily industrialized catchments the importance of atmospheric inputs in terms of concentration and downward mass flow should be determined. However, quality standards on industrial emissions, if these are significant, can only be formulated on a site-specific basis.

1.3 EXPORT OF WATER FROM A CATCHMENT

1.3.1 STATISTICAL PROPERTIES

While the export of water from a catchment (surface and subsurface) is clearly a function of atmospheric precipitation on the catchment, it is the post precipitation evaporation process that governs both the proportion of the precipitation that runs off the catchment and its variability.

The overall picture in southern Africa and also in other southern sub-continental regions experiencing similar hydroclimatic conditions is that, as annual average precipitation decreases, evaporation losses increase. Consequently a smaller percentage of the already low precipitation reaches the river systems, and this component is subject to large year-to-year variation. These trends are illustrated in Table 1.3, in respect of eight representative dam sites in South Africa.

The methodology now exists to produce historical flow records from precipitation data, as well as to generate synthetic flow sequences based on the statistical properties of river flow. It is in routine use by hydrologists and engineers.

1.3.2 EFFECTS OF MAN ON THESE VALUES

1.3.2.1 Rural

Man can influence water export from rural catchments in several ways.

- Afforestation/deforestation: Afforestation reduces streamflow throughout the year, by amounts which depend upon the species planted. Annual reductions in streamflow of up to 440 mm per year have been recorded. Clearfelling of pine stands results in an immediate increase in streamflow. Changes in evapotranspiration rates following clearfelling are influenced by the rate of recovery or regrowth of the vegetation.

- Burning: Burning of vegetation during different seasons and on different cycles results in changes in the composition and structure of the vegetation, and thus evapotranspiration. The effect may be less significant than expected. Nanni (1960) has, for example, shown no immediate effect on water yield following burns in grassland, while small increases of ± 60 mm in water export for a period of about 10 months followed burning of fynbos. Vegetation recovery was presumably sufficient to bring water yield back to pre-fire levels. The effect of fire on water yield in South Africa is discussed in detail by Bosch et al (1984).

- Riparian treatment: Manipulating vegetation type and structure in riparian zones has a direct and significant effect on water yield. The effect of vegetation on streamflow is dependent on factors such as climate and catchment characteristics. Preliminary results of riparian treatments in South Africa have indicated that the effects, for example, of clearing the vegetation are very short-lived, and depend on the recovery rate of vegetation in such zones.

- Irrigation: Irrigation attenuates water yield from catchments and thus increases evapotranspiration to the detriment of streamflow. Water from the river is intercepted and repeatedly spread over the catchment for crop production. Over 80% of the water used by man in the Murray-Darling system, for example, is used for irrigation and has contributed to marked decreases in river flow especially in years of low rainfall.

- Draining wetlands: The role of wetlands in the hydrology of catchments is poorly understood. Little is therefore known about the effects of farming practices on wetlands, such as cultivation and draining of vleis.

- Road construction: Certain forest and farming practices require dense networks of roads. Roads change the natural drainage pattern in catchments and may divert water from one catchment to another. Little is known about the effects of such networks on water export from catchments.

1.3.2.2 Urban

The runoff coefficient (millimetre runoff/millimetre rainfall) from urban landuse catchments is usually appreciably higher than that for rural catchments. The coefficient for a particular rainfall-runoff event is dependent upon inter-acting variables such as rainfall intensity, pervious area, catchment form, antecedent dry period and soil and surface moisture conditions. The relationship between rainfall and runoff amounts has been found to be curvilinear rather than linear, with increasing runoff coefficients with increasing rainfalls. Yields from a 90 ha urban landuse catchment have indicated coefficients in the region of 0,30 for rainfalls of about 10 mm, 0,35 for rainfalls of 20 mm and 0,40 for rainfalls above 40 mm. Most events were less than 10 mm rainfall. For a catchment with an estimated impervious surface area of 75%, a mean runoff coefficient of 0,50 was found over a two-year study period. It should be borne in mind that only surface runoff is considered here (Simpson and Kemp 1982).

With increasing urbanization, increased runoff volumes and peak flow rates can be expected compared to undeveloped conditions. For example, basins ranging in size from 3,5 to 471 km^2 and percentage urban development from 37 to 99% showed a factor of change of 4,2 for the two year recurrence interval and 4,9 for the 50 year interval. Development can increase peak flows up to four times that of predevelopment flows (Bedient 1982). For a 12 ha urban catchment the time of concentration (difference between rainfall and runoff peaks) was found to be only two minutes and for a 90 ha catchment only eight minutes (Simpson, unpublished). This illustrates the 'flashy' nature of runoff in urban catchments and the erosion potential resulting from high velocities produced in receiving waters.

1.3.3 LIMNOLOGICAL CONSEQUENCES

If there are no impoundments on a water-course, then river flow tends to be in the form of seasonal high-flood peaks of short duration. Impoundments alter the natural flow regime of rivers, and exert qualitative influences:

- Retention time of water in the river may be greatly increased during low flows, resulting in increased growths of algae and aquatic plants.

- Flow alteration may influence the water quality in the river through evaporation or dilution effects.

- Alteration or interference with the seasonal timing and magnitude of the flow regime will have an influence on various biota. Such changes in flow regime may alter the habitat with subsequent influence on biotic components including man (eg change in recreational potential).

- Discharge patterns from impoundments may have important impacts on downstream river sections, wetlands, floodplains and estuaries.

- Increased downstream turbidity can occur due to bottom releases from upstream impoundments.

- Alteration of downstream temperature regimes can occur due to cold bottom water discharges.

- Increases in downstream particulate organic matter can occur due to discharge of water with high algal biomass.

- Unwanted downstream spread of floating aquatic plants may take place due to the pattern of water releases from impoundments (eg water hyacinths in the Vaal River, South Africa).

- Oxygen depletion due to hypolimnetic discharge can cause problems for aerobic biota. Oxygen depletion has not been observed to have a widespread downstream effect under South African conditions at any rate.

1.3.4 POINTS FOR PLANNERS AND MANAGERS TO CONSIDER

1.3.4.1 Catchment development

The vegetation cover of a catchment has a marked effect on streamflow. Removal or alteration of this cover will change the volume and perhaps the temporal pattern of streamflow. The present trend in some areas is a reduction in catchment vegetation cover. In consequence stormflow increases and baseflow decreases. This trend needs to be reversed because in these areas flash floods are becoming more common and damaging. In this context the particular importance of the vegetation on the catchment flanks in regulating stormflow should be taken into account. The type and extent of vegetation and the use of porous asphaltic surfaces should be taken into consideration in any new catchment developments.

Along with man's development of catchment slopes, has been the development of floodplains. Apart from the obvious increased likelihood of the flooding of these areas, such development has often involved damage of important wetlands or their isolation from rivers, reducing the interchange of water and nutrients between rivers and wetlands to the detriment of the river ecosystem and the estuary. The practice of developing floodplains and then using engineering approaches, such as canalization, levee bank construction, and drainage cuts through macrophyte stands, to prevent flooding is unsatisfactory. In new developments, stream side zones and flood-prone areas should be delineated and managed to achieve limnological and ecological goals. Fringing vegetation around standing waters and along river banks should remain intact to act as sediment traps, water purifiers, bank stabilizers, and a habitat for aquatic and water-allied biota. In existing developments, holding areas set aside for the reception of floodwaters could be established. These would take the pressure off the flood prone rivers, avoiding the destruction that spates can cause, and precluding the need to canalize or cut quick exit channels through reedbeds. Such holding areas can be at a series of elevations with different uses (eg the lowest could be sports fields).

In some areas storm runoff floods water-treatment plants, resulting in higher phosphorus and nitrogen loads in rivers during spates than during times of low flow. The problem of disposal of stormwater from developed catchments needs to be considered.

1.3.4.2 Storage and yields

When dams are to be constructed, it is necessary for limnologists to have the same professional input as the engineers, geologists, and hydrologists, and to have the same amount of time to study a new development before making recommendations. Common questions that need attention relate to the quantity and timing of water releases from a dam required to maintain a stable river ecosystem and estuary (see Chapter 2) and the possible appearance of aquatic pests with the new regime. A first stage management guide would be to aim for a release pattern that simulates the natural condition as closely as possible.

Riparian strips including fringing wetlands (Section 1.3.4.6) are integral parts of river systems, with the aquatic biota as dependent on them as they are dependent on the water. Efforts should be made to maintain the riparian vegetation intact and to manage it in a way that takes into consideration the important influence they have as bank stabilizers and as a prime source of potential energy and nutrients for aquatic ecosystems.

With the restricted flows present in impounded rivers every effort should be made to reduce the input of pollutants.

1.3.4.3 Intercatchment transfers

When water is moved from one catchment to another, the donor stream may change from strongly to weakly perennial. Additional water may have to be disposed of in the receiving catchment. Often reductions or enhancements of flow are not taken into account when such schemes come into operation. Attention must be paid to the rates of nutrient loading into receiving streams, the ability of these streams to cope with these inputs, and the possible flooding of lower catchments that may arise as a consequence of the extra input.

1.3.4.4 Groundwater

Extraction of groundwater and its replacement through irrigation practices changes its quality and quantity. These processes are not well documented. Urgent problems that need attention are the contamination of groundwater by infiltration of low quality irrigation water, leakage from dumps and nitrate accumulations below plant rooting zones.

1.3.4.5 Evaporation

A considerable proportion (up to 80% in inland New South Wales, Australia) of the water entering a catchment as precipitation is lost through evaporation both from the vegetation and from land and water surfaces. Management of vegetation to increase water yield in streams and decrease evaporative losses is well understood. Losses from open waters are important especially in the case of storage dams.

1.3.4.6 The role of wetlands

In this context wetlands can be divided into two types:

Fringing communities which vary in type and size from narrow riparian strips of grass or forest to wide floodplains and reedmarsh which can extend for kilometres on either side of the stream. Their common factor is that the hydrological regime is dominated by surface inflow and outflow.

Endorheic systems such as pans, bogs and vleis in lowland and upland areas, which differ from fringing communities in that they have surface and/or groundwater inflows but no surface outflow.

It is important to realise that macrophytic plants, attached algae and bacteria and the substratum (organic or inorganic sediments) form the functional units of these wetlands. The role of wetlands in catchments is determined by interactions of these factors, rather than by any one alone. Furthermore, the roles of wetlands must be viewed in terms of the nature and extent of the catchment. For instance, pan systems of the Highveld of South Africa will have a small effect on the flow of large rivers such as the Vaal but may have a significant effect on smaller local catchments. In contrast, fringing communities will affect sediment generation over the whole catchment. Water export can be via flood, low (including base-) flow, groundwater and evaporation.

Fringing communities offer physical resistance to water flows and thus dampen peak flows and increase low flows. The extent of this modification depends upon the size of the community in relation to riverflow, slope and cross sectional area of river basin. The effects of these communities on riverflow will thus be more important in higher order streams and rivers where reduced slope provides a greater area for colonization.

Losses of water which occur through evapotranspiration in these communities will vary in relation to the area of wetland but in general will be a small proportion of riverflow. The role of endorheic systems in modifying export of water from the catchment is threefold. Firstly, recharging of these systems, particularly at the beginning of the rainy season, will reduce runoff. Secondly, water stored in impervious basins is lost via evaporation and, thirdly, retention of water in bogs and its subsequent slow release can markedly affect stream baseflow in the dry season. The bogs of Lesotho and other mountain catchments are important in this respect.

The effects of wetlands on evaporation will vary in relation to the area of wetlands and water volume or flow. Generally these effects are not large. Absolute, but not relative, evaporative losses may increase downstream.

1.4 EXPORT OF FLUVIAL SEDIMENT AND OTHER PARTICULATES FROM A CATCHMENT

General statement: Catchments yield both organic and inorganic particulates, which range in size from inorganic colloidal or clay particles to large organic debris. These predominantly arise from diffuse sources in undisturbed natural catchments, while human activities may result in point source yields.

1.4.1 MOBILIZATION OF PARTICULATES: PRINCIPLES AND QUANTIFICATION

The export of particulates from a catchment is predominantly mediated by surface runoff events and wind.

Sediment yield to water is determined by a variety of interactions. It is a function of rainfall erosivity, soil erodibility, slope steepness, slope length and vegetation cover. The first factor cannot be controlled but the latter three are variously modified by activities in a catchment. No single component factor is consistently the most important. Areas of intermediate precipitation appear to be the most susceptible to sediment production for in very arid areas runoff is insufficient to move large amounts of sediment while in wet humid areas, good vegetation cover stabilizes soil loss.

The long-term export of fluvial sediment from a catchment is a direct result of the interaction between the weathering processes acting on the parent material and the hydraulic properties of flowing water which detach sediment particles, take them into suspension (or move them in continuous or discontinuous steps along the riverbed), and transport them to a point further downstream. Finer material such as the colloidal and silt fractions will tend to move through the system in a single flood event. This flow may be intercepted by impoundments, or in estuaries and wetlands where flow velocities are reduced to the point where they can no longer maintain the sediment in suspension.

Coarser particles are not taken into suspension but 'leap frog' from point to point down the river bed. These size fractions constitute the bed material after the passage of the flood event and the grading of this material, which is a function of the hydrological regime, has important limnological consequences as it determines physico-chemical conditions at the sediment/water interface of the riverbed.

Sediment export from a catchment cannot be determined with the same precision as that of the export of water. The reasons are two-fold. Firstly, it is difficult to obtain quantitative measurements, particularly of the bed-load fraction. Secondly there is no direct relationship between the transport of water and the transport of sediment in a river. The volumetric transport of sediment in a single flood event is a function of the time interval between consecutive runoff events. On an annual basis this is a function of the magnitude of surface runoff in the preceding year (Rooseboom 1981).

Routine bathymetric surveys provide the best available information on the volumetric transport of sediments. Such data are available for major reservoirs in South Africa. Statistics relating to sediment concentrations or riverflow are less comprehensive but are available. (Division of Hydrology of the Department of Environment Affairs - South Africa).

1.4.2 EFFECTS OF MAN ON THESE VALUES

1.4.2.1 Rural

In South Africa mountain catchments cover about five million hectares and are managed primarily to maintain water yields. Associated water quality issues and sediment exports must be considered in this context since burning, clearing or spraying of mountain catchment and/or riparian vegetation is carried out to increase water yields.

In winter and summer rainfall areas sediment loads in streams increase mildly following burning of the natural vegetation. Timing of the burns in relation to the rainy season influences sediment mobilization. For example, autumn and summer burns preceding the winter rains result in lowest sediment exports.

Burning of grasslands in the Natal Drakensberg area resulted in a mean increase of 258% in suspended sediment during stormflow compared with the pretreated and an untreated catchment. Fires in pine plantations can have disastrous effects on the suspended sediment load of stormwater. In one case in the Natal Drakensberg, a suspended sediment concentration of 640 g l^{-1} was measured in river stormflow five months after a burn. In this case there was no organic litter left on established natural vegetation to prevent continuous soil creep taking place. Before the burn, mean annual sediment concentrations were 4 and 105 mg l^{-1} under baseflow and stormflow conditions, respectively, compared with a mean annual export of 3,9 g l^{-1} under stormflow conditions after the burn.

Clearfelling and burning of riparian zones in the sub-tropical areas of the Transvaal have not resulted in any noticeable increase in suspended sediment export due to the quick recovery of the vegetation.

It can be concluded that the removal of vegetation and litter by fire in unstable areas or even other forested areas where fire is not a natural phenomenon can seriously increase sediment exports.

The effects of agricultural landuse on sediment production have not been considered here but are very significant (Maaren 1981; McColl and Hughes 1981). Likewise, mining activities contribute particles both in urban and rural environments.

1.4.2.2 Urban

Particulates are produced in urban areas by a number of physical processes such as erosion of buildings, paved surfaces, soil and grassy areas; littering by people; accidental spills of materials during industrial/commercial activities and wear/emission products of vehicles. Street surfaces are major collection areas of heavy metals and other pollutants with tyre wear deposits as a source of zinc, lead and cadmium, copper and asbestos from anti-freeze and brake linings, zinc and hydrocarbons from motor oil and lead from gasoline (Wigington et al 1983). Vehicle exhaust particulates range in size from 0,2 to 20 m and are a major source of lead deposits (Pitt and Shawley 1981). Between 40 and 90% of street surface contaminants are reported to occur as particles smaller than 246 m in diameter and since particles of this size can be resuspended by air currents with velocities of less than 8 km per hour, turbulence caused by passing vehicles can redistribute them onto areas which are not regularly swept. In any event street cleaning practices are not very effective in removal of such fine particles which contain most of the metal contaminants and adsorbed phosphorus (Barkdoll et al 1977). The size range of suspended sediments mobilized by a particular runoff event will depend upon rainfall intensity. Median particle size will be smaller after light rainfall and larger after heavy rain which will dislodge and transport coarser particles.

An export of 360 kg ha^{-1} yr^{-1} of suspended solids was measured for a commercial landuse catchment during a drought year. With a 24% higher rainfall in a second year the export value rose to 600 kg ha^{-1} yr^{-1} (Simpson and Kemp 1982). This shows the variable nature of suspended solids loads washed off urban catchments. A survey of North American catchments showed that loads of suspended sediments, phosphorus and nitrogen from cultivated land and urban areas were 10-100 times greater than forested and fallow lands (Sonzogni et al 1980).

1.4.3 LIMNOLOGICAL CONSEQUENCES

Suspended sediments have an influence upon both water quality and the functional processes of aquatic communities including wetlands. Similarly dissolved matter exported from catchments can influence the limnology of receiving waters.

The transport of sediments in river systems without impoundments tends to be important as deposits on flood plains. Alterations of river habitat due to redeposition of these sediments also have important influences on river biota such as benthos, fish and aquatic plants. The transport of sediments also plays an important role in determining the meander and alteration of the water course with all the ramifications of this action on adjacent development.

In rivers with impoundments, sediments cause turbidity in the water column. Increased sedimentation results in loss of storage capacity. Figure 1.1 shows the frequency distribution of sedimentation rates in 78 South African impoundments (C A Bruwer, unpublished), related to specific sediment yields from their respective catchments. This trapping of sediments in impoundments may have the following downstream effects:

- a possible increase in downstream bed erosion due to sediment-hungry discharge waters;

- a reduction in sediment deposition on downstream floodplains and estuaries;

- habitat alterations selecting for or against certain biota;

- the possibility of downstream fish kills induced by smothering of gill surfaces (eg the Olifants River below Phalaborwa Dam, C A Bruwer, unpublished).

From a water quality viewpoint suspended solids are important in nine of fifteen water uses addressed by Kempster et al (1980). Many toxicants and heavy metals are transported in association with sediments (see Chapters 3 and 5), as are plant nutrients (see Chapter 6). Agricultural potential is reduced by erosion, and attempts to make good this deficit may further aggravate the problems of salinization and eutrophication.

The most obvious effect of sediments in water is to increase turbidity. The implications of this on underwater light climate, primary and secondary production etc are considered in Chapter 5.

Aquatic invertebrates have been classified according to functional feeding groups (Chapter 2) whose feeding ecology may be modified by changes in the nature and amount of particulate matter entering streams. Species endemic to the upper reaches of streams are especially vulnerable to reductions in

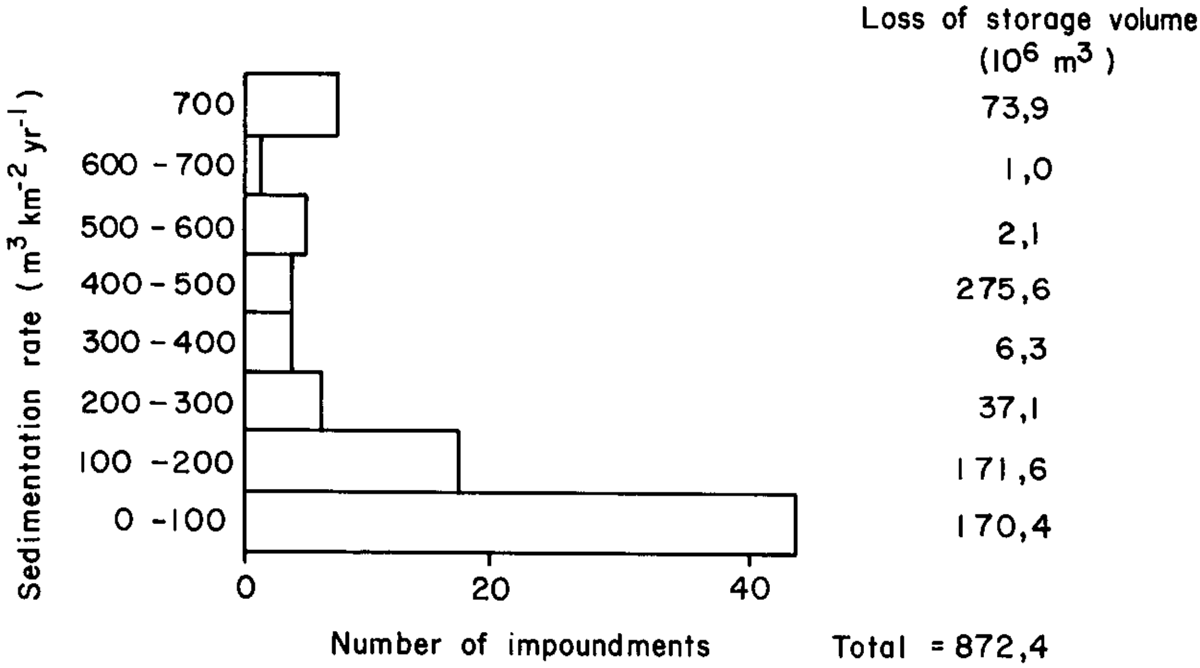

FIGURE 1.1 Reservoir sedimentation rate in cubic meters of sediment per km^2 of catchment per annum for 78 South African impoundments. (C A Bruwer, unpublished.)

oxygen levels, and altered amounts and timing of river flows consequent upon catchment manipulation. Increased sediment deposition can smother the benthic habitat.

The range of organic and inorganic chemicals and matter which reach rivers as a result of catchment activities is diverse (see Chapter 3). They generally have adverse affects upon aquatic ecosystems in the short or long term. Several impacts are considered in subsequent chapters.

1.4.4 POINTS FOR PLANNERS AND MANAGERS TO CONSIDER

1.4.4.1 Rural

Basically, good landuse practices will reduce the loss of sediments from catchments. Methods include contouring, ridging, maintaining vegetation cover etc to reduce rainfall erosivity and transport capacity (a function of water velocity). Afforestation, dryland crops, or irrigation will differentially affect the timing, duration and extent of soil protection by vegetation cover. Grazing animals, on the other hand, may exert a direct influence on vegetation in certain regions (Roux 1981). Stocking densities, and the use of rotation grazing camps are important agricultural considerations which ultimately affect the drainage streams. Certain catchment manipulations may reduce soil mobilization. For example, burning or clearfelling can reduce the gravitational forces of plant biomass and wind stresses exerted upon the soil through stands of vegetation sufficiently to prevent land slips following heavy rainfall events in some mountain catchments (eg Western Cape in South Africa).

Of particular significance is the maintenance of riparian vegetation, wetlands and natural vegetation over partial source areas. While water yields may be increased by the removal of riparian vegetation and fringing wetlands, the quality of that water may deteriorate as a result of both the loss of the sediment trapping potential of plants and the reduction in binding along streambank channels. Physiographic considerations modify this, since as stream order increases stream gradients generally decline and deposition rather than erosion may dominate.

Endorheic wetlands play little role in trapping sediments since their catchments are usually small. Transport and dumping of solid wastes in these depressions, however, markedly affect the quality of water stored within them.

Fringing wetland communities alone have a role in promoting the export of particulates. They generate particulate organic matter (POM) which may form an important energy source for downstream ecosystems.

1.4.4.2 Urban

In the urban context, the increased response time of runoff associated with impervious surfaces leads to stream erosion, reservoir infilling, reduced infiltration and groundwater baseflows. Various means of preventing peak stormflows (sub-surface disposals, detention storages) and of treating urban runoff to reduce dissolved and suspended contaminants are being developed and have been reviewed (D E Simpson, unpublished). Many man-made inputs of particulate matter in urban catchments are point source in nature and therefore more amenable to manipulation than rural inputs.

Pathogens arising from reticulated human wastes may be controlled. Those arising from animal excrement, or the malfunction or absence of sewage reticulation are less tractable.

Small impoundments, slow flowing reaches of rivers, and fringing wetland communities in urban areas may play an important role in retaining particulates of all types and so reducing export from the catchment.

1.5 EXPORT OF DISSOLVED MATERIAL FROM A CATCHMENT

General statement: Dissolved material consists of inorganic nutrients and minerals (nitrogen, phosphorus, potassium, etc), inorganic toxins (heavy metals etc), conservative inorganic substances which alter little in concentration as they pass through the aquatic system (sodium, chloride, etc), toxic organic substances (pesticides, etc) and harmless organic substances (humic substances).

The quantities of each of these components are affected by complex processes in the catchment involving interacting physical, biological and socio-economic factors. Each interacts with the physical and biological components of the aquatic ecosystems that they enter.

Human activity is usually directed towards increasing the biological productivity of a catchment, whereas management objectives for the water bodies that drain the catchments are usually aimed at ameliorating the consequences of excessive biological productivity. This conflict in objectives is exacerbated when:

- the agricultural or forestry output is inefficient in terms of fertilizer inputs;
- the aquatic ecosystem is small in relation to the capacity of its catchment to generate limnologically perturbing substances;
- there is a high variability in output from time to time and from place to place (variability and output could be due to inherent factors affecting runoff or to the nature of human enterprise in the catchment).

Change in catchments and aquatic systems is particularly dependent on rates of flux of substances, periodicities of plant growth and production and the interaction between the two. This is a complex matter that is inadequately understood and requires research.

1.5.1 STATISTICAL PROPERTIES

As in the case of fluvial sediment, dissolved material is a product of the interaction between the weathering process which produces it and the hydrological processes which transport it from the catchment. However, the transportation process and consequently the statistical properties of the export of this constituent of the weathering process are quite different.

Once taken into solution, dissolved material will only be redeposited in situations where evaporation concentrates the solution to beyond saturation point. This only becomes significant in semi-arid and arid areas.

A summary of ionic concentrations occurring in headwater streams of various regions in South Africa is presented in Table 1.4. These values indicate that the waters of the Natal region have a much higher alkalinity than the waters of the other areas. Phosphate, nitrogen, bicarbonate and sulphate are present in the waters of the Transvaal and Natal while only traces of these occur in the waters of the western Cape. The higher levels of sodium and chloride found in the headwaters of the western Cape streams compared to the levels observed in the water of other regions, may be ascribed to the effect of deposition from the sea in the form of aerosols. The highest total nutrient levels occur in the headwaters of the Natal regions while the lowest nutrient content is to be found in the headwaters of the northern Transvaal.

1.5.2 THE EFFECTS OF MAN ON THESE VALUES

1.5.2.1 Rural

Controlled and uncontrolled burning of fynbos and grasslands, clearfelling and partial clearfelling of pines, and clearing of riparian zones (slashing, burning, clearfelling and herbicide spraying) are forestry management applications which influence total nutrient and mineral exports.

TABLE 1.4 Mean ionic concentrations (mg l^{-1}), specific conductance (mSm^{-1}) and pH of headwater streams in different areas in South Africa (D B van Wyk, unpublished)

	NATAL	TRANSVAAL		CAPE
	Cathedral Peak	Northern Transvaal Westfalia	Eastern Transvaal Witklip	Western Cape Zachariahoek Jonkershoek Jakkalsrivier
Na	3,203	3,379	5,276	5,936
K	0,362	0,700	0,647	0,358
Ca	9,524	1,038	2,030	0,575
Mg	3,936	0,367	0,651	1,040
CL	3,033	4,302	4,508	11,254
SO_4	1,816	1,660	2,490	5,000
TAL = CO_3	39,553	7,876	15,535	5,000
NH_4 - N	0,046	0,040	0,047	0,040
NO_3 - N	0,033	0,025	0,052	1,000
F	0,039	0,046	0,082	-
SI	12,242	5,906	8,498	-
PO_4	0,013	0,016	0,035	0,100
Specific Conductance (25°C)	9,660	2,847	4,859	5,000
pH	7,070	6,020	6,490	5,000

After spring and early summer burns in mountain fynbos of the western Cape in South Africa the total outflow of dissolved solids rose by 1 kg ha^{-1} $month^{-1}$. This effect only lasted for ten months. The first two spates (more than 20 mm) after the burn exported above normal concentrations of dissolved solids. In these cases sodium and chloride showed a noticeable increase after burning under base-flow conditions but changes in concentrations of magnesium, calcium and potassium could only be detected under stormflow conditions. No increased export of nitrogen and phosphorus was found after the burns. However, no significant changes in TDS of stream water have been observed over a four year period after clearfelling of a catchment planted with pines in the western Cape. In the eastern Transvaal partial clearfelling (30%) of a pine catchment resulted in a 10% reduction in TDS content of streamflows compared with initial values. This may have been due to the rapid regrowth of the vegetation in this area.

These observations suggest that different mechanisms control the export of dissolved substances in different climatic zones and in different vegetation types. The cause and effect relationships are, however, poorly understood.

Agricultural practices in catchments (eg fertilizer and pesticide application and irrigation) can markedly increase the concentrations of dissolved solids and toxins entering receiving waters via runoff (McColl and Hughes 1981), particularly with the first heavy rains following application. This is a well documented phenomenon and will not be discussed here.

1.5.2.2 Urban

The quality of runoff from urban catchments is extremely variable during runoff events. High concentrations of solid-related contaminants such as phosphorus, COD and heavy metals usually occur during a 'first flush' in initial runoff or with the first peak of flow. The average water quality characteristics of runoff from a commercial landuse catchment over a two year period, together with the range of mean event concentrations, is shown in Table 1.5. The concentrations of suspended solids, nitrogen and phosphorus are significantly higher than that normally found in undisturbed natural catchments. Apart from the erosion and wear products produced in urban areas (1.4.2.2), both wet and dry atmospheric fallout is a significant source of dissolved and particulate materials. Analyses have indicated that precipitation is the major source of inorganic nitrogen as ammonia and nitrate.

The contribution of atmospheric fallout to soluble phosphorus, heavy metals and suspended solids in runoff has been found to be, on average, 30%, 23% and 25% respectively.

Because of the higher runoff coefficients of urban than rural catchments, and the generally higher concentrations of contaminants, export coefficients are much greater for urban than rural catchments. Table 1.6 shows the export coefficients determined for urban catchments in South Africa.

1.5.3 LIMNOLOGICAL CONSEQUENCES

Broadly speaking, dissolved components exported from catchments fall into two categories, conservative and non-conservative fractions. Both are transported by waterflow but they contrast in their chemical characteristics and biological importance. Whilst both have important limnological consequences, the processes controlling their transport from catchments and the water quality problems they may cause are different. For the purposes of this discussion single examples will be used to demonstrate general principles but it should be stressed that the two examples represent extremes between which a continuum of possibilities exists.

TABLE 1.5 Weighted mean runoff water quality characteristics and range of event concentrations for an urban catchment (after Simpson and Kemp 1982)

Parameter	December 1978 to November 1979	Range
Suspended solids mg l^{-1}	117	12-422
Phosphate-P µg l^{-1}	50	2-412
Soluble-P µg l^{-1}	79	19-560
Total-P µg l^{-1}	438	65-5887
Nitrate-N µg l^{-1}	404	8-2687
Ammonia-N µg l^{-1}	109	11-2105
Soluble Kjeldahl-N µg l^{-1}	565	142-4925
Total Kjeldahl-N µg l^{-1}	1 956	449-28365
Soluble COD mg l^{-1}	35	13-228
Total COD mg l^{-1}	108	26-643
Total BOD mg l^{-1}	18	1-170
Copper µg l^{-1}	38	2-255
Lead µg l^{-1}	260	14-1084
Zinc µg l^{-1}	665	259-19800
Iron µg l^{-1}	3 860	342-32480
Chromium µg l^{-1}	23	5-71
Manganese µg m^{-1}	86	12-408
Conductivity, mSm^{-1}, 20°C	8,3	3-60

TABLE 1.6 Annual export of solids, nutrient and metals from urban catchments (all values in kg ha^{-1} yr^{-1}). (After Simpson and Kemp 1982)

Suspended solids	363 - 601
Orthophosphate	0,15 - 0,20
Soluble phosphorus	0,22 - 0,33
Total phosphorus	1,51 - 1,91
Nitrate nitrogen	1,30 - 1,60
Ammonia nitrogen	0,38 - 0,42
Soluble Kjeldahl-N	2,00 - 2,15
Total Kjeldahl-N	6,84 - 8,29
Chemical Oxygen Demand	355 - 513
Copper	0,12 - 0,19
Lead	0,84 - 1,26
Zinc	2,34 - 2,79
Iron	12,36 - 19,00
Chromium	0,04 - 0,10
Manganese	0,29 - 0,41

Conservative components (eg chloride) occur in abundance in the biosphere. They are of little short-term importance in plant nutrition and their concentrations in fresh waters are not markedly influenced by abiotic exchanges in catchments. Consequently they are extremely mobile in catchments and are readily dissolved and transported by surface and groundwaters. With increased water recycling within catchments, the concentrations of conservative components can build up in surface and groundwaters as a result of evaporation, resulting in water quality problems (salinization). Interbasin transfer (from low to high TDS systems) has been effectively used to ameliorate salinization problems by dilution. Because the concentrations of conservative soluble components are not markedly influenced by processes within the catchment their rates of transport to lakes can be reliably estimated directly from hydrological and chemical data.

Non-conservative components (eg soluble phosphate) are relatively scarce in the biosphere. They can be extremely important in plant nutrition and are involved in abiotic exchange processes in catchments. For these reasons they are relatively immobile in catchments and are transported in low quantities in comparison with conservative components in surface and groundwaters. In response to increased loading rates, catchments can consequently serve as effective traps for soluble fractions such as phosphate, a phenomenon that can be optimized by management in the catchment (eg construction of pre-impoundments and farm dams) as a supplementary eutrophication control option. Because of the strong interactions with soil particles some non-conservative components (eg phosphate, some heavy metals and some soluble organic compounds) are not transported by groundwaters to any great extent. However, in view of the importance of nitrogen and phosphorus in water quality, empirical relationships between catchment landuse and exports of the soluble component via runoff have been used widely for general prediction. In South Africa such relationships are currently being used to predict the impact of eutrophication control measures in catchments on the trophic status of existing and planned impoundments (Grobler and Silberbauer, in press). Nitrogen is a notable exception because, although being clearly non-conservative due to abiotic and biotic nitrogen transformations in catchments, groundwaters are commonly high in nitrates. Export of some non-conservative components from catchments, by virtue of their growth-limiting influence on aquatic primary producers, can result in eutrophication problems in receiving waters. However, unlike conservative components, loss processes within catchments make it more difficult to predict the loading rates of non-conservative elements from hydrological data.

1.5.4 POINTS FOR PLANNERS AND MANAGERS TO CONSIDER

Point sources of undesirable dissolved substances must be identified and quantified. Limnological impacts should be assessed preferably by an independent assessor. Point sources may need to be monitored in any case.

Diffuse sources can be identified directly on an area (sub-catchment) basis or indirectly in terms of biotic responses or chemical changes. Bioassays may provide a means of verifying the presence of polluting substances, but great caution is needed in interpretation of bioassay data.

The identification and assessment of diffuse sources may require the division of the catchment in terms of 'partial source areas' or in terms of distance and types of land cover between the receiving water body and the generation of the 'polluting' agent. Thus land-water interfaces, riparian vegetation, river and stream channel banks, areas liable to flooding, etc may require different management procedures to those used in upland areas. Such management procedures have to take account of forms of landuse and other socio-economic practice.

Relationships between landuse, soil type, topography and runoff (quality and quantity) must be studied and modelled. Such studies have proved somewhat unproductive up to now, perhaps because they have been too widespread and superficial.

Catchment developments, such as irrigation systems, which are likely to result in marked changes of dissolved substances entering the receiving water from the catchment, require prior environmental assessment.

In some catchments the generation of high concentrations of dissolved and particulate organic matter may be natural processes, often closely coupled to hydrological events. The existence and importance of such natural processes should be appreciated.

1.5.4.1 The role of wetlands

Both fringing and endorheic wetlands generate dissolved organic matter (DOM) and increase its export from the catchment. DOM can impart colour and odour to water supplies and act as a potential energy source for heterotrophic organisms in receiving waters.

Both wetland types play a role in reducing export of all dissolved substances from the catchment but characteristics are site-specific. It is important to recognize that the interactions of all biotic and abiotic components of a wetland lead to its capacity to reduce export of dissolved substances. In general the processes which provide this capacity are understood qualitatively but not quantitatively and so predictive potential is thus poor. The most important variables which require quantification to improve predictive potential are load and concentration of the substances, flow rate, water depth, retention time, organic sediment depth and growth rate of the dominant macrophyte species. While the plants are the dominant feature of the wetland, they account for only 5-15% of the nutrient standing crop at any one time. Harvesting to enhance nutrient removal is thus seldom economical.

The role of endorheic wetlands in reducing export of natural loads is generally small because their individual catchments are small. In local mining and urban areas, however, discharge of effluents can increase their role. The concentration effects in these basins can have important consequences for biota and water quality (stored and groundwater) and their deliberate use is encouraged.

Fringing wetland communities play a most important role in reducing export arising from diffuse sources and in many systems (eg the vleis of the Witwatersrand) they form important buffers against industrial pollution. While the extent of buffering cannot be quantified it is held that their reduction of:

Nitrogen	- is generally good
DOM	- is generally variable
Phosphorus	- is seasonally irregular
Pesticides	- is potentially good
Hydrocarbons	- is unknown
Acidity	- is good

Wetlands are generally intermediate stages in a natural progression from aquatic to terrestrial systems. Management techniques may be required to maintain wetlands as entities.

1.6 THE CATCHMENT AS A MANAGEMENT UNIT

1.6.1 MANAGEMENT CONSIDERATIONS

Here we consider what size the catchment unit should be for most effective management. For management to be effective, it must have clear objectives that are consistent with the needs of the community in the short term, while providing adequate protection for the environment and its resources in the long term. The identification of suitable objectives requires consultation between relevant experts, representatives of community interests and policy/decision makers. The formulation of management programmes to meet these objectives requires in turn the provision of suitable data by experts in water resources (hydrologists, limnologists, engineers), landuse (agriculturalists, foresters, urban and town planners) and other relevant fields, such as economics. These must be supported by relevant criteria to enable choices and trade-offs to be made between the various options available. Similar criteria are required to evaluate the success or otherwise of the management procedures. The processes of setting objectives, management formulation and actual management are interactive, iterative processes which must be planned in order to achieve optimum benefit from consultation, data provision, decision making and the administration of management procedures.

Competing forms of landuse and water demand result in conflicts which have to be resolved during the formulation of management programmes. For this, it is essential that all actual and potential uses be identified and ranked in order of importance to different community interests. The conflicts that are likely to result from these different perceptions will require careful resolution. When objectives cannot be met at the same site, consideration can be given to transferring landuses or water demand to other catchment units. Another approach is to identify sacrificial areas in order that other areas can be conserved. Similarly it is necessary to identify those areas of catchments which are not to be sacrificed at any cost. It is desirable to have flexible rather than rigid programmes of management so that these may take account of change and relate more precisely to local needs in different parts of the catchment.

Additional prerequisites for effective catchment management are the designation of the responsible management authorities and the size of the catchment areas under their control. This is a complex matter involving socio-economic, political, legal and environmental factors. At one end of the scale, catchments may be large and encompass portions of several countries, states or provinces. Subdivisions of these catchments therefore already exist in terms of factors which have little to do with water use. Even within one country or state, authority for catchment management can be so divided as to make the formulation of an integrated overall programme very difficult. At the other end of the scale, some catchments are uniform in terms of political administration and landuse and fall under the control of a single authority. Whatever the situation, it is necessary to identify the optimum size of a catchment unit for the most effective management. As far as limnological criteria are concerned, the size of the catchment which will provide the most appropriate management unit will be a function of three main factors and their interactions. These factors are water yield, demand for water use and the nature and complexity of limnological perturbations arising from the catchments.

The role of limnologists in the management of catchments is to provide the appropriate data to guide planners in the optimum utilization of water draining from catchments, while at the same time preserving some measure of protection for the integrity of aquatic ecosystems in the catchment.

1.6.2 MANAGEMENT DECISIONS

It has to be recognized, however, that most if not all catchments are already subjected to forms of landuse that have developed over time in a more or less unplanned and uncoordinated fashion and are not managed in relation to water quality at all. Indeed impacts on water quality are generally only measured when they are severely adverse and are brought to the attention of the community by their obnoxious nature. Even when catchment management has been planned, most decisions have been taken in relation to the perceived economic benefit of different forms of landuse in relation to current market forces, and impacts on water quality are only considered when they are especially adverse.

This situation is unlikely to change until administrative authorities take the decision to rigorously review current practice. The case for this to be done is compelling. Water is an increasingly precious resource and water quality levels have been progressively declining during the past fifty years or so.

Governmental water resources authorities are urged to undertake a comprehensive review of all catchments to obtain quantitative data in terms of water quality and forms of landuse to add to the hydrological information that is generally already available. This process should commence with the most heavily utilized catchments. Selected limnological criteria (section 1.6.3) can be used to assess water quality. Where necessary, catchment management can then be modified following the consultation procedures that have been outlined.

Management decisions require answers to the following limnological questions.

- What is the limnological effect of changing runoff through catchment use practices?

- What is the ability of rivers and standing waters to withstand sudden pollutant loads (ie what is the regenerative capacity of the water body); sustained pollutant loads (ie what is the assimilative capacity of the water body); deficient flows during droughts; and removal of riparian vegetation?

- What is the capacity of rivers, standing waters and wetlands to dilute or process effluents to the benefit of downstream biota as well as downstream users and what is the effect of these processes on aquatic systems in the short term and in the long term?

- If high productivity in an aquatic system is inevitable, is it preferable that it should occur in terms of excessive algal blooms or as large populations of macrophytes, such as water hyacinth?

1.6.3 LIMNOLOGICAL CRITERIA REQUIRED TO ANSWER THE ABOVE QUESTIONS

These criteria are designed to assess:

biotic communities;
limnological water quality;
functional ecosystem processes.

The reliability of the assessment will increase with the frequency of sampling in time and space. One set of measurements at one place is of such limited value as to be nearly useless. In consequence it is important that limnologists be consulted at an early stage in development planning so that their assessment of likely limnological consequences of development and their inputs to decision-making are based on adequate data. Different criteria are needed for lotic, lentic or wetland communities. Any competent limnologist should be able to provide a suitable programme of assessment.

However managers need a clear statement of biological or limnological goals. It is not feasible to manage for unspecified goals.

1.7 MONITORING AND STANDARDS

1.7.1 MONITORING

The problem here is to select what and how much to monitor. Too many factors measured too frequently results in an unwieldy and often incomprehensible amount of data as well as constituting an inefficient use of manpower and technical resources. Too few factors measured too seldom will leave gaps in the record and it is likely that important changes will be missed. The tendency to 'play it safe' and follow the first course is real and reasonable but must be resisted. Clear evaluation of specific objectives is essential for the formulation of an adequate and appropriate monitoring programme. Experience of the situation to be monitored is also an important requirement. If this is not immediately available, it is highly desirable that advice be sought from experts, since the alternative trial and error approach can be expensive and result in such a confusing amount of largely incomprehensible data that the errors in the programme will not be apparent.

The broad aims in a monitoring programme are to record the occurrence, nature and extent of changes in the ecosystem together with aspects relevant to the problem. Specific objectives to give effect to these goals have to be formulated for each situation.

We can distinguish three types of monitoring for catchment management.

- Baseline monitoring (measuring). This takes place irrespective of any catchment use - even in undisturbed catchments. Data collected include continuous hydrographs, precipitation, and grab sampling at weekly intervals for some aspects of water quality.

- Research monitoring for specific objectives. Here, water quality sampling is done on a flow or time related basis. Aspects of catchment landuse are studied in detail. Parameters monitored depend on research objectives.

- Surveillance monitoring. This is done at intervals when there is no research need but some concern exists that a particular event may be occurring. In such cases there may be one or two specific indicators of the general process one wishes to monitor. These should be identified and only these need be followed.

1.7.2 STANDARDS

A distinction needs to be made between criteria (ideal situations one would like to achieve) and standards (legally binding quantities). In South Africa for instance the whole question of water quality standards is under review by the Standards Group under the auspices of the Council for Scientific and Industrial Research. However it should be recognized that there may be a need to set standards other than those relating to water quality.

1.8 RESEARCH NEEDS

There are a number of recommended research needs which are not covered by the other chapters in this book.

1.8.1 HYDROLOGY

- The effect of different landuses and catchment management practices on hydrology, and particularly on the quantity, quality, and temporal distribution of runoff.

- The importance of spatio-temporal variations in hydrologic inputs, subterranean flows, and their influence on the dynamics of dissolved and particulate matter in different climatic zones; hydrological budgets and loading rates.

- Hydrologic processes in wetlands: their temporal variations in relation to flood events, and the nature of flow (laminar or turbulent); the development of hydrologic models for wetlands.

1.8.2 WATER QUALITY

- Factors and processes which control and regulate nutrient and sediment mobilization and export from catchments particularly in relation to landuse.

- Assessment of nutrient transformations that may take place in groundwater (in arid regions especially).

- Consideration of receiving waters from a viewpoint of effluent disposal rather than effluent standards alone, and criteria for disposal of noxious flows into sacrificial areas, and the beneficial utility of saline and other liquid wastes.

- The effects of cascading pre-impoundments upon nutrient, toxicant and sediment loadings of downstream waters.

- The structure and function of aquatic biota along rivers.

- The regenerative/self purification potential of rivers and their capacity to tolerate shock perturbations or incipient stresses (pollutants and altered flows).

- The limnological effects of 'controlled' floods - eg sustained flooding of billabongs and pans - and inadequate or excessive flooding of riparian floodplain vegetation.

- Impact of the loss of riparian vegetation upon the community structure and function of aquatic biota; determination of the minimum areas of riparian vegetation and wetlands commensurate with the maintenance of their ecological/environmental function; the validity of the partial source areas concept with regard to the extent of riparian areas.

- Relevance of minimum flow concepts upon the biological structure and functioning of rivers and estuaries.

- Process oriented studies of wetlands with a view to improving predictive capabilities. Studies on artificial wetlands will contribute to this objective.

- The role of inter-basin transfers upon spread of aquatic pests/disease vectors.

- The nature of the response of specific biota to roughness coefficients and hydrological regimes of artificial water carriers - eg irrigation canals.

- Application of palaeolimnological methods to record historical events in catchments should be developed as a means of establishing baseline information for management purposes.

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CHAPTER 2 STREAM REGULATION

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2.1 INTRODUCTION

The exploitation of water resources for both consumptive (urban water supply, irrigation) and non-consumptive (hydro-electric power) use usually involves the impoundment of rivers. Impoundments are customarily operated so that there is a minimum downstream flow (the compensation flow) sufficient to meet the demands of downstream water users. Compensation flows are determined regardless of the functioning of the downstream riverine ecosystem, but recently the requirements of the river estuary for freshwater have begun to be recognized. Multiple impoundment river systems provide an opportunity for regulation of discharge within the constraints of other legitimate uses of the water.

All impoundments obviously modify downstream flows and flow patterns, but less obviously they change other physico-chemical variables and biological properties of the controlled river. This chapter will present a brief outline of important limnological concepts pertinent to the functioning of rivers as ecosystems, followed by an account of the impact of impoundments on downstream riverine, floodplain and estuarine ecosystems. The ecological consequences of dam site selection and dam design are reviewed and recommendations regarding these matters are made. Advice regarding impoundment management to maximize downstream benefits and to minimize downstream adverse effects is offered. Finally, priorities for research on and monitoring of regulated streams are identified.

2.2 DEFINITIONS AND SCOPE

For the purposes of this chapter, regulated streams are defined as running water segments (tailwaters) influenced by an upstream impoundment. The spatial extent of such influence may be considerable, extending for tens or even hundreds of kilometres downstream from the dam (Ward and Stanford 1979a). The phenomena occurring within reservoirs that are responsible for the downstream alterations will not, however, be detailed herein. Discussion is largely limited to the influence of major dams on downstream reaches and management strategies to optimize the regulated stream environment within the constraints posed by multiple use of the water resources. The chapter on catchment management includes consideration of abstraction, irrigation return flow and other diversion schemes.

2.3 CONCEPTS OF STREAM ECOLOGY

In the development of a scientific discipline the emphasis turns gradually from basic data collection to analysis and prediction. Concepts are important catalysts in this transition. These are frameworks within which predictions (hypotheses) may be formulated and tested. They are subject to progressive refinements, and to modifications that suit different constraints; they are not fixed, and they need not be site-specific. Simon Levins, a mathematical ecologist, introduced the maxim that a model (that is a concept) can never satisfy more than two of three ideals, namely precision, generality and realism.

Stream ecology is a young science: perhaps the greatest stimulus to its development was the publication of Hynes' Ecology of Running Waters in 1970. The conceptual basis for stream studies, therefore, is at an early stage. Presently there are four cornerstone concepts, each described briefly in this chapter. An understanding of these concepts is fundamental to effective management of river systems.

The physical, chemical and biological features of streams change along their courses. In the ecological literature this is recognized in various schemes of river-zonation, including that of Harrison (1965) for southern Africa. The River Continuum Concept of Vannote et al (1980) is a formal statement of the nature of these changes. The concept suggests that plant and animal communities adjust to spatial resource gradients imposed by downstream changes in environmental conditions. The biological adjustments are evident in the changing balance of production and decomposition (cf the photosynthesis - respiration ratio, P/R; Figure 2.1), and in changes of species composition. Further, the concept suggests that changes in community composition will be expressed as a downstream succession of 'functional groups'. Leaf material imported to the headwaters section of a stream is subject to the action of 'shredders', and plant material produced within the stream is utilized by 'grazers'. The general pattern is of a continuum, whereby coarse particulate organic matter (CPOM) is progressively reduced to fine particulate organic matter (FPOM) by the successive actions of these functional groups, or 'litter processors'. The continuum may be visualized as a 'sliding scale' which is shifted upstream or downstream depending on 'macro-environmental' forces, or reset following the application of more localized 'micro-environmental' forces (Minshall et al 1983).

Some general features of the River Continuum Concept are shown in Figure 2.1. Further information may be found in Cummins (1979). The general validity of the concept, and particularly its validity for streams in Australia and New Zealand, has been questioned by Winterbourn et al (1981), Winterbourn (1982), Barmuta and Lake (1982) and Lake (1982). These objections are founded partly upon the problems inherent in imposition of an essentially deterministic model upon a loosely-structured ('stochastic') system. Another point of debate, perhaps less well-founded, is the claim that many streams (eg in Australia and New Zealand) are physically and biologically unlike those of the deciduous forested regions of North America, where the concept originated. The weakness of this argument is that it overlooks the flexibility inherent in the nature of any scientific concept: the River Continuum Concept might easily be recast to comply with different environmental situations.

The Nutrient Spiralling Concept refers to one of the salient differences between lake and river ecosystems. In a 'closed' system, such as a lake, nutrients are cycled, being taken up by living organisms and returned to the environment in the process of decomposition. In the stream - a more 'open' system - the cycling nutrients are continually displaced downstream, so that they are said to traverse an imaginary spiral (strictly, a helix). The concept, represented in Figure 2.2, lends itself to quantification in terms such as the distance over which a given nutrient is returned to its original state (ie the length of the spiral). Information about the concept is provided by Webster (1975) and Newbold et al (1982). As with the River Continuum Concept, this concept has applications in situations where nutrient transfer in streams is interrupted by an impoundment. It may be used to determine the 'resilience' (resistance to perturbation) of a river ecosystem.

The Intermediate Disturbance Hypothesis concerns the processes that maintain diversity in communities of plants and animals. It was first formulated for marine ecosystems, but has been applied to many other environments; its applications for streams are discussed by Ward and Stanford (1983a).

The hypothesis is represented in Figure 2.3. It suggests that it is the level of disturbance that determines the diversity of plant and animal species in particular environments. 'Disturbance' here refers to the extent of change, and need not imply intervention by Man. For example, a springfed stream may have near-constant flows and temperatures year-round; it would experience a low level of disturbance, and consequently it would sustain a relatively small variety of plants and animals. At the other extreme, a stream subject to rapid, unpredictable changes would experience a high level of disturbance, and it too would sustain few plants and animals. Maximum diversity would be attained at an intermediate level of disturbance. At this point, a balance is struck between environmental heterogeneity (in time and space), and the ecological characteristics of the flora and fauna. The implication, then, is that imposition of a controlled flow regime on a river environment may affect community diversity by changing the level of disturbance.

The Serial Discontinuity Concept, formulated by Ward and Stanford (1983b), builds directly upon the River Continuum Concept. Given that river communities do represent a continuum, the construction of a dam creates a discontinuity. In the case of the dam, the pre-impoundment conditions are not restored for some distance downstream. The effect on any given characteristic may be visualized, and quantified, in terms of a 'reset distance', expressing the recovery distance following the perturbation.

Figure 2.4 illustrates the Serial Discontinuity Concept for a number of basic river characteristics. In its original formulation, this concept presumes that the River Continuum Concept is valid for the situation under study. Future refinements, however, may allow it to develop an independent status.

Each of these concepts has implications for the siting, design and operation of flow-regulating structures. These are dealt with later in this chapter.

2.4 OVERVIEW OF EFFECTS

2.4.1 RIVERINE EFFECTS

The regulation of running waters by impoundment has diverse manifestations which are unique for each system, although generalized responses are evident (Ward 1982). The flow regime of regulated streams is influenced by the type of impoundment holding back the water. Hydro-electric and irrigation dams lead to short term flow fluctuations in association with reduced seasonal amplitudes. Storage impoundments also lead to seasonal flow constancy, and diversion weirs and intercatchment transfers (eg Orange-Fish River Tunnel) lead to either increased or decreased flows in the recipient and donor river systems.

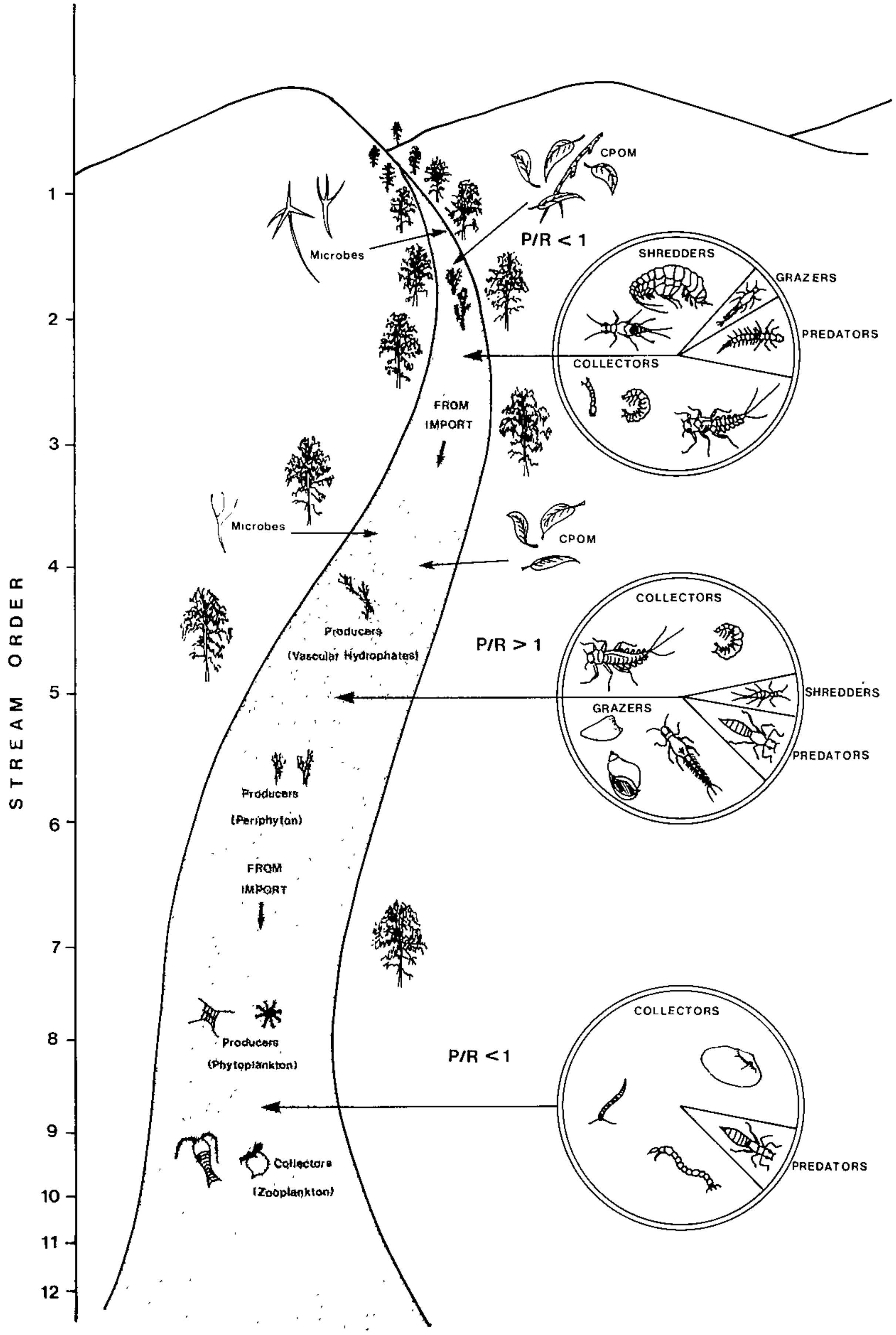

STREAM ORDER
1
2
3
4
5
6
7
8
9
10
11
12
CPOM
Microbes
P/R < 1
SHREDDERS
GRAZERS
PREDATORS
COLLECTORS
FROM
IMPORT
Microbes
CPOM
COLLECTORS
Producers
(Vascular Hydrophates)
P/R > 1
SHREDDERS
GRAZERS
PREDATORS
Producers
(Periphyton)
FROM
IMPORT
COLLECTORS
Producers
(Phytoplankton)
P/R <1
PREDATORS
Collectors
(Zooplankton)

FIGURE 2.1 A pictorial representation of the River Continuum Concept, showing the downstream gradient of physical factors and the corresponding biological adjustments. From Cummins (1979). The diagram represents the river continuum as a single stem of increasing order (actually the number of branches increases with decreasing stream order). General range of stream widths (in metres) for each order is given, and orders have been roughly grouped into headwaters (orders 1-3), mid-sized rivers (4-6) and large rivers (7-12), considering the Mississippi River as order 12 at its mouth. The headwaters and large rivers are shown as heterotrophic (P/R, or ratio of gross photosynthesis to community respiration, < 1) because of restricted light, a consequence of shading by riparian zone vegetation in the headwaters and attenuation from depth and turbidity in the large rivers. The mid-sized rivers are depicted as autotrophic, with a P/R >1, through a combination of reduced riparian shading, relatively shallow and clear water. The importance of terrestrial inputs of CPOM decreases and the transport of FPOM increases down the continuum. The ratios of macro-invertebrate functional feeding groups shift from shredder-collector headwaters to collector-grazer (scraper) mid-sized rivers to collector-dominated large rivers, which are lentic-like, with plankton communities. Fish populations are shown to shift from cold- to warm-water invertebrate feeders. Mid-sized rivers have piscivorous forms as well, and large rivers have both bottom feeders and planktivorous species.

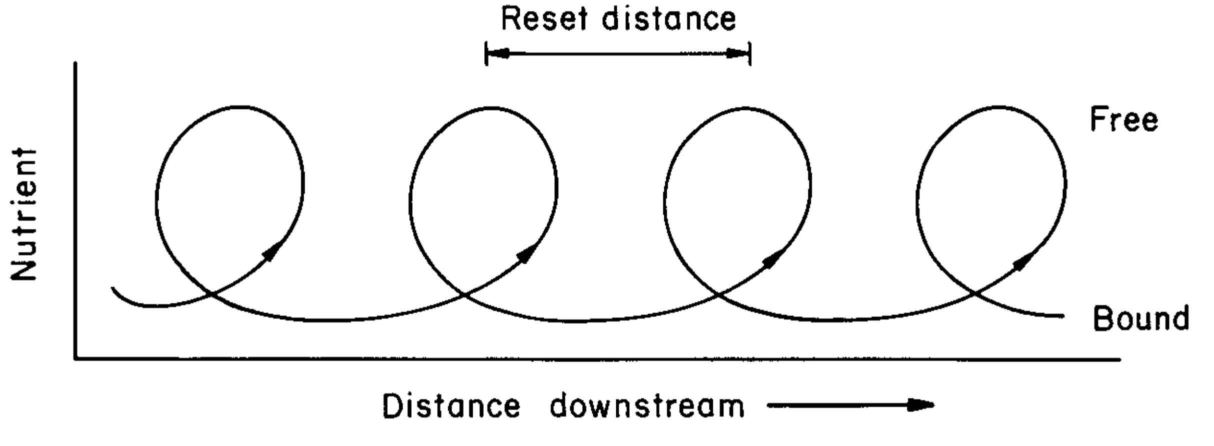


FIGURE 2.2 A simple representation of nutrient spiralling in a stream. Nutrients are taken up and released by the stream biota, in the course of metabolism. The 'spiralling distance' refers to successive points along the stream, where a given amount of nutrient begins and completes the cycle.

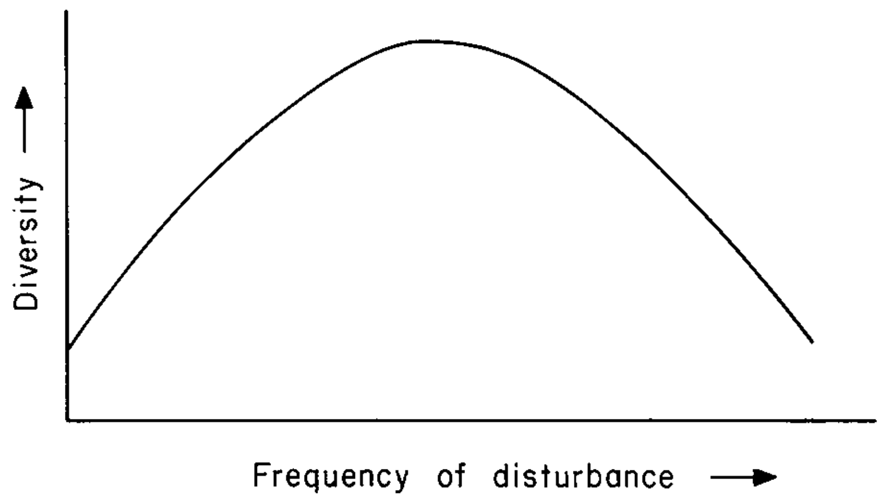


FIGURE 2.3 Theoretical relationship between biological diversity and environmental disturbance (From Ward and Stanford 1983a).

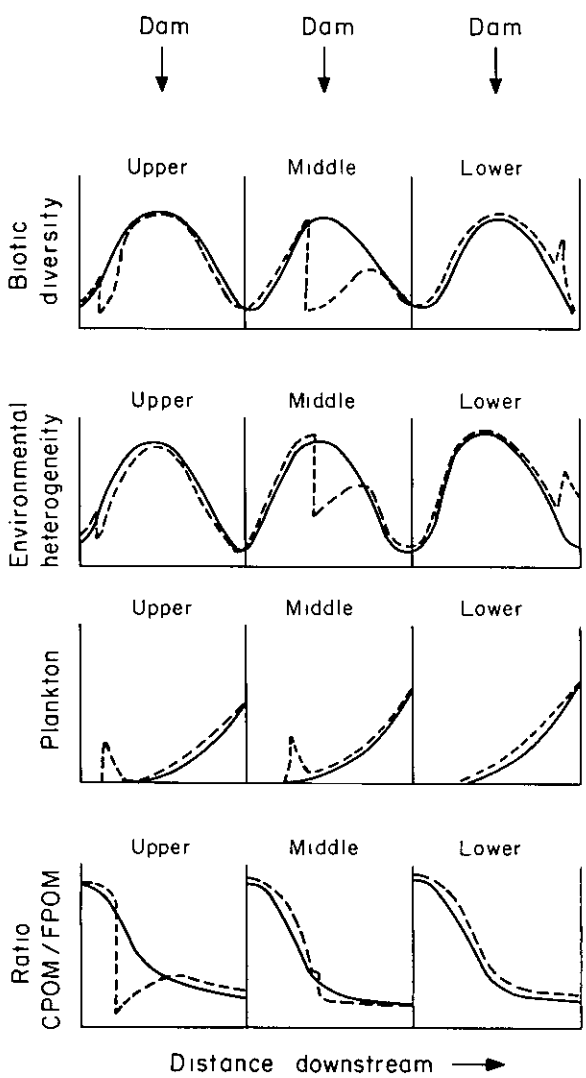


FIGURE 2.4 Relative changes in physical, chemical and biological variables as a function of distance downstream. This illustrates the nature of the discontinuity created by dams in the UPPER, MIDDLE and LOWER reaches of a river. From Ward and Stanford (1983b).

The release of water from various depths of the storage reservoir has a number of consequences (Table 2.1). Quantitative and qualitative components of organic detritus transport in streams are all modified by impoundments. For example, large quantities of phytoplankton, zooplankton and floating macrophytes may be released from surface waters of impoundments.

TABLE 2.1 Some generalized qualitative responses of downstream reaches of regulated streams compared with unregulated streams. Modified from Ward (1982)

Variable	Surface-released water	Deep-released water
Turbidity	Reduced	Reduced
Silt and sediment load	Reduced	Reduced
Nutrients	Reduced	Reduced less
Plankton	Increased	Increased less
Detritus	Reduced	Reduced
Discharge	Variable	Variable
Temperature	Increased	Decreased
Dissolved oxygen	Saturated	Anoxic-supersaturated
Erosive capacity	Increased	Increased
Benthic species diversity	Decreased	Decreased
Benthic faunal biomass	Variable	Variable
Salinity	Variable	Variable

Seasonal constancy of water flow favours multivoltine species, such as Simuliidae, more than their natural invertebrate predators and this has subsequently led to explosive population increases of pest species. Benthic algal and macrophyte growth is enhanced by reduced flow variation. Dense growths of such aquatic plants can cause severe reductions in stream flow and this in turn favours the development of large populations of mosquitoes. Both these examples support the idea of intermediate disturbance of the river system by using periodic flow disruptions to prevent any one species from dominating and to keep overall species diversity high (Figure 2.3). Even a minor alteration in flow rates can significantly alter the invertebrate drift component of a stream which would have diverse ecological consequences (Gore 1977).

A generalized diagram of the influence of flow variation on zoobenthos is given in Figure 2.5. The development of a riparian flora in the upper reaches of streams serves to maintain stream bank stability and provides energy input to maintain the integrity of the river continuum. Reduced flow fluctuation and increased periodicity of floods allows the invasion of the riparian zone by non-riparian plants which have little tolerance to flooding, and this increases the devastating impact of a severe flood. Fish too are severely disrupted by stream flow regulation and migration and breeding sites are severely reduced. Sudden flow termination below hydro-electric impoundments also causes large mortalities of fish.

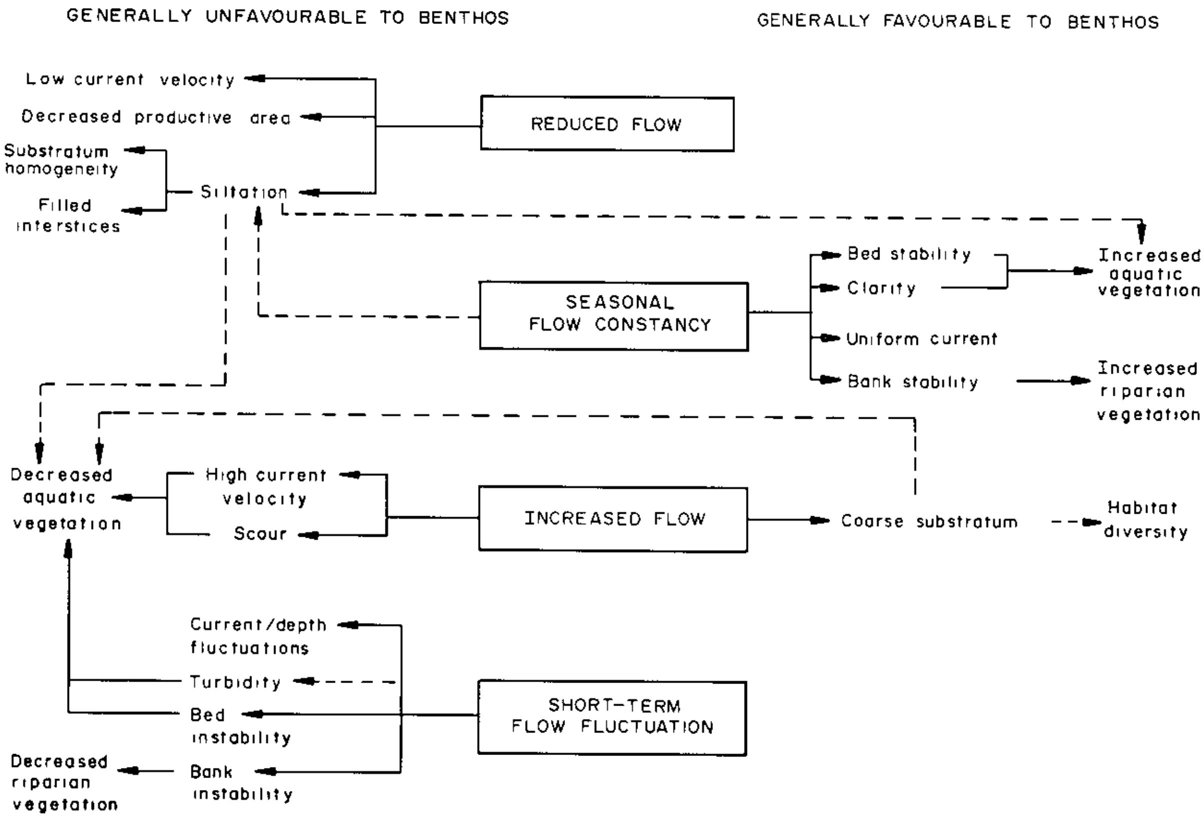


FIGURE 2.5 Potential effects of various flow patterns below dams on ecological factors having an important influence on stream benthos. Dashed lines indicate less definite relationships. See text for discussion of specific effects of benthic community. From Ward (1976a).

A series of impoundments on a river system also has a cumulatively more severe impact on detritus transport than does a single impoundment (Ward 1982). The river continuum is considerably disrupted, leading to 'a truncation of the detrital transport and processing which significantly alters the energy base of the river' (Ward 1982). This in turn will lead to a reduction in the faunal diversity with the possibility of increased numbers of pest organisms such as Simuliidae (de Moor 1982a, 1982b).

The low sediment loads in waters released from impoundments increases the erosive capacity of the water (Simons 1979) and leads, together with a modified flow regime, to degradation of the river channel downstream of the impoundment (Figure 2.6). Decreased turbidity also leads to greater water clarity with consequent development of benthic algal mats (Chutter 1968). Permanently turbid waters in some South African and Australian impoundments lead to perennially high turbidity levels in the downstream regions, a factor which would not have been encountered prior to impoundment. High mortalities in fish juveniles follow increased silt deposition in the dry early summer season. The discharge of H_2S and waters supersaturated or devoid of dissolved oxygen from hypolimnial release dams can have toxic effects on the downstream fauna of regulated rivers. The reduced frequency and severity of floods can either increase or decrease salinization of floodplain pans (Davies 1979; Ward 1982). For example, the species composition of diatoms changes with increasing salinity gradients, changes being noticeable at concentrations above 2 parts per thousand (Archibald 1981).

Modification of the thermal regime by impoundments (Table 2.2) can lead to severe disruption of the life cycles of biota in the regulated stream. Vannote and Sweeney (1980) studied the effects of varying temperature regimes on benthic fauna and concluded that each species has an optimum temperature regime or equilibrium at which maximal development and fecundity is attained. Altered temperature regimes can lead to species elimination, as summarized in Figure 2.7.

In summary, stream flow modification has led to an alteration of the general riverine habitat and functioning of the river as a dynamic ecosystem. Stream regulation has altered the temporal and spatial environmental heterogeneity to which the biota has evolved.

2.4.2 FLOODPLAIN EFFECTS

Major factors and phenomena which influence the environment downstream of a dam and the resultant biological effects have been reviewed elsewhere (Heeg and Breen 1982) and are illustrated in Figure 2.8. Deviations from the natural hydrological regime exert profound effects on both the processes which occur and their duration. For example, flood alteration may cause some areas on the floodplain to be deprived of floodwaters, causing the balance between submergence and exposure to be altered both spatially and temporally. To understand the implications of stream regulation requires an appreciation of the time scales over which the components and processes on floodplains respond.

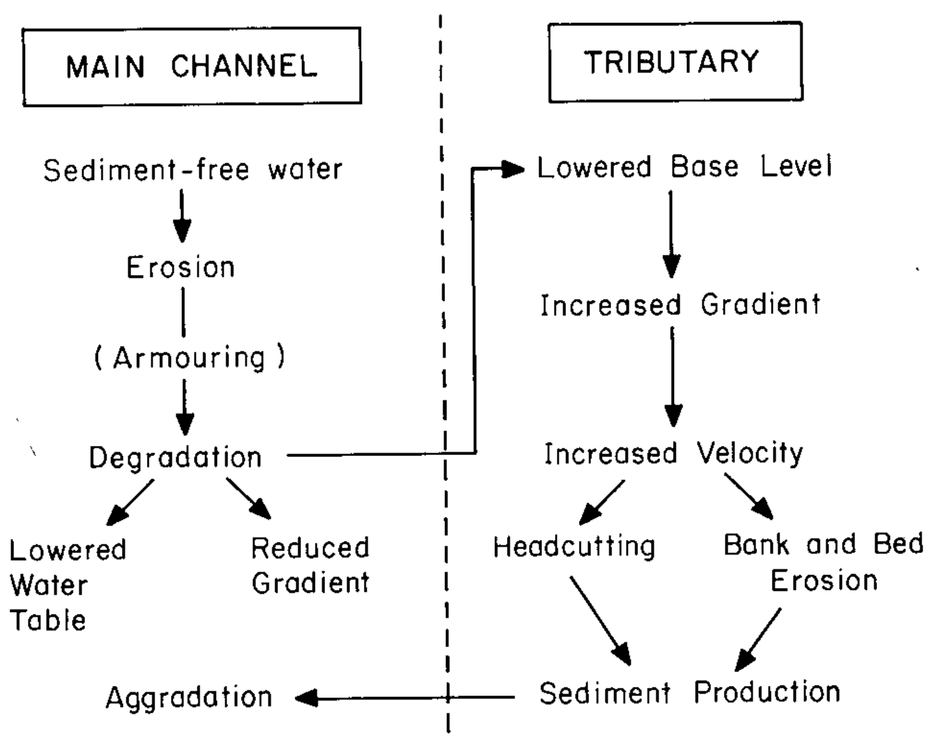


TABLE 2.2 Idealized thermal alterations of the middle reaches of temperate streams, induced by upstream impoundments with dimictic patterns of stratification

Thermal alteration	Surface-release	Deep-release
Diel range	Variable	Reduced*
Annual range	Expanded	Reduced
Summer temperature	Elevated	Decreased
Winter temperature	Similar	Increased
Seasonal maximum	Delayed	Delayed
Vernal rise	Delayed	Less rapid
Autumnal decline	Delayed	More rapid

* Diel ranges below hydro-electric dams may be increased in summer.

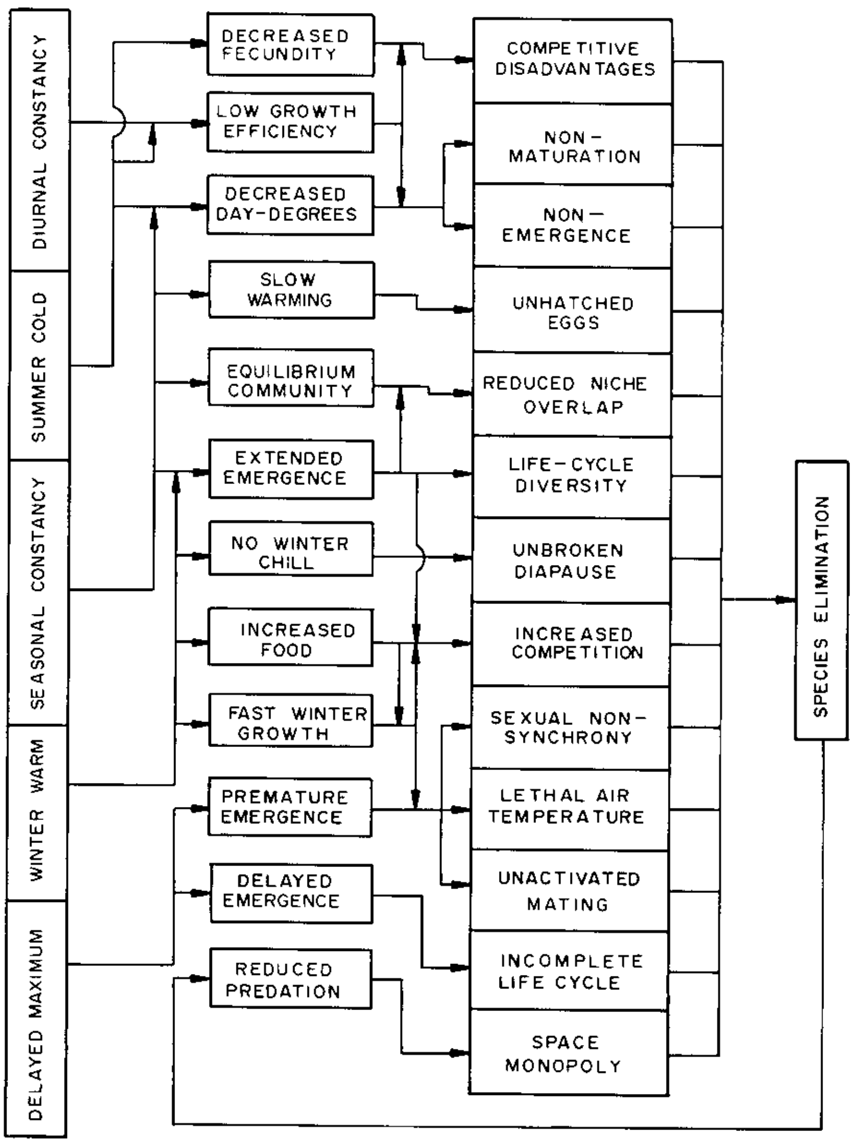


FIGURE 2.7 Thermal modifications below deep-release dams and resulting relationships hypothesized as partly responsible for the selective elimination of zoobenthic species. Modified from Ward (1976b).

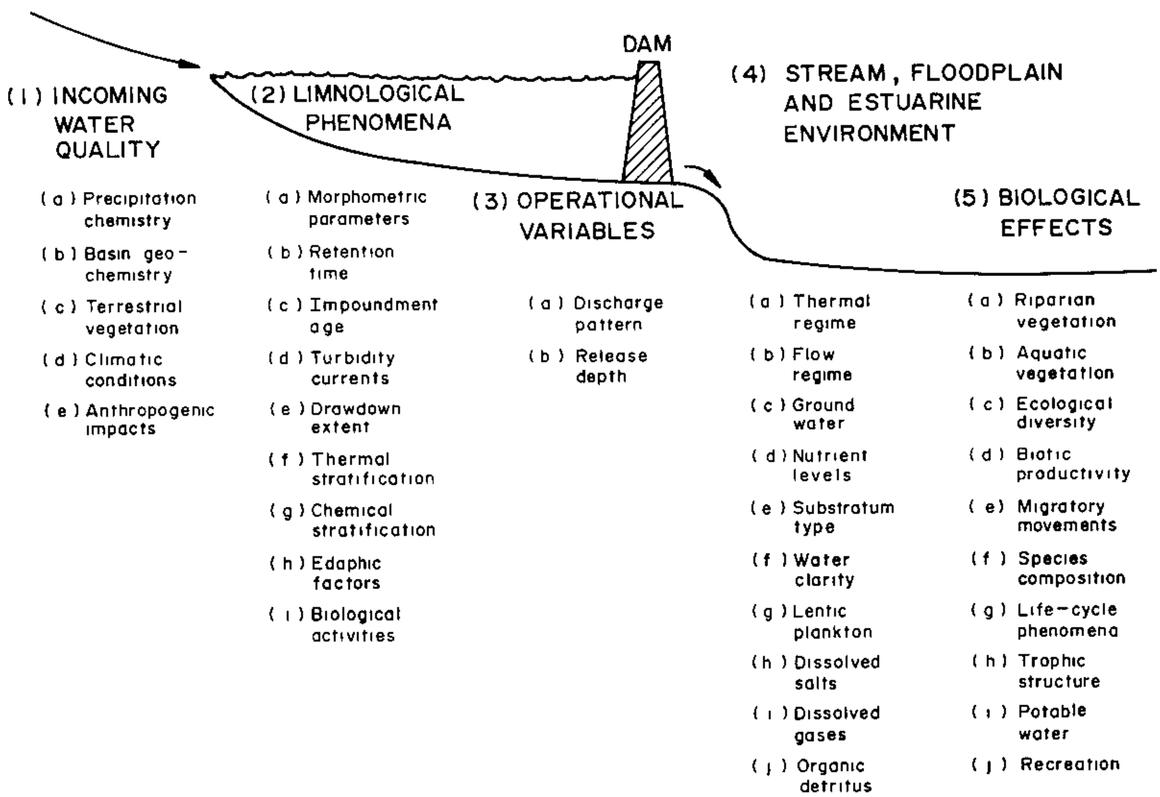
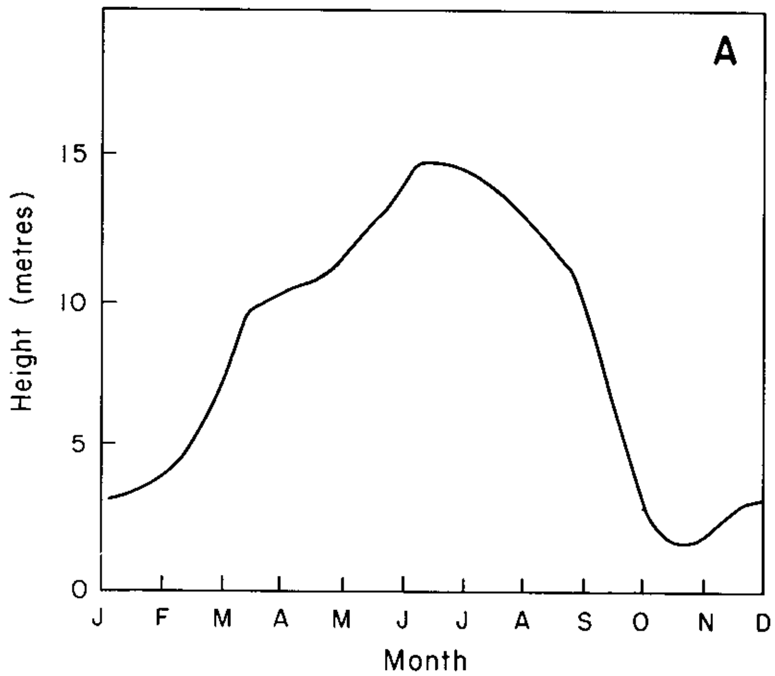


FIGURE 2.8 Major factors and phenomena influencing the environment below dams and resultant effects on biota. See text for further explanation. Modified from Ward and Stanford (1979b).

2.4.2.1 River flow and the time scale of responses

The pattern of river flow determines the timing, duration (time scale) and nature of floodplain processes. In large unregulated rivers where the floods build up and recede slowly (eg Amazon tributary Solimoes, the Zaïre, and pre-regulation Pongolo, Figure 2.9) floodplain processes vary gradually in response to the flow regime. In these systems the cue which initiates or terminates responses is less distinct and the duration or time scale of processes may be measured in months or longer. In contrast, where short rivers with disparate seasonal flow are associated with floodplains, responses may be initiated within hours (eg migration of fish in response to the rising stage of a flood) and they may have time scales measured in days (flood duration) and months (the intervening period between floods). All floodplains also have responses measured over even longer periods for two reasons. First, the hierarchical structure of ecosystems allows the consequences of modifying processes, occurring over short time scales, to influence processes with longer time scales, gradually compounding the effects until they become disproportionately large. Secondly, infrequent episodic events destabilize the system, which takes time to return to equilibrium.

All floodplains are characterized by a hierarchy of time scale responses which largely reflect the pattern of flow and the residence time of water on the floodplain. The response of a floodplain to stream regulation cannot be adequately quantified until processes are measured over the relevant time scales.



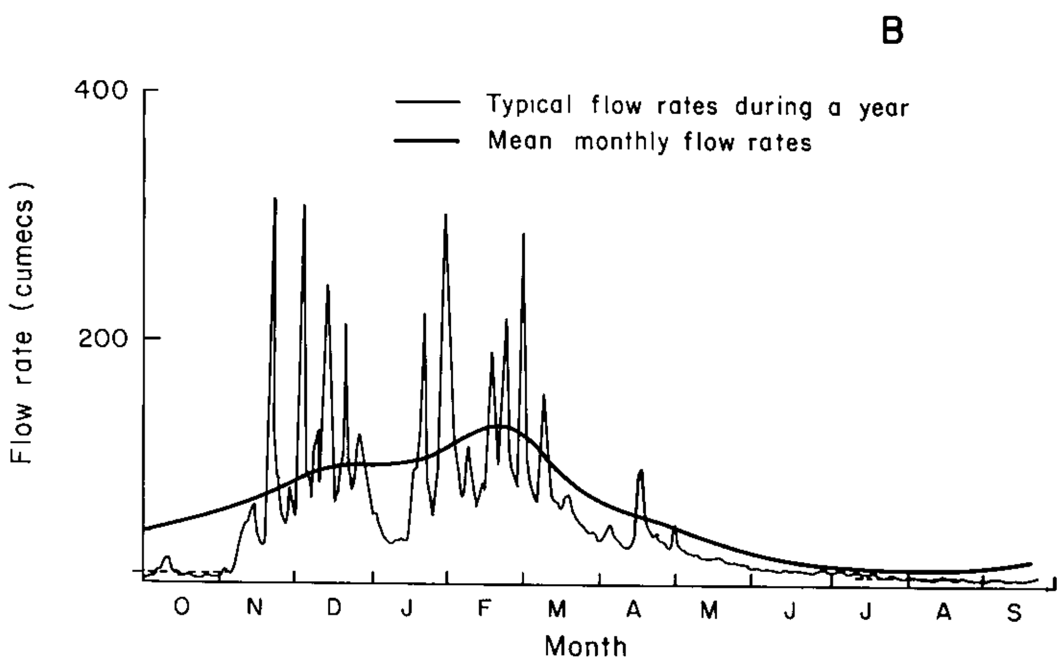


FIGURE 2.9 A. Relative height of the Solimoes River (tributary of the Amazon) at Manaus, illustrating the seasonal fluctuations of a large tropical river. (Data from J Melack, University of California, Santa Barbara; personal communication).

B. Flow rate in the Pongola River (South Africa), illustrating the highly variable flow rates during the flood season. (Data from Heeg and Breen 1982, Furness 1981).

2.4.2.2 Time scales as determinants of response to regulation

The relevance of time scales in the assessment of response to variation in river flow can be illustrated by a consideration of processes associated with the fish (Figure 2.10). Rising waters stimulate the fish to migrate, a response measured in hours or days. Breeding success however depends on maintenance of high water conditions for a longer period (weeks) and survival of fry requires favourable conditions over months. Since it may take one or more years for a juvenile to mature sexually, recruitment into the breeding population occurs in a time scale of years. It can therefore be years before the effect of a perturbation becomes evident as a significant change in the adult population. Identification of the cause of a decline in the fish population requires analysis of both the time required for each phase in the life of the species and its synchronization with flooding. Once this is known the hydrological regime can be managed in accordance with the species requirements. Since it is not practical to collect this information for all species and processes, it is the river biologist's responsibility to identify the key components and processes on which management and monitoring should be based.

These principles can be illustrated by analysis of the responses by the vegetation of the zone of periodic inundation. Rising water levels inundate exposed vegetation and initiate decomposition, a process which, although only taking days, markedly influences both the aquatic system which receives the products of decomposition, and the terrestrial system. The vigour and viability of terrestrial vegetation is reduced during submergence. On re-exposure recovery takes months, particularly if the vegetation is exposed to additional stresses brought about by declining water availability and grazing. The consequences of alternating

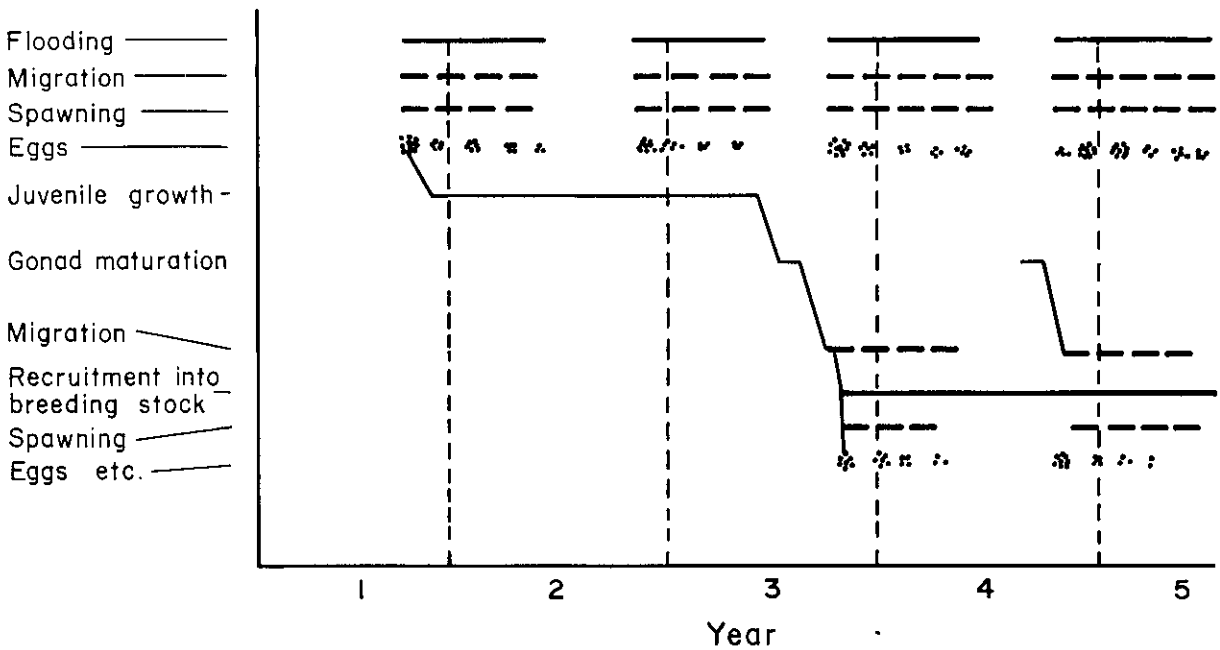


FIGURE 2.10 Sequence of events in the life of a typical floodplain fish with flood-dependent spawning. Time scales of important phases for a given generation are illustrated by a single, serially spawning individual. Perturbation effected in year one may only overtly manifest itself in the population structure during years three or four.

submergence and exposure for large mammal grazers are therefore introduced gradually as yearly pulses, the effects of which are cumulative and are measureable over years. Thus whilst some of the effects of stream regulation may become evident as changes in response on short time scales, propagation of their effects to other components of the system (particularly those with long lifespans) makes it difficult to both predict and quantify the extent and period over which a system will respond to perturbation.

These concepts have particular relevance in the structuring of research and monitoring programmes. Inappropriate sampling frequencies can result in misinterpretation of both short- and long-term trends. In most research programmes, processes measured periodically over two or three years are used to predict long-term trends not only for the processes measured but also for some not measured, although known to be influenced. Predictions may also have to be extended to processes which are not clearly understood. Accuracy of prediction is greatest for the process measured and understood and decreases markedly with extrapolation to unmeasured or poorly understood processes. Within these restraints, however, it has been possible for river biologists to specifically recommend river flow regulation with quantification of timing, duration, rate and volume (sections 2.6.2 and 2.6.3).

2.4.3 ESTUARINE EFFECTS

2.4.3.1 Physical effects

Generally the physical impact of impoundments on the downstream stretches of a river is a function of distance from the dam: rivers, being linear systems, can eventually recover from such a disturbance and reach a new equilibrium determined by the new flow regime. Reduction in flow may, however, have serious consequences for an estuary even if long stretches of the intervening river have otherwise recovered from the effect of the impoundment upstream. This is particularly true in arid regions, where flow may be minimal or highly variable.

2.4.3.1.1 Flow regime and morphology

Estuaries are current-driven systems, the distribution of their soft sediments being determined by the flow of water from both the river and the sea. The estuarine nature of river mouths is dependent on the interaction of river water, which scours the major channels and the mouth, and seawater, which imports sand during each tidal cycle. Rivers flowing through, or from, well-watered areas or deeply-dissected landscapes usually have large, deep estuaries in which a moderate reduction in flow due to upstream regulation has little apparent effect on their morphology. But in more arid areas riverflow is strongly seasonal so that there are long periods of aggradation of sediment on the bed of the estuary, particularly towards the mouth. Obviously if enough sediment builds up at the mouth, and the flow of water is insufficient to remove it, the mouth will become extremely restricted and may close. Many natural systems in the more arid parts of the Southern Hemisphere undergo a natural annual cycle of mouth closure during the dry periods of the year. But arid areas are also characterized by very seasonal rainfall so that floods during the wet season are usually large enough to scour the mouth and open the estuary. Thus, in natural systems the regular tidal cycles cause the mouth to narrow or close when riverflow is low, although paradoxically they may contribute to the scouring of the mouth during periods of flood.

The flow of water in regulated rivers tends to be less episodic over periods of weeks or months so that seasonal peaks and troughs become less pronounced. As a result, even if the total amount of water reaching the estuary is not reduced, the critical floodwaters are not available. Thus the most significant effect of river regulation on estuaries in arid zones is perhaps less due to the overall reduction in the amount of water entering the system than to the mediation of floods at an appropriate time of year.

2.4.3.1.2 Sediments

The substratum of estuaries is usually composed of silts, muds and sands derived from the catchment upstream and/or from the sea. These sediments trap nutrients from the same sources, becoming organically enriched. The overall distribution of such sediments on the bed of an estuary, and their fine structure (particle-size), are determined by a combination of water currents and topography. Reduced flow of water alters channel morphology and increases the deposition of particulate matter, resulting in aggradation of sediment on sand- and mud-flats. The effect on the extremely rich and productive biota usually associated with natural estuarine sediments is discussed below.

2.4.3.1.3 Other effects

Alterations in flow regime also alter the length of time during which river water is retained in the estuary. This in turn affects the amount of sediment and particulate organic matter dropping out of suspension, and thus the clarity of the water. This increase in the extent of the euphotic zone has in a few cases been shown (Rozengurt and Herz 1981) to increase primary production and subsequently to reduce the oxygen content of the water.

Significant reduction in flow may also result in decreased interactions between the estuary and its associated lagoons and salt marshes. Severe reductions can lead to such systems becoming entirely cut off from the main body of water, and consequently to radical alteration in their physical, chemical and biological attributes.

Although one of the main effects of stream regulation on the downstream biota of rivers is due to alterations in thermal regime (Ward and Stanford 1979a), this effect seems to be less significant in estuaries, not least because there is usually sufficient distance between the impoundment and the estuary for a normal thermal environment to be re-established within the river.

2.4.3.2 <u>Chemical effects</u>

The most dramatic consequences of stream regulation can be seen in those estuaries which have become entirely closed as a result of reduction in riverflow. Due to evaporation, salinities may greatly exceed those of seawater; as crystallization begins there may even be changes in the proportions of different chemical species. In more humid regions where rainfall is higher and groundwater more abundant, the reverse may occur, the estuary gradually being converted to a brackish or freshwater lagoon.

The chemical environment even of open estuaries may be altered by stream regulation. Salt water may penetrate a greater or lesser distance upstream, altering the distribution of the estuarine biota and affecting those chemical interactions that take place at the interface between fresh and saline waters, and between the water and the sediment.

Many estuaries are highly stratified with a 'salt wedge' of more saline waters in the deeper parts of the basin. This stratification, which effectively inhibits mixing of river water with the deeper layers, may be enhanced or reduced, depending on the timing and the amount of discharge water as well as on meteorological conditions.

The nutrients in estuaries are largely allochthonous (imported), most being brought down by the river from the catchment or, more rarely, being imported from the sea by tidal exchange. Altered patterns of flow will then also alter the nutrient regime in the system.

The effect of pollutants such as pesticides is often enhanced in estuaries fed by regulated streams when retention times of the water are increased and flushing is reduced. It is likely that heavy metals, which might otherwise have been lost to the sea, will precipitate out and be adsorbed onto sediment particles if the seawater/freshwater interface occurs higher up in the system.

2.4.3.3 Biological effects

The effects of stream regulation on the biota of an estuary are generally similar to those on the downstream reaches of a river (see above). In particular, it is worth noting that, as flow is reduced, the system depends more and more on marine influences: there is a change in the relative importance of marine and estuarine food-sources in the form of detritus and particulate organic matter imported into the system and in the relative abundance of marine plants and animals. On the other hand, peripheral salt marshes, mangrove swamps and lagoons may become less influenced by the sea: where rainfall is high enough to leach the salts from the soil, truly terrestrial vegetation may develop, while in arid areas seasonal salt pans are more likely to occur.

It is worth noting that these biological effects in the estuaries of regulated rivers often have more impact on the man-in-the-street than do similar effects in regulated rivers per se because estuaries are prime recreational areas. Thus reductions in the number of angling fish and bait organisms, or dramatic increases in nuisance organisms such as mosquitoes or the alga Cladophora, may have a social and an economic impact.

The most serious economic impact, however, concerns commercial and recreational estuarine fisheries. Nursery areas in the estuary are important for recruitment of many marine fish species. Reduced flows can drastically alter these areas, and fish kills can occur due to a build-up of industrial effluents. Temporary closure of the mouth can interrupt movement in and out of the estuary to the detriment of certain fish species.

2.5 SITING OF DAMS AND DESIGN OPTIONS

2.5.1 SITING OF DAMS

According to the River Continuum Concept (Figure 2.1), resource gradients (eg temperature, food) continually change as rivers flow from headwaters to the sea. For example, whereas terrestrial leaf litter provides the major energy source for headwater reaches of forest streams, leaf detritus from shoreline vegetation is of little consequence to the energy budgets of large rivers. A major element of the Serial Discontinuity Concept is the differential effects of dam position on parameter modification. Damming a headwater reach will greatly alter the ratio of CPOM/FPOM below the dam by truncating downstream transport of coarse detritus, whereas impounding the lower reaches of a river system will have little effect on the size composition of detritus which is already dominated by fine particles (Figure 2.4). Because stream detritivores partition food resources according to particle size (Cummins and Klug 1979), any major alteration of the size composition of transport or sedimentary detritus will also alter the functional characteristics of the affected stream reach.

The release of plankton from impoundments typically results in enhanced populations of filter-feeders, such as blackflies and net-spinning caddisflies, in the tailwaters immediately below dams in upper and middle reaches where true plankton may not otherwise occur (Figure 2.4). In contrast, damming river segments that already contain reproducing populations of plankton will have a much less dramatic effect in this regard.

Environmental heterogeneity generally, and species diversity specifically, both tend to be altered by damming any segment of a river system. If unregulated streams exhibit the spatial pattern indicated in Figure 2.4, it has been postulated that damming upper and especially middle reaches will depress diversity, whereas a dam on the lower reaches will elevate the values of these variables. Many other, perhaps all, environmental variables are also differentially affected by dam position.

2.5.2 DESIGN

No branch of engineering has contributed more to the development of civilization than the art and science of controlling the flow of water (Baxter and Claude 1980). The type of dam built at any particular site depends on such considerations as its intended purpose (ie flood control, generation of electricity, storage etc) and the nature and location of the site. It is essential that stream ecologists are involved in the early stages of planning. This will allow them the necessary time to assess possible impacts and to suggest different sitings and design options.

Dams which are built with more than one release depth allow greater control of tailwaters. A multi-level outlet structure would theoretically allow complete control of the thermal regime of the receiving stream. The depth at which the water is released also affects nutrient and salinity levels, concentrations of dissolved gases and the amount and type of lentic plankton discharged into the tailwaters (Ward and Stanford 1979a). In small impoundments artificial mixing to destratify the water body and thus to prevent the release of deoxygenated waters is a design option. It is also technically feasible to install high-level intakes on a completed dam constructed with a low-level intake (Peters 1979). In addition it may be possible to utilize the temperature gradient between the hypolimnion and the epilimnion to generate additional energy (McNichols et al 1979).

When water plunges over a spillway or passes through a turbine chamber it may become supersaturated with gases, especially nitrogen. When these gases come out of solution within the bodies of fish and other aquatic organisms, the resulting bubbles may cause serious injury or death (Weitkamp and Katz 1980). Spillway deflectors are a means of reducing supersaturation levels to prevent gas bubble disease in aquatic organisms. Air drafts installed in release valves will normally alleviate oxygen deficits which may otherwise occur in the receiving stream.

Engineers in the Northern Hemisphere have devoted a great deal of effort to the design of structures to permit fish to by-pass dams. Dams can obstruct the movement of both anadromous and catadromous fish species and interfere with adfluvial migrations. The juveniles of several catadromous mullet species can by-pass low-level weirs if a series of rocks is placed on the sloping downstream face of the weirs (Bok 1983). Below large impoundments tailwater fisheries might be a better option than ensuring upstream migration. Migrating elvers can negotiate some dam walls depending upon dam design. At Bridle Drift Dam on the Buffalo River, South Africa, elvers are attracted to a river flow outlet pipe. However, due to the flow volume they cannot negotiate any further upstream unless the dam spills and then the elvers can continue their migration up the spillway. The use of elver ladders should be considered.

The design could also include access below the dam wall for tailwater fisheries. Obstacles would also have to be removed to ensure the ease of harvesting this resource.

It is also necessary to ensure the proper construction of hydro-electric equipment to avoid leaks of potentially toxic insulating liquids from transformers and other electrical devices.

2.6 MANAGEMENT STRATEGIES

2.6.1 ISSUES AND OPTIONS

Stream regulation is rarely specifically directed towards maintenance of the natural environment; indeed impoundments are usually constructed with modification of the environment in mind. Rivers have a natural resilience but if pushed too far in one direction will move to a new functional state. Thus the primary goal of the manager should be to operate within the narrow constraints placed upon him by the river. In this context it is important to remember that nearly all reservoir manipulation will have profound impacts upon the river below the dam and for some distance downstream. The manipulated system may, in some cases, be used to minimize other adverse effects. For example, timing inputs of treated wastewater to coincide with periods of water release from a dam (to enhance dilution) may in fact ameliorate deleterious effects of pollutants.

The catchment manager is therefore faced with a number of possible primary and sometimes conflicting concerns:

- flood control
- fisheries development
- disease vectors and the invasion of exotic species and pests
- irrigation, domestic and industrial water supply
- recreation
- salinization
- hydro-electric power generation
- effluent removal
- wildlife management
- riverbank, floodplain and estuarine conservation
- extirpation or reduction of indigenous species.

In the past, attempts by the manager to address only a few of these concerns have had many deleterious environmental effects. It should be realised that it is only the promotion of the continued functioning of the ecosystem, as near to the original unregulated form as possible, which will alleviate many of the problems currently encountered in the operation of existing dams. Limnologists have, therefore, to provide catchment managers with options that are compatible with management responsibilities. For his part the manager must carefully reconsider the rationale which has tended to lead to the construction of single or limited purpose barrages and he should address multi-purpose use more frequently. He should also seek rigorous predictions of the effects of different waterflow management strategies upon the downstream environment from limnologists.

In order to provide specific quantitative advice, limnologists and associated specialists need time and resources to investigate the river system at the planning stage of regulation schemes. Without facilities to collect baseline data in undisturbed systems and to measure the frequency of natural variation, limnologists will not be in a position to offer constructive advice. If these requirements can be met then management will be in a position to obviate some of the more dangerous deleterious effects of stream regulation by mimicking the natural system.

2.6.2 MANAGEMENT OF RIVERINE SYSTEMS

The overriding limnological principle for management should be the continued maintenance of river structure and functioning as close to the original system as possible. For instance, if management simply addresses the question of the effects of water releases from an impoundment upon the downstream fisheries, then the implications of such discharges upon the river recreational potential, or its riparian vegetation, or for wildlife management on floodplains, or disease vectors etc, might be missed. So what can the limnological input of this chapter tell the manager?

First, the River Continuum Concept (Figure 2.1) shows us that the stream is a continuum of resources and this concept, together with the Serial Discontinuity Hypothesis (Figure 2.4), may help us to decide upon WHERE to site future regulatory structures: structures which are inevitable, given the foreseeable water resource requirements of the Southern Hemisphere.

Secondly, managers have two basic operational variables under their direct control:

- the timing, duration, rate and pattern of release of discharges, and
- the release-depth of discharges.

However, control of these two variables influences a multitude of other factors (Table 2.3). Dams with multi-level outlet structures that impound large, deep stratified reservoirs provide the greatest potential for managerial control over downstream environmental conditions.

An additional management option involves the periodic flushing of sediment that accumulates behind the dam (Gray and Ward 1982). This practice, used to increase reservoir life (ie reduce the rate at which the reservoir fills with sediment), is often conducted without regard for the downstream environment or aquatic biota.

An example of ecological research and management interacting to alleviate a problem arising from stream regulation, is the waterflow manipulation of the lower Vaal River to control pest populations of Simulium chutteri (de Moor 1982a). In this instance an integrated control programme was devised by using life cycle data on various aquatic riverine species and manipulating the waterflow to cause maximum disruption to the development of the pest species but not its natural enemies. Furthermore, ecological knowledge of the various species made it possible to reduce populations of the target species with apparently minimal effects on the river ecology. In addition, flow regulation had a minimal disruptive influence on the riparian farming community as it was applied at a time of the year when water demands on the river were not yet excessive. Other examples may be found in the literature (Davies 1979).

Thirdly, design of future regulation structures will considerably enhance the armoury. Air vents or cascading discharges will eliminate oxygen deficiency problems while incorporation of simple fish 'ladders' will considerably enhance certain types of fishery. In addition, multiple level draw-off should be considered as inexpensive, relative to the cost of the dam, and yet an extremely effective management tool. By mixing draw-off from different levels of the reservoir during releases for irrigation, hydro-electric power generation and so on, effective amelioration of flow, chemical, nutrient and thermally related impacts can be achieved. Some other associated design options may include canalization, silt gates, inflatable weirs and ponding weirs below impoundments.

The principle that an allocation must be made for the maintenance of the lotic environment (Roberts 1983), has been welcomed by limnologists. However, it should be emphasized that requirements for each river will vary widely. A global estimate of 11% of the total exploitable water requirements for South Africa (in the year 2000) has been suggested by Roberts as a rule-of-thumb basis for the maintenance of lotic environments within nature reserves and estuarine habitats. A higher figure would be needed for the maintenance of the riverine habitat outside reserves (the vast majority of South Africa's lotic systems). Tennant (1975) has provided a simplistic method for estimating environmental flow requirements

TABLE 2.3 Some of the environmental conditions in regulated streams that may vary as a function of release-depth and discharge pattern. Parentheses indicate an indirect influence (Modified from Ward and Stanford in press)

	Release-depth	Discharge pattern
Temperature	+	(+)
Nutrients	+	
Dissolved Oxygen	+	(+)
pH	+	
Salinity	+	
Turbidity	(+)	+
Substratum		+
Channel Morphology		+
Bank and Bed Erosion		+
Riffle/Pool Ratio		+
Benthic Detritus		+
Transport Detritus	+	+
Particulate Organic Carbon	+	+
Dissolved Organic Carbon	+	
Plankton	+	

in specific rivers in the United States. He recommends that no river should ever be reduced below 10% of its natural instantaneous flow. Care should be taken in the application of any global figure to specific systems. The seasonal and spatial variations within and between different rivers will have to be measured before allocations can be made.

2.6.2.1 Riverine fisheries

Fish population density, growth, biomass, fecundity, production, species composition and movements can undergo changes after stream regulation. There is a vast literature on Instream Flow Methodology for Northern Hemisphere fish species (Wesche and Rechard 1980). The manager must know what water release patterns, with regard to temperature, flow rate, chemical composition and timing, are necessary to act as cues to initiate spawning migrations and breeding in any section of the regulated stream. The instream flow requirements of all the life history stages of the fish species should be met. It is essential not to isolate one aspect, such as flow to stimulate spawning, from requirements for egg and larval development. The incorrect timing of draw-down for the control of Simuliidae could strand eggs and larval fish, seriously affecting recruitment.

The fisheries manager must determine whether a fish by-pass or tailwater fishery or hatchery is required for the system. This should be assessed at an early planning stage. Special attention should be given to the habitat requirements of endangered fish species. The need for habitat improvement schemes, such as ensuring suitable spawning substrata at selected breeding sites, must be assessed. The recreational aspect of the river fisheries should be assessed to determine its requirements.

2.6.3 MANAGEMENT OF FLOODPLAINS

Water releases which simulate the characteristics of the normal flood regime can be used to compensate floodplains which have been deprived of their allogenic water supplies by impoundment. While this will not normally restore the supply of allochthonous river-borne material, particularly plant nutrients adsorbed onto suspended particles, it can maintain a level of ecosystem functioning albeit at a reduced level. Of primary importance in developing such an artificial flooding strategy is its annual periodicity, which must perforce be timed to coincide with the natural flooding cycle. Frequency and amplitude will have to be governed by the premium on the impounded water, considered in relation to the asset value of the floodplain. Costing has to be based on the intended use of the impounded water and the pre-impoundment use or unrealized potential of the floodplain (Heeg and Breen 1982). Such economic considerations will also determine whether secondary engineering structures, designed to optimize the effectiveness of the released water on the floodplain, are warranted.

Heeg and Breen (1982) have applied simple cost-benefit analysis to the Pongolo Floodplain based upon a comparison of the volumes of water required to maintain floodplain functioning by unrestricted flows (126 x 10^6 m^3) or by using inflatable weirs (42 x 10^6 m^3). The irrigation potential of the water savings effected by the use of inflatable weirs, based upon a requirement of 1600 mm ha^{-1} yr^{-1}, amounts to 5250 ha.

The above volumes, which represent 12 and 4% of the mean annual runoff respectively, were determined from biological and hydrological studies. A premium on the water would be derived from the profitability of growing sugar under irrigation in the area. A premium could also be assigned to subsistence agriculture and fisheries under the natural flooding regime, as well as to an unrealized tourist potential. Details of the analysis are set out in Table 2.4. The value of released water and any river feature downstream of an impoundment can be readily determined in this way provided the functioning of downstream ecosystems is understood. How closely simulated floods released from the impoundment need to mirror the natural flow regime will depend on the principal floodplain concern variables. Managing for the preservation of, for example, riparian vegetation, imposes different demands from those necessary for the management of a floodplain fishery or a coastal wetland. In this context, management strategies are concerned with the short-term fluctuations in flow within the seasonal cycle, and these ultimately find expression in the residence time of water at any given point on the floodplain. Control therefore needs to be exercised such that low-lying areas are inundated for an appreciable time, whereas high-lying areas are subjected to infrequent flooding of short duration. Climate, size of catchment and the morphology of the river course and of the floodplain, all contribute to the pattern. Limits of these fluctuations on any particular floodplain (Welcomme 1979) must form the basis for management through flood simulation.

The water requirements of any given management plan form an important cost factor in its implementation, and can only be determined by an appropriate hydrological/hydraulic survey. However, the cost-benefit analysis for such a plan needs to take cognisance of the possibility of increasing and controlling residence time of water on the floodplain by structures such as inflatable weirs, sluices etc, the use of which becomes feasible under a controlled flow regime. The cost of these structures is negligible when considered against the cost of construction of the dam, yet they can effect a substantial saving of impounded water. The use of such secondary engineering structures must take account of the possible need for flushing to remove solutes accumulated over the dry season and for through flow to allow for the upstream migration of fishes or other aquatic animals whose recruitment into the floodplain community is deemed desirable.

The management requirements for some of the various floodplain concern variables are given in Table 2.5.

TABLE 2.4 Cost-benefit analysis summarizing losses and gains derivable from conservation of the Pongolo Floodplain

Source	Cost (R X 10^6 yr^{-1})		Source	Benefit (R X 10^6 yr^{-1})	
	Assessed likely maximum	Achievable minimum (inflatable weirs)		Assessed likely minimum	Possible maximum
Agriculture @ R200 ha^{-1} annual profit	R1,575	R0,525	Fisheries	R0,200	R0,680
			Subsistence agriculture	R0,600	R2,500
			Tourist potential	R0,025	R0,090
	R1,575	R0,525		R0,825	R3,270

TABLE 2.5 Synopsis of management requirements for maintenance of different floodplain components and processes

Concern Variable	Management Requirement
1. Water quality	Provide sufficient flow for flushing of solutes accumulated over the dry season (Heeg et al 1978).
2. Floodplain vegetation	
Rooted aquatic plants	Sufficient water to provide for growth period timed according to the life cycle and reproductive strategies of the species concerned. Perennial water availability will generally favour all submerged macrophytes.
Vegetation of off-channel draw-down areas	Fluctuating water levels during the wet season. Exposure during dry season.
River bank vegetation	Maintaining floodplain water table.
3. Floodplain fisheries	
Recruitment from downstream	Sufficient flow to reach downstream refuges and to allow recruitment into floodplain population.
Spawning	Flood of sufficient magnitude to create shallow water spawning areas. Many fish will only spawn on newly flooded ground. Medium-term oscillations (weeks) of water level to ensure spawning by all potential spawners. Flood peaks to be spread over the whole breeding season to allow for multiple (serial) spawning.
Maintenance of nursery areas	Maintain water level on floodplain at or above FSL of permanent water bodies (lakes, billabongs, pans) immediately following spawning.
4. Crocodiles	Maintenance of adequate permanent water bodies. The maintenance of adequate fish stocks.
5. Floodplain birds	
Waterfowl	Maintenance of aquatic macrophyte stands.
Waders	Maintenance of sufficient shallow feeding areas.
Divers	Maintenance of adequate fish stocks.
6. Mammals	Maintenance of adequate grazing through appropriate flooding cycle. Provision of adequate water depth for aquatic mammals such as hippopotamus.

2.6.4 MANAGEMENT OF ESTUARIES

2.6.4 .1 Release-depth

A manager of an impoundment can affect an estuary as well as a river downstream of a dam by regulating the amount of water released and also sometimes by regulating the release-depth. Since estuaries are usually some distance from the nearest dam, the depth of release is unlikely to be of great significance to the estuary as far as levels of dissolved oxygen, temperature and plankton are concerned: these are likely to have been modified within the river. On the other hand, release-depth will also determine the levels of nutrients, suspended organic matter and sediment entering the river and thus perhaps the estuary.

Release of suspended sediments, if it must occur, should be done with sufficient water to flush these rapidly through the estuary and out to sea, or these suspensoids will simply increase the rate of siltation already exacerbated by reduced riverflow. It should be remembered that fine suspended solids flocculate very rapidly in salty water.

Nutrients and suspended organic material may be in short supply in some estuaries, particularly those cut off from the sea and fed by oligotrophic rivers. The release of some hypolimnetic water may in fact substitute for some of the nutrients which would normally be received from the sea.

2.6.4 .2 Discharge pattern

Although an impoundment manager may have little choice as to how much water he may release in order to maintain an estuary, he will usually have some opportunity to decide on the timing of those releases. Again, it is necessary to examine the natural flood cycle for each estuary, since the impact of releases of small amounts of water each day will differ from that due to releases of the same amount of water in one or two floods a year. This consideration may be unimportant in well-watered areas, but becomes highly significant in arid regions where water released from impoundments may form the bulk of the flow reaching an estuary.

Since estuaries depend by their very nature on currents, in areas where flow is naturally low and seasonally variable it may be possible to mimic fairly closely the natural flow-patterns, if not the volume, and thus maintain the system in a reasonably undisturbed state. Two features need to be considered, salinity control and mouth opening or widening.

Evaporation and poor flushing affect the fish fauna as well as the rest of the biota, including birds. It should be possible to calculate the amount of compensation-water necessary to maintain salinities within the natural levels and to release this as frequently as necessary, even if these small amounts of water are insufficient to have much effect on flushing.

Hydrological models are available for determining the quantity of water and duration of flood required to open or widen the mouth (Bruun and Gerritsen 1960; Coastal Engineering Research Centre 1973; Moes 1979; Swart 1976).

Perhaps as few as one or two flood-mimicking releases will be all that is necessary for the purpose. Again, timing of releases is extremely important. The biota is often adapted to floods or spates at a particular time of year. For example, the breeding of several angling fishes is timed to coincide with periods when the mouth is open, since juveniles use estuaries as nursery feeding-grounds. Thus, one particular season will be the most suitable for the operation. Under certain circumstances it may be possible to determine more exact timing to coincide with appropriate tidal conditions.

2.7 RESEARCH AND MONITORING NEEDS

2.7.1 A COMPARISON OF PRE- AND POST-IMPOUNDMENT ENVIRONMENTAL CHARACTERISTICS AND BIOTA IN THE DOWNSTREAM STRETCH OF THE IMPOUNDED RIVER

Records which allow comparison of the pre- and post- impoundment conditions in Southern Hemisphere rivers are incomplete and usually cover only flow characteristics. The objective of this study would be to provide a data base from which inferences might be drawn for management.

2.7.2 A STUDY OF CHANGES IN THE RIVERINE ECOSYSTEM DURING DAM CONSTRUCTION

Perturbations arising during the dam construction phase have received little attention in the Southern Hemisphere. Information arising from such a study would be used in delimiting site management practices to minimize undesirable impacts.

2.7.3 THE VALIDATION OF THE MODIFIED RIVER CONTINUUM CONCEPT AND OF THE SERIAL DISCONTINUITY CONCEPT UNDER SOUTHERN HEMISPHERE CONDITIONS

Both these concepts are fundamental to understanding the functioning of river ecosystems. They were developed in the northern wet-temperate zone and the River Continuum Concept has been challenged in the southern wet-temperate zone (New Zealand). Their applicability to wet-tropical and arid zones needs consideration. Validation has important implications for management.

2.7.4 THE IMPACT OF DAMS AND FLOW REGULATION ON INDIGENOUS FISH, PARTICULARLY AS REGARDS SPAWNING MIGRATIONS

Many fish species make spawning migrations, usually during summer floods. The impact of obstructions in water courses and of flow regulation on such migrations and on other aspects of fish biology are insufficiently well-known to make sound management decisions regarding dam siting and flow management.

2.7.5 THE DEVELOPMENT OF METHODS FOR THE EFFICIENT AND RAPID EVALUATION OF THE CONSERVATION STATUS OF STREAM SYSTEMS

Until now evaluation of stream quality has been very largely in terms of the chemical quality of the water and of the biological response to changes in water chemistry. The objective of this research would be to broaden the base of stream quality evaluation to include physical variables such as temperature, flow-patterns and stream bed and bank stability. The objectives would not be to identify streams worthy of conservation, but to be able to classify the overall quality of all rivers using objective criteria.

2.7.6 TAXONOMIC STUDIES AND ENVIRONMENTAL REQUIREMENTS OF CRITICAL SPECIES

Several noteworthy cases of undesirable species such as the water weed *Salvinia*, the mosquito *Anopheles* and the black fly *Simulium* have involved taxonomic confusion. For instance, *Anopheles gambiae* (a malaria vector) and *Simulium damnosum* (the vector of river blindness) involved complexes of species masquerading under single names. In these cases the separate species were shown to have importantly different environmental requirements and roles in the spread of disease. The objective of this research would be to eliminate wasted research effort on control of problem species through neglecting to give taxonomic studies their rightful prominent place in research priorities and to follow these studies with ecological studies.

2.7.7 QUANTIFICATION OF THE RELATIONSHIPS BETWEEN TIME SCALES ASSOCIATED WITH HYDROLOGICAL PROCESSES AND THOSE OF THE BIOTA

The implications of the intensity, duration and timing of hydrological events for the biota are poorly understood and not quantified. Information arising from such a study would be crucial in defining the optimum strategies for controlling hydrological events.

2.7.8 THE EFFECTS OF RIVER REGULATION BY FARM DAMS, WEIRS, BARRAGES AND CANALS IN RELATION TO THOSE ARISING FROM LARGE DAMS

Over much of the Southern Hemisphere arid zone, weirs, barrages, canals and farm dams dominate the landscape. We should be investigating the cumulative regulatory effects of such small structures on the final river system draining the catchments involved, in terms of their effects on salinization, turbidity, invasive exotic species, modification of local and catchment-wide groundwater inputs, chemistry and nutrient and temperature impacts.

2.7.9 LIMNOLOGICAL STUDIES OF THE CONSEQUENCES OF REVERSED RIVER FLOW

Reversal of river flow using cascades of weirs and pumping is a stream management strategy which has been proposed. Limnologically this is likely to convert a stream into a series of impoundments, but limnological experience of flow reversal is completely lacking. Should such schemes come about, limnological comment should be sought at the design stage, predictions should be made and monitoring of limnological change should take place.

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CHAPTER 3 POLLUTANTS

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3.1 INTRODUCTION

Increasing population in many countries of the Southern Hemisphere is placing greater demands on the available water resources. Water is required to satisfy the associated needs of industrialization, urbanization, agriculture and recreation. All these needs may lead to pollution of inland waters by point and diffuse sources. The potential for degradation of existing water resources is greatest in the more arid zones of southern Africa, Australia and southern America. In these zones, flows in watercourses and inputs to lakes are often highly variable because of prevailing irregular rainfall patterns. Stormwater runoff after dry periods will often carry larger pollutant loads than occur in areas which receive regular rainfall. Low and variable rainfall also affects catchment vegetation cover and often leads to greater degrees of erosion and hence suspended materials in runoff. In South Africa, current legislative requirements to return treated effluents to receiving waters to help meet increasing water demands may enhance the deterioration of water quality. Controls on the quality of effluents are but one means by which gross deterioration can be prevented.

In this chapter, we have addressed the effects of pollutants and the principles involved in management of pollution. We have drawn mostly on South African and Australian examples. The philosophy has been to provide a broad overview of pollutants and methods of pollution control available to managers. Detailed information on individual pollutants is available in the literature (Sladecek 1973; Welch 1980; National Research Council 1982; World Health Organization 1984) and only selected citations have been made.

3.1.1 DEFINITIONS

The word pollutant means different things to different people but, for the purposes of this discussion, a pollutant will be taken to mean 'any entity whose addition to an aquatic ecosystem by man or his activities actually or potentially changes the characteristics of the system such that biota are adversely affected or the system is no longer as suitable for a specified range of beneficial uses'. It is implied in this definition that anything which affects the longevity, reproduction, growth or movement of any aquatic organism or is carcinogenic, mutagenic, teratogenic or toxic must be regarded as a pollutant. A particular pollutant may affect man and aquatic biota to different extents and thus, as discussed below, different criteria must be applied.

Fifteen different categories of use of waters have been identified b) Kempster et al (1980). Each has its own specific water qualit) requirements. However, the major categories of beneficial uses are potabl(supply (including industrial), recreation, agriculture an ecosystem functioning. Water quality in impoundments and streams should b no worse than the criteria specified for the major categories.

Limnological criteria are interpreted as criteria derived frc considerations of the physical, chemical, hydrological and biologic characteristics of aquatic systems and their varying interactions.

3.1.2 NATURE OF POLLUTANTS

The main categories of pollutants are chemicals, suspended materials, thermal aspects, pathogens and radioactivity (Table 3.1). Chemicals include acids, trace metals, salts (Chapter 4), inorganic compounds and organic compounds (biodegradable and relatively non-biodegradable). Suspended materials are particles which are temporarily suspended in water; they may affect light transmission and accumulate in stream sections or impoundments but they do not rapidly interact chemically with aquatic biota (Chapter 5). Colloids may affect light transmission and act as transport means for trace metals. Thermal aspects include heated cooling waters and cold waters from hypolimnetic discharges. Pathogens include bacteria, parasites and viruses, all of which vary in their capacity to cause disease. Radioactivity may induce genetic changes in biota if present at elevated levels.

A number of the above pollutants may be present in a given water. Synergistic or antagonistic interactions may occur.

3.1.3 SOURCES

Many activities of man lead to pollutant inputs to inland waters. For example, agricultural activities may lead to major land disturbance and consequent erosion and turbidity problems as well as inputs of nutrients, pesticides and herbicides. Return flows from irrigation may also transport pollutant loads. Mining can result in discharge of saline effluents, acid mine drainage, erosion and trace metal pollution. Urbanization, which involves extensive catchment disturbance, may lead to pollution of stormwater by a range of pollutants such as suspended materials, pesticides and animal litter. Industrial and household wastewaters are usually treated at a sewage treatment works in inland areas before discharge or reuse. Industries may not always remove all pollutants present in their gaseous emissions and these may be deposited as wet or dry fallout in neighbouring or even distant areas. Waterway and wetland modifications, which include dam and weir constructions, dredging, canal construction and flood mitigation works, may change water quality characteristics.

3.1.4 PATHWAYS

Pollutants are introduced into aquatic ecosystems in various ways. Direct discharges may arise as a result of accidental spills but more commonly occur by deliberate action, often licenced by government regulatory authorities. Other discharges arise from industry, agriculture and sewage treatment works. Licencing and its associated permit conditions provide a means by which the quantities of pollutants being discharged to a system can be controlled as:

- licence conditions are normally reviewed on a regular basis;

- conditions may be varied depending upon available technology, needs and economic circumstances;

- non-adherence to licence conditions may result in court cases and fines whilst, in extreme cases, industries may be forced to close or relocate.

Such discharges are more amenable to control.

Less obvious inputs, often called diffuse sources, may arise from ground water, aerial fallout, stormwater runoff from rural or urban areas, remobilization from sediments, resuspension as a result of varied hydrological or meteorological conditions and activities in agricultural and mining areas. Such inputs will often require forward planning, management or a change in operating practices to reduce input loads.

The impact of any pollutant may be magnified as a result of bio-accumulation through the food chain or by a change in its chemical nature. Examples of the former include the accumulation of trace metals by shellfish. An example of a change in chemical nature is the conversion of inorganic mercury to methyl mercury which may then be accumulated by fish.

3.2 IMPLICATIONS

3.2.1 USES

The implications of pollution are both user- and determinand-specific. Climatic and hydrological factors generally have an important bearing on the implications of pollution. General adverse effects are shown in Table 3.1. The water uses which may be detrimentally affected by pollution can be broadly classified as follows:

3.2.1.1 Potable water

Health risk: This is the major concern as regards potable water. Health effects may be either acute or chronic. Acute effects may be caused by pathogenic organisms and chemicals toxic to man.

In the Southern Hemisphere, parts of the population are dependent upon water supplies with little or no treatment. Transmission of infectious diseases by water is therefore of great concern. The control of such diseases is partly dependent upon an understanding of the pathogens and/or the aquatic intermediate hosts.

Chronic effects are those which pollutants may cause in the longer term and include:

- chronic toxicity as a result of bioaccumulation;

- carcinogenic risks as a result of long-term exposure to pollutants;

- mutagenic risks arising from pollutants which are capable of inducing genetic changes.

TABLE 3.1 Examples of types and effects of pollution

Water pollutants	Industry or activity	Adverse effects
Colour	Pulp and paper, textiles, abattoirs, steel, dairy, yeast, tanneries	Aesthetically objectionable, some colour producing pollutants toxic
Suspended solids	Pulp and paper, textile, abattoirs, tanning, canning, breweries, steel mills, boiler-house operation, sewage, mining, agriculture, urban	Blockage of sewer lines and equipment, damage to rivers by solids deposition and oxygen depletion. Interfere with disinfection
Oil and grease	Abattoirs, wool washeries, dairy plants, steel mills, galvanizing plants, oil refineries, tanneries, sewage, urban	Blockage of sewer lines and equipment, floating scum on water which prevents oxygen transfer, anaerobic conditions, smell and fly nuisance. Production of objectionable tastes on chlorination
Organic wastes	Pulp and paper, textile, yeast, sugar, abattoirs, tanneries, canning, brewing, starch, sewage, agriculture, urban	Overloading of conventional sewage treatment plants, oxygen depletion in rivers. Objectionable tastes on chlorination, and production of trihalomethanes
Insecticides, pesticides	Chemical, food, textile, agriculture	Toxic to bacterial and aquatic life placing sewage treatment works out of action. Also health risk to man, plants and animals
Trace metals	Pickling, galvanizing, plating, mining, urban, power generation, motor vehicle emissions	
Cyanides	Metal finishing, plating, coking, oil refinery, mining	
Chemical wastes	Coking, synthetic dyes, chemicals, plastics, solvents, textile finishing	Taste and odour, toxic to aquatic life, plants, animals and man

TABLE 3.1 (cont.)

Water pollutants	Industry or activity	Adverse effects
Acids (mineral and organic)	Steel pickling, chemical, food, mining, power generation, synthetic fuels, motor vehicles	Corrosion, mobilization of pollutants from sediment. Oxygen depletion, acid rain
Alkalis	Metal finishing, plating, pulp mills	Toxic to biota, mobilization of pollutants from sediments
Nitrogen, phosphorus	Fertilizer plants, synthetic detergents, sewage, agriculture	Eutrophication, nitrates may have health implications, ammonia may be toxic to fish
Thermal aspects	Cooling, hypolimnetic discharges	Adverse ecological effects
Detergents	Textiles, metal finishing, sewage	Foaming, possible toxicity
Pathogens and parasites	Hospitals, abattoirs, sewage, agriculture	Spreading of disease
Salts	Mining, agriculture, sewage, many industries	Pose irrigation, industrial and potable water problems
Radioactivity	Hospitals, mining, nuclear plants	Genetic damage and health effects

Prenatal, neonatal and geriatric subgroups of the population, and patients with chronic disease may be particularly susceptible to chronic influences.

<u>Aesthetics</u>: The odour, taste and appearance of potable water is important. Over and above the aesthetic considerations, complaints from consumers may be the first indicator of a problem of wider relevance (Zoeteman 1980).

<u>Costs</u>: Pollution can increase the cost of purification and maintenance of the distribution system which have to be met by the consumer. Specialized technology may be necessary to remove certain pollutants. Problems related to water stability (eg corrosion, scaling) in the distribution system and the users' equipment have major economic implications and are greatly influenced by the quality of the water. The cost implications to the health of the consumer, while of considerable importance (particularly in the case of chronic diseases), are difficult to quantify.

3.2.1.2 Industry

Cost: In many countries, the major supply of water to industry will be of potable quality. Industry may often require further treatment of water to remove a specific determinand or group of determinands before the water is suitable for its use. The stability of water is often of concern.

3.2.1.3 Recreation

Health risks: These can be divided into two categories:

- toxicity, for instance, from exposure to toxic organic pollutants which are lipid soluble and which may be absorbed through the skin during water contact sports;

- risks from pathogens in the water body.

Certain insects, dependent upon the presence of inland waters, may serve as vectors of disease.

Aesthetics: Besides colour, appearance, odour and taste, secondary effects arising from pollutants such as excessive growth of algae and macrophytes and populations of nuisance insects will severely affect the utilization of recreational facilities.

Costs: Pollution may restrict siting of recreational resorts and impede recreational activities such as angling, boating and other water sports resulting in losses to related industry and commerce.

3.2.1.4 Agriculture

The implications of pollution can be considered with respect to three broad categories of agricultural water use, namely irrigation, stock watering and aquaculture.

3.2.1.4.1 Irrigation

- Possible toxicity with damage to crops; this can be either acute or chronic.

- Crop type is of relevance as regards sensitivity to damage from a given pollutant. Variation between crop species as well as intra-specific genetic variation must be considered.

- Effects due to bioaccumulation within crops may not be apparent and may only be experienced by the end-user ie man and his health.

- Cost implications of pollution include:

  1. Decreased production yields.

  2. Damage to a crop as a consequence of a toxic pollutant.

3. Condemnation of a crop as a consequence of absorption of a toxic pollutant.

4. Corrosion and/or blockages of irrigation systems.

5. Changes in agricultural practices and consequent socio-economic implications, necessitated by pollutants.

3.2.1.4.2 Stock watering

- Health risks to the stock as a result of pollutants capable of producing either acute toxicity with disease and death of animals.

- Species sensitivity. A pollutant which may kill one species may have relatively little effect on some other animal species.

- Bioaccumulation of pollutants in animals affects the health of animals as well as the suitability of carcasses for human consumption.

- Cost implications

  1. Stunted or abnormal growth of animals with consequent economic losses.

  2. Unsuitability of a polluted water for certain animal species may necessitate the provision of an alternate supply or the raising of less sensitive species.

  3. Bioaccumulation of pollutants may result in condemnation of carcasses by abattoirs.

3.2.1.4.3 Aquaculture

Fish farming is especially influenced by water quality. The effect of potentially toxic pollutants may be classified broadly into the categories as for stock watering, with an especial emphasis placed on the potential for bioaccumulation of toxic pollutants and the risk of the end product being condemned through excessive concentrations of pollutants. For example, phenols impart tastes and pesticides may exceed the levels recommended for human consumption.

3.2.2 ECOSYSTEMS

Changes in the water quality of aquatic ecosystems are reflected by changes in the biota (Suess 1982). Pollutants may therefore change community structures and species diversity. Variations in species diversity are often applied to indicate the presence or absence of pollution. Changes in ecosystem assemblages and structure may have secondary consequences apart from aesthetics such as the appearance and explosive growth of nuisance organisms, or the development of malodours under anaerobic conditions. Secondary consequences which tend to accelerate the deterioration of an ecosystem are, for instance, reduction of the self-purification capacity of a water body.

The build-up of pollutants within any of the many components of an ecosystem may also have long-term effects and could go unnoticed in the initial stages.

3.2.3 POLLUTERS

'The Polluter Pays' is a commonly applied policy whereby a specific industry is responsible for treating its effluent. The cost of treating effluents to comply with effluent standards is, however, not the only cost implication to industry. As industry often requires water of adequate quality and quantity, the questions of availability and quality of source waters together with the volume and nature of effluents produced have considerable bearing on the siting of industries.

A further problem of both a planning and a cost nature arises where recycling or sequential use of water within a system occurs. Where practiced, a beneficial saving of input water will occur together with a build-up of pollutants in the recycle stream and effluent. Recycling and sequential use may often necessitate more stringent effluent standards with consequent cost implications. For example, irrigation of recreation areas with treated sewage effluent may require greater degrees of disinfection than if the effluent was disposed of by alternative means.

Diffuse sources of pollution must also be addressed in order to prevent deterioration of the environment. For example, the successful control of diffuse sources of pollution often involves planning and alternative management practices in mining and agriculture. If not used, adverse effects upon the quality of runoff and groundwater with consequent effects on water bodies can occur. Use of mining and agricultural practices which minimize pollution problems may have cost-implications. Risk analysis (White and Burton 1980) and cost/benefit relationships must be considered in the implications of pollution.

3.2.4 BENEFICIAL EFFECTS

Apart from the many detrimental effects of pollutants, the same substances which have toxic effects at high concentrations, often have no effect or even a beneficial effect at low concentration. This is particularly applicable to inorganic substances; for example, some trace metals are biologically essential and deficiencies of these micronutrients in the diet of animals may result in disease. Where a population is deficient in a given micronutrient, limited pollution by that element could have a beneficial effect. Consideration of this aspect of water quality is of particular relevance where desalination technology is applied.

3.3 <u>MANAGEMENT</u>

3.3.1 OBJECTIVES

The principal objective of water quality management is to maintain and improve the quality of rivers and groundwaters in relation to their use, in the face of developing demand and increasing pollutant loads.

3.3.2 MANAGEMENT OPTIONS

Different strategies have been used to deal with pollution. The most frequently used method in the Southern Hemisphere has been to set and apply blanket standards or regulations, which operate over the whole of a specific country or state. For example, Table 3.2 summarizes the standards applicable to industrial effluents in South Africa. Where standards or regulations are operative, generators of effluents must usually apply for permission to discharge the effluents. Permits for discharge are therefore based on a process of dialogue between the discharger and the regulatory authority. It is not uncommon that temporary exemptions to standards or regulations may be granted upon special request or considerations. However, as pollutant loads discharged to the total environment increase, the granting of exemptions will become more stringent. Dialogue between dischargers and the regulatory authority often results in remedial actions to reduce pollutant loads being taken without the necessity for costly litigation. However, in instances of persistent pollution, notices requiring remedial actions to be taken may be issued. Should no action occur, court cases may result in fines.

Numerical criteria for the various pollutants have been established in many countries as a guideline for water uses and have been reviewed by Kempster et al (1980), Hart (1974, 1982a and b) and the United States Environmental Protection Agency (1976).

Pollutants limit the use to which any water can be put and extensive literature is available on this subject. The use of the principle of compliance with water quality criteria represents an open-ended approach to pollution control. This means that there must be a continuous review to add or subtract from a list of pollutants and this requires a continuous research effort.

Compliance with water quality criteria requires analytical capabilities, usually operated by the regulatory authority. Analytical techniques may be specified by legislation but research has to be carried out to ensure that the best available analytical methods are used in pollutant detection. Certain water quality criteria are based on toxic concentrations which are established by bioassay methods (Suess 1982). The development of water quality standards for specific catchment basins is dependent upon limnological research. Research to understand the functioning of aquatic ecosystems, their capacity to receive pollutants without adverse effects and the ability to predict future behaviour is an integral part of pollution control.

As measurement of the various water quality characteristics of an inland water may involve considerable time, cost and analytical effort, indicators of potential pollution have commonly been used as follows (Table 3.3).

Waters destined for potable use should be clear and free of objectionable taste, odour and colour and have low conductivity and bacterial concentrations. Recreational waters should have a high clarity and be relatively free of faecal bacteria. The presence of a balanced aquatic flora and fauna is an indication that a system is not heavily polluted.

TABLE 3.2 South African Effluent Standards (from Republic of South Africa, 1984)

Determinand*	General Standard	Special Standard
Colour, odour and taste	None	None
pH	5,5 - 9,5	5,5 - 7,5
Typical faecal coli 100 ml^{-1}	None	None
Dissolved oxygen % saturation	75	75
Temperature °C	35	25
Chemical oxygen demand, mg l^{-1}	75	30
Oxygen absorbed mg l^{-1} in 4h	10	5
Conductivity mS m^{-1}	75 above intake	250*
Suspended solids mg l^{-1}	25	10
Sodium mg l^{-1} increase above intake water	90	50
Soap, oil, grease mg l^{-1}	2,5	None
Residual chlorine mg l^{-1}	0,1	None
Ammonia-nitrogen mg l^{-1}	10,0	1,0
Nitrate-nitrogen mg l^{-1}	N.S	1,5
Arsenic mg l^{-1}	0,5	0,1
Boron mg l^{-1}	1,0	0,5
Hexavalent chromium mg l^{-1}	0,05	N.S
Total chromium mg l^{-1}	0,5	0,05
Copper mg l^{-1}	1,0	0,02
Phenolic compounds (as phenol) mg l^{-1}	0,1	0,01
Lead mg l^{-1}	0,1	0,1
Cyanides mg l^{-1}	0,5	0,5

TABLE 3.2 (cont).

Determinand*	General Standard	Special Standard
Soluble ortho-phosphate (as P) mg l^{-1}	N.S**	1,0+
Iron mg l^{-1}	N.S	0,3
Manganese mg l^{-1}	0,4	0,1
Sulphide mg l^{-1}	1,0	0,05
Fluoride mg l^{-1}	1,0	1,0
Zinc mg l^{-1}	5,0	0,3
Cadmium mg l^{-1}	0,05	0,05
Mercury mg l^{-1}	0,02	0,02
Selenium mg l^{-1}	0,05	0,05

* The waste water or effluent shall contain no other constituents in concentrations which are poisonous or injurious to trout or other fish or other forms of aquatic life.

** Wastewater or effluent arising in specified sensitive catchment areas shall not contain more than 1 mg l^{-1} soluble orthophosphate (as P).

\+ Applies to upper catchment areas.

N.S = Not specified.

TABLE 3.3 Examples of indicators of potential pollution

Determinand	Conclusion
Faecal coliforms/streptococci	Possible presence of human or animal faecal pollution
Iron	Possible presence of other heavy metals
Conductivity	Presence of dissolved salts
Biological Oxygen Demand (BOD)/ Dissolved Organic Carbon (DOC)/ Chemical Oxygen Demand (COD)	Organic pollution

The creation of catchment associations (water boards or water authorities) has been practised in the Northern Hemisphere (for instance in Great Britain) but less extensively in the Southern Hemisphere. Standards for effluent quality are normally based on the capacity of specific catchment streams to receive discharges of effluents. As a country's population grows and it becomes industrialized, the desirability of catchment associations may increase.

3.3.3 POLLUTION ABATEMENT OPTIONS

Pollution abatement normally has to deal with effluents or wastes derived from industrial, domestic and agricultural origins. Various options exist to deal with such effluents in order to ensure adherence to standards. The following techniques are common:

3.3.3.1 Dilution

Dilution is often used as a means of meeting standards but can take many forms. It is dependent on factors such as the hydrological regime (quantity of dilution water available) and the type of pollutant. It is expected that in the semi-arid regions of the Southern Hemisphere, there will be limited quantities of water available for the dilution of pollutants particularly during low flow periods. Dilution is also not applicable to compounds which can bioaccumulate or are persistent in the environment. Dilution may occur in the receiving water or at a sewage treatment works. The former situation is discussed in Section 3.3.3.5. An example of the latter would be the acceptance by an authority of effluents generated by a specific industry and the dilution of pollutants by sewage derived from other sources serviced by the local authority. Such dilution may not reduce pollutant loads discharged to a receiving water and is not favoured in many countries by regulatory authorities. Increasingly, local or regulatory authorities may require effluents discharged to sewers to meet the trade waste criteria by control at source (Section 3.3.3.3).

3.3.3.2 Diversion

Diversion of effluents, untreated or treated, is an abatement option that is often practised to overcome localized problems. For example, this could involve the diversion of saline effluents to another catchment or the discharge of sewage effluents below water supply intakes. This technique needs to consider the catchment's water requirements ie whether the catchment can afford to export valuable water in such a fashion. It also assumes that there is a suitable disposal area.

3.3.3.3 Control at Source

When standards are set to which effluents must conform, the principle used is that 'The Polluter Pays'. This approach is probably the best option for the control of non-conservative pollutants, but not necessarily for conservative pollutants. The conservative pollutants often are difficult to remove from the water and require complex technology and costly processes.

Cost considerations often result in a choice between best available technology (BAT) and best practical means (BPM) for pollutant removal. The choice of the use of BPM could be in conflict with ecological principles. Ignorance of, or non-consideration of, the capacity of an aquatic environment to receive pollutants will increasingly create problems in countries where water resources are limited and water demand and consequent effluent volumes are rising rapidly due to population growth.

The control of pollutants at source is usually enforced by legislation. Research should be undertaken into the development and re-evaluation of standards and regulations in order to ensure the safety of water supplies, the wellbeing of aquatic ecosystems and acceptable costs to the community. This concept implies flexibility in the approach to pollution control and the use of novel approaches. In this regard, it might be necessary to use more stringent discharge conditions ie to take into account the presence of national parks or more sensitive catchments. Increased stress due to pollution might also necessitate a higher frequency of monitoring; continuous chemical or biological monitoring might even have to be considered by government or local authorities for particular industries located in sensitive areas.

Removal and disposal of highly concentrated or highly dangerous wastes (eg radioactive wastes) also require the development of adequate waste disposal procedures. Where such wastes are disposed of by burial or other means, extensive research should be carried out to ensure that future contamination of ground or surface waters does not occur. This places an important responsibility on the authority, whether local, regional or national, which eventually determines the disposal method.

3.3.3.4 Other corrective measures

Pollutants entering impoundments are in either the dissolved or particulate form. A number of techniques are used either to reduce the concentrations of dissolved pollutants or to fix them permanently in the sediments. In-lake treatment techniques include precipitation of metals, phosphates or organic matter from solution. Liming can increase the pH and thus enable a balanced aquatic life to return to lakes adversely affected by acid rain or acid mine drainage. Destratification, or hypolimnetic aeration of stratified waterbodies may restore aerobic conditions in their bottom waters and lead to oxidized conditions in the surface sediment layers (Smalls and Petrie 1983). This prevents or reduces the release of pollutants such as phosphates, trace metals and hydrogen sulphide to the overlying water. Differential (or selective) withdrawal of water from impoundments helps minimize pollution effects on factors such as dissolved oxygen, trace metal contents, taste and odour. In Germany, the control of the phosphate input from diffuse sources to the Wahnbach reservoir involves chemical treatment of the whole inflow to the reservoir (Bernhardt and Clasen 1982).

3.3.3.5 Assimilation

Aquatic ecosystems can assimilate limited loads of certain pollutants such as nutrients (nitrogen and phosphorus compounds) and biodegradable organic materials without noticeable adverse effects. This self-purification capacity is often used to mitigate the effects of pollution, and assimilation models have been used for predictive purposes for aquatic ecosystems, particularly with respect to streams (State Pollution Control Commission, New South Wales 1983b). This approach can be used with pollutants which are biodegradable but not with those which will bioaccumulate. Persistent and non-biodegradable pollutants can often accumulate in the biota of aquatic ecosystems. They may be concentrated in the higher levels of food webs and could constitute health hazards in the long term. Knowledge about the bioaccumulation of pollutants is an important part of pollution control, particularly where long-term low-level chronic effects may occur.

Effluent discharge licences are usually based upon the quality of the effluent at the point of discharge and may not take into account assimilation which is regarded as an additional safeguard to water quality. In New South Wales, Australia, licence conditions may take into account dilution achieved at the edges of a specified mixing zone. Research into the efficiency of natural and man-made wetland systems for nutrient and pathogen removal, if successful, could alter this approach.

Suspended matter, particularly clays in turbid waters, are capable of adsorbing some pollutants. These suspensoids act as a major transport mechanism for bacteria and pathogens, toxic organics and trace metals. Certain organic acids and metals (eg boron) are not associated with the suspensoid phase.

After deposition, the sediments of rivers, lakes or impoundments may act as a sink for certain pollutants, but there is a risk of remobilization. Remobilization through the activity of organisms could lead to the reappearance of the pollutant in the water phase. The remobilization of mercury from sediments is a well-known example of such a phenomenon.

3.3.3.6 Sequential use

Pollution control can be enhanced by the sequential use or reuse of effluents. For example, the use of secondary treated sewage effluents as cooling water in power generation or for the watering of parks and other public recreational areas, reduces both the demand on potable water supplies and discharges of pollutants to the aquatic environment. Increasing concentrations of salts will often limit the number of cycles of reuse before an effluent has to be diluted or disposed of. This approach should be considered where possible and economic.

3.3.3.7 Planning

Urban, mining and agricultural activities and waterway structures (such as dams) can pollute the aquatic environment. Diffuse input loads from the former activities normally occur in associated stormwater runoff. Deleterious effects can be minimized, and pollutant loads contained in runoff reduced, by adequate planning before developments commence. Similarly, the inclusion of selective withdrawal structures in the construction of deep water storages and provision for aeration can reduce future water quality problems and provide the resource manager with more control flexibility.

Urban runoff control facilities can be constructed to minimize drainage costs associated with new urban developments, and to provide an unchanged hydrological regime, improve runoff quality and increase infiltration rates. Such methods are used in the USA and some Australian catchments. Relevant guidelines have been published (Soil Conservation Service, New South Wales 1976).

Mining often involves extensive land disturbance. Consideration of the characteristics of mine spoil (State Pollution Control Commission, New South Wales 1983a) may influence the choice of mining methods and the emplacement of spoil. Water management plans for mine sites should be developed and include such aspects as separation of 'clean' and 'dirty' waters (eg by diverting stormwater around disturbed areas) and collection and use of 'dirty' waters for purposes such as road watering. Such practices are used in New South Wales.

Agricultural practices may use excessive quantities of water for irrigation with resultant salinization problems (Chapter 4). Research into minimal water requirements can reduce water use and salinization. Cultivation near waterways may increase erosion whilst slow release fertilizers, currently being evaluated in Western Australia, may reduce nutrient losses to waterways. Alternative farming practices can thus reduce pollutant inputs.

3.3.4 MANAGEMENT REQUIREMENTS

Varying levels of management exist, each with its own specific information requirements.

3.3.4.1 Information generation

Management objectives will ultimately determine the design of surveillance networks. For example, day to day operation of a potable water treatment plant will require monitoring of a supply for one set of parameters, while ecosystem management may require examination of a different set.

By contrast, a pollutant 'spill' or an 'illegal discharge' may require continuous measurement for selected determinands, provided that the constituents of the 'spill' are well defined. Although technological advances have made it possible to consider placing micro-processor controlled measuring equipment at selected sites, it has proven to be difficult to obtain sensors which measure accurately and cover a range of determinands. At present, if considering this approach, the trade-off between sampling frequency and analytical accuracy must be accepted.

It is essential to support staff with the best available tools. Of major concern is the adequacy of analytical capabilities in the face of an increasing spectrum of contaminants occurring at low concentrations. Ideally, management should acquire analytical facilities in anticipation of a need, but economic constraints will often limit the extent to which this can be achieved.

For effective management, data should be readily accessible and available in a usable form. Data processing to manipulate the information into the form required for management often entails statistical and/or modelling methods. Modelling techniques can be used as a management tool to:

(i) predict future conditions based on historical data;

(ii) simulate system reactions under increased or decreased stress conditions; and

(iii) analyse trends to give warning of deteriorating water quality conditions.

Such modelling requires an integrated data base of chemical, biological, physical and hydrological observations.

Management should have access to information that will enable them to evaluate the implications of a certain pollutant, should it be released to the environment. This implies a data base of criteria, and toxicological and organoleptic data.

3.3.4.2 Information and Advisory Services

For management to have available maximal options, a wide range of expert advice concerning waters is required. Expertise capable of addressing the whole spectrum of water associated problems is seldom found within one organization. This creates a demand for a central advisory/information service. Such a service would draw upon the expertise from organizations actively involved in limnology, water quality and related fields as well as commercial consultants.

3.4 KEY QUESTIONS AND RESEARCH NEEDS

The following key questions need to be addressed:

3.4.1 ARE EXISTING WATER QUALITY DATA BASES ADEQUATELY USED?

Motivation

Many organizations in individual countries have water quality data bases which are used to varying extents in water quality management. Such data should be investigated to optimize water quality management. The availability of water quality and flow data and its accuracy and precision should be evaluated.

3.4.2 DO RISK ANALYSES HAVE A ROLE IN WATER MANAGEMENT?

Motivation

Certain risks in life are regarded as acceptable. This approach also forms the basis for the optimal management and utilization of water resources. Risk analysis is particularly applicable to the setting of criteria for carcinogenic substances. Complete removal of these substances is often not economically viable. Methods must be sought and continuously updated and refined to assess economic and aesthetic impacts.

3.4.3 DO BIOLOGICAL INDICES HAVE A ROLE IN WATER QUALITY SURVEILLANCE?

Motivation

Chemical sampling programmes are often based on grab samples. Since the intermittent discharge of toxicants or the sub-acute presence of toxicants may only be detectable through changes in biological assemblages in aquatic ecosystems, there is a need to develop and use biological indices in water quality surveillance. This might involve the use of biological assemblages (biotic indices) or the use of indicator organisms.

3.4.4 DO ABIOTIC (CHEMICAL) INDICATORS HAVE A ROLE IN WATER QUALITY SURVEILLANCE?

Motivation

Frequent use is made of abiotic indicators of specific deterioration in water quality. Examples of such are conductivity to detect salinization, chloroform concentrations as a measure of trihalomethanes, the use of ultraviolet fluorescence to determine aromatic organics and the use of biological oxygen demand to detect pollution by biodegradable organic compounds. There is a need to further develop the use of abiotic indicators in water quality surveillance.

3.4.5 WHAT IS THE ROLE OF WASTEWATER TREATMENT PROCESSES IN OPTIMAL WATER QUALITY MANAGEMENT?

Motivation

Countries or authorities faced with pollution as a significant limiting factor in water resource management have to consider all ways and means by which water and wastewater treatment can be upgraded. Awareness of best available technology (BAT) and best practical means (BPM) of combating pollution are necessary. Development of regional (larger) wastewater treatment systems as opposed to local or (smaller) systems should also be addressed. The philosophy and applicability of water authorities (and catchment associations) which treat potable as well as wastewaters should be investigated.

3.4.6 ARE EXISTING WATER QUALITY STANDARDS APPLICABLE AND JUSTIFIED?

Motivation

Toxicological research is revealing new facts on the pathogenicity of chemicals particularly as regards synergistic/antagonistic effects or effects of speciation. This necessitates a continual updating of water quality criteria. There is continuous attention worldwide to the further development of water quality criteria. Local information should be continually upgraded and incorporated into water resources and quality management strategies.

3.4.7 HOW SHOULD INTRACTABLE (PROBLEMATIC) WASTES BE DISPOSED OF?

Motivation

Radioactive or hazardous organic wastes constitute environmental pollutants of considerable importance. Examples in Northern Hemisphere countries with dioxin and radioactive wastes have illustrated that safe long-term disposal of these pollutants can be a problem. Safe procedures for handling such wastes should be developed.

3.4.8 IS ACID AND SALINE POLLUTION OF AQUATIC ENVIRONMENTS A REAL CONCERN?

Motivation

In countries where coal and other minerals are mined, acid mine drainage and discharge of brackish waters cause environmental problems. The extent of this problem needs to be ascertained and means of overcoming or minimizing it must be developed. Information from the Northern Hemisphere may provide guidance. Techniques such as the selective handling of overburden material at open cut coal mines may be necessary. The use of fossil fuels such as coal in power generation and the production of petrol from oil results in the emission of large quantities of sulphur and nitrogen oxides to the atmosphere which can give rise to acid rain. The presence of acid rain, and the susceptibility of the environment to this problem requires investigation in Southern Hemisphere countries.

3.4.9 ARE HAZARDOUS COMPOUNDS TRANSMITTED TO THE AQUATIC ENVIRONMENT THROUGH ATMOSPHERIC POLLUTION?

Motivation

Atmospheric pollution by industries and motor vehicles could, after deposition, enter the aquatic environment. The extent and importance of such pollution should be investigated.

3.4.10 IS POLLUTION OF GROUNDWATER A SIGNIFICANT FACTOR IN WATER RESOURCE MANAGEMENT?

Motivation

Groundwater contributes to the base flow of rivers and is a resource. Should such groundwater be polluted, it may have a significant effect on the quality of stream water particularly during low flow periods. Little is known about the extent of groundwater pollution in many Southern Hemisphere countries and this aspect should be investigated more fully.

3.4.11 ARE HAZARDOUS CHEMICALS TRANSPORTED BY SUSPENDED MATERIALS?

Motivation

Indications have been obtained in Northern Hemisphere industrial countries that sediments and suspensoids are important in the complexing and transport of hazardous chemicals. Little is known of this phenomenon and it should be investigated. Aspects which deserve attention are absorption/desorption processes, biological activity and associated release of hazardous chemicals and the role of this phenomenon in biological accumulation.

3.4.12 IS THERE A NEED TO DEVELOP PREDICTIVE CAPABILITIES WITH REGARD TO WATER QUALITY MANAGEMENT?

Motivation

Models are used extensively to manage systems. Further development of models for nutrients, conservative constituents and toxicants in relation to water resource management should take place.

3.4.13 WHAT FACTORS CONTROL THE ECOLOGY OF PATHOGENS AND PARASITES?

Motivation

The control of diseases caused by pathogenic organisms is based on the principle of destruction or interference with the metabolism of the pathogen at some stage within its life cycle, or destruction of intermediate host vectors. Where the aquatic environment includes part of the life cycle of a pathogen, either via a water-associated vector, through an aquatic phase in the life cycle, or by mechanical dissemination of the pathogen via water, then the opportunity of influencing the epidemiology of the disease exists through control techniques applied to aquatic systems. An example is the absolute metabolic dependence of *Vibrio cholerae* on sodium. Decrease in sodium concentrations in water may thus decrease the viability of *Vibrio* in the water phase.

3.4.14 IS THERE A NEED TO INSTITUTE AND OPERATE A TOXICOLOGICAL DATA BASE?

Motivation

Each year, new chemicals are marketed which could enter the aquatic environment. Many may be hazardous. There is a need for countries to compile, operate and update a data bank on toxicants which may be present in the aquatic environment.

3.4.15 ARE MEASURES AVAILABLE TO REDUCE POLLUTION FROM DIFFUSE SOURCES SUCH AS RURAL AND URBAN RUNOFF?

Motivation

Diffuse sources of pollution such as stormwater runoff from urban and rural areas may transport large quantities of pollutants into receiving waters. Such inputs may decrease the beneficial effects of controls which are applied to point sources. There is a need to develop and evaluate measures to reduce pollutant loads from diffuse sources.

3.4.16 ARE THE PROPERTIES (SUCH AS NUTRIENT AND PATHOGEN REMOVAL) AND PERFORMANCE OF WETLANDS UNDERSTOOD OVER THE LONG TERM?

Motivation

Wetlands may act as sinks for nitrogen and phosphorus compounds present in wastewaters (such as sewage) and cause large reductions in bacterial and pathogen densities. Their capacity and performance in these respects are poorly understood, as are the requirements for their manipulation (eg harvesting) to optimize these functions. Their use should be further investigated as they offer a low cost alternative system for water treatment suitable for developing countries.

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CHAPTER 4 SALINIZATION

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4.1 INTRODUCTION

Salinization is the process whereby the concentration of total dissolved solids in inland waters is increased. Mineralization is the term frequently used in South Africa, but to avoid confusion with that term as used by ecologists to describe the conversion of organic matter to mineral salts, we recommend that mineralization not be used as a synonym for salinization. Salination is another synonym we do not recommend.

The process is of considerable and increasing importance since it often renders waters less suitable for use by man and may affect the natural ecology of inland waters. It arises from both natural and man-made causes, but the latter are of most concern in water management. Essentially, it is man's disturbance of the natural hydrological cycle which is the focus of the problem. To distinguish natural from man-made salinization, the latter is sometimes referred to as secondary salinization.

Salinization is a particular threat in semi-arid regions, or in regions of reduced rainfall. There, it provides a significant hazard to water quality and supplies and poses an important potential threat to the structure and function of natural aquatic ecosystems. The extent of the ecological threat remains largely unresolved, is subject to little effective investigation and monitoring, and is often ignored even in otherwise comprehensive accounts of salinization (eg Peck et al 1983). If this chapter does no more than draw the attention of limnologists to the broad environmental damage that salinization may lead to, its compilation will have been worthwhile, and the objectives of the Workshop on which it is based will have been achieved.

It should be stressed that although salinization induced by man may finally produce highly saline waters, even saturated ones, the most important economic and environmental effects relate to relatively slight increases in salinity at the lower end of the salinity spectrum. Thus the process is most significant in converting fresh waters of salinities less than about 500 mg l^{-1} to waters of salinity between 500 and 10 000 mg l^{-1}. It is this conversion of fresh waters to waters that are relatively saline as a result of man's activities which provides the basis for this chapter. Processes which lead to the formation of salt lakes in endorheic basins, while of considerble limnological interest, are not matters for discussion here. Also not discussed are processes (eg river diversion) which lead to increased salinities in naturally saline lakes.

It should also be stressed that considerable differences exist between the perceptions of water managers and limnologists of 'fresh', 'slightly saline' 'saline' and 'highly saline' waters. This is illustrated in Table 4.1 based upon informal discussion between limnologists and water managers at the Workshop of which this chapter is the report. Clearly 'highly saline' waters to water managers may well be regarded as quite 'fresh' waters by limnologists. All the major ions as well as some minor ones may be implicated. Na^+ and Cl^- are particularly important in Australia and South Africa, but divalent cations, and carbonates and sulphates inter alia can play important roles.

TABLE 4.1 Perceptions of salinity. Values as mg l^{-1}

Perceptions of:	Fresh	Slightly saline	Saline	Highly saline
Water Managers	300	300- 700	7 000- 1 500	1 500
Limnologists	3 000	3 000-10 000	10 000-100 000	100 000

Total dissolved solids are often estimated by measurement of conductivity and by applying a conversion factor. It should be recognized, however, that considerable error may be involved in this procedure according to ionic strengths and proportions. A more accurate value may be obtained gravimetrically. Usually, total dissolved solid concentration is not significantly in excess of salinity, ie the concentration of total dissolved salts. Salinity, of course, is accurately determined by analysis of individual ions and summation. In this chapter all values of total dissolved solids (TDS) are expressed as mg l^{-1}.

4.2 ORIGINS AND CAUSES OF SALINIZATION

Salts in inland surface waters derive from various sources. Principally these are terrestrial sources, the atmosphere and from groundwater. The relative proportions of contributions from each are determined by a variety of factors, but rainfall, topography, distance from the sea, the direction of the prevailing wind, and the geology of catchments are all important. The processes involved in the natural addition of salts to inland waters are not dealt with here.

Man may elevate salt concentrations in inland waters either by accelerating rates of salt accretion from essentially natural sources, or by directly adding salt as a result of mining, industrial, urban or other activities.

There are two major activities of man which accelerate or exacerbate the input of salts to inland waters from essentially natural sources: irrigation and dry-land farming following the removal of native vegetation. Salts added directly from essentially non-natural sources include those contributed in sewage effluents, industrial discharges, mine drainage water, and from atmospheric pollutants. They are considered briefly below.

4.2.1 IRRIGATION

Of all man's activities, the effects of irrigation have had the most significant effect in terms of salinization.

When water of low TDS is supplied to the soil, part of it evaporates or runs off the soil surface. The remainder infiltrates into the soil from which a further part evaporates and is transpired by plants, while the rest may percolate through the soil. In passing through the soil it will leach salts and may undergo significant chemical alteration through ion exchange and other processes before reaching a body of surface water. The end result is that the salts present in the supply water are greatly concentrated in the return water and may also be added to.

Inadequate drainage can greatly increase evaporation losses, and mixture with subsurface saline water bodies or formations through which the return flow percolates may further influence final composition and salt load. The application of inorganic chemical species, such as fertilizers and gypsum to soil, also add to the salt content of irrigation return flows. Evaporation (and consequential salt concentration) from water stored for irrigation use is a further cause of salinization.

4.2.2 DRY-LAND FARMING

In Australia and the Americas, and probably in Africa as well, widespread salinization has resulted from the removal of native vegetation and its replacement with dry-land crops.

The main effect of dry-land agriculture on salinization is related to a change in the infiltration capacity of the soil. This can be brought about by various means such as by changing or destroying the natural vegetation, or by deep ploughing. This in turn may mobilize deep-seated soluble salts, which under virgin conditions would not have been reached by the wetting front.

4.2.3 MUNICIPAL EFFLUENTS

Most forms of urban water use and re-use result in water losses, concentration of salts, or salt addition. Mostly, the TDS concentration of municipal effluents is from 150 to 500 mg l^{-1} higher than that of municipal water supplies.

4.2.4 INDUSTRIAL EFFLUENTS

Many industries significantly increase the salinity of water used by them. A single example will suffice to make the point. Heavy industries, including mining-metallurgical processes, located within the Pretoria-Witwatersrand-Vereeniging region of South Africa, discharge effluents with a TDS concentration on average approximately 1 000 mg l^{-1} higher than that of the supply water. The disposal of blowdown water from power generation is said to pose a salinity problem in some areas of Australia.

4.2.5 MINE DISCHARGES

Many mining activities result in the discharge of saline water to the environment. This may result inter alia from metallurgical activities, from drainage, or from disturbance of saline groundwater bodies. Whatever the case, the salinities of water discharged may be very high. Thus, saline drainage water from mine workings in South Africa often exceeds

10 000 mg l^{-1}, and water of this sort accounts for a third of the salt load of the Pretoria-Witwatersrand-Vereeniging complex. Seepage from abandoned mines may exhibit similarly high salinities. Leachate from overburden and waste dumps poses a potential problem in certain areas of Australia.

4.2.6 ATMOSPHERIC POLLUTION

Many industries and thermal power stations disperse large quantities of chemicals into the atmosphere. Following rain, or as dry fallout, some of this reaches the ground and ultimately surface waters. An example is provided by the Vaal Dam basin of South Africa (38 000 km^2). The waters in this basin, and in particular Vaal Dam, have exhibited over the past years a steady increase in salinity. It is strongly suspected that the construction of thermal power stations in and adjacent to its catchment may be important factors in this increase.

4.3 DISTRIBUTION

Areas subject to salinization are known from many countries, and the phenomenon has been recognized as a deleterious process for centuries. A recent estimate is that salinization affects about one-third of the earth's irrigated areas. Salinization, moreover, seems to have been a problem to the agriculturalists of ancient Mesopotamia some 2 500 BC.

4.3.1 IN SPACE

Salinization is particularly significant in countries with low rainfall and where most of the available water is used for agricultural, domestic, stock, industrial and other requirements. Details of the geographical extent need not be given but a brief resumé of its particular and increasing significance in certain regions is appropriate here, viz South Africa, Australia, the Middle East and North America.

In South Africa, salinization is a hazard or potential threat in most areas west of the Drakensberg. The approximate distribution of surface water salinity in South Africa is indicated in Figure 4.1. As the figure illustrates, most areas west of the Drakensberg already have water salinities in excess of 300 mg l^{-1}, that is, so far as water managers are concerned, waters are already slightly to highly saline.

In Australia, areas with salinization problems occur in south-western Western Australia, south-eastern South Australia, western Victoria and parts of New South Wales and Queensland (Figure 4.2). A summary of the extent of salinization upon both the terrestrial and aquatic environment of Australia is given in Table 4.2. Perusal of the table indicates that the largest areas of salinized land occur in south-western Western Australia and the Murray-Darling Basin. The greatest impact upon stream salinities occurs in south-western Western Australia.

TABLE 4.2 The extent of terrestrial and aquatic salinization induced by man in Australia. After Peck et al 1983

Drainage Division (see Figure 4.2)		Area of salinized agricultural land		Streamflow with TDS concentration 1,000 mg l^{-1}	
		Dry-land* (km^2)	Irrigated (km^2)	Volume ($10^6 m^3 yr^{-1}$)	% of total discharge
I	North-East Coast	80	6	Nil	0
II	South-East Coast	620	Nil	2010	4
III	Tasmania	50	Nil	Nil	0
IV	Murray-Darling	620	1219	70	1
V	South Australian Gulf	170	Nil	70	7
VI	South-West Coast	2420	5	2590	39
VII	Indian Ocean	220	Nil	170	4
VIII-XII	Others	80	Nil	Nil	Nil

*Does not include saline scalds.

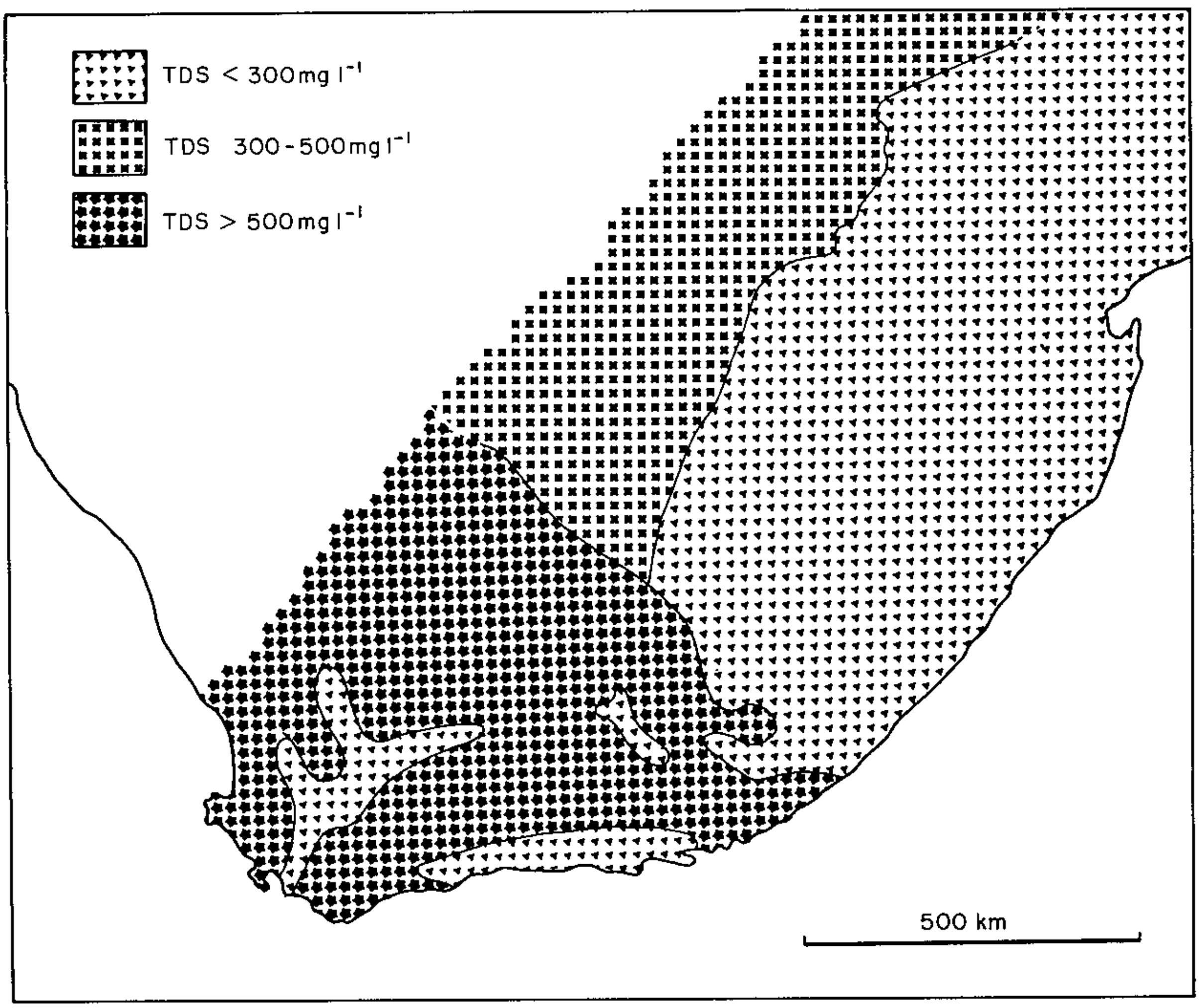

FIGURE 4.1 Approximate regionalization of surface water salinity in South Africa. Political boundaries have been ignored. Map based upon data derived from the Directorate of Water Affairs, and the National Institute for Water Research, CSIR.

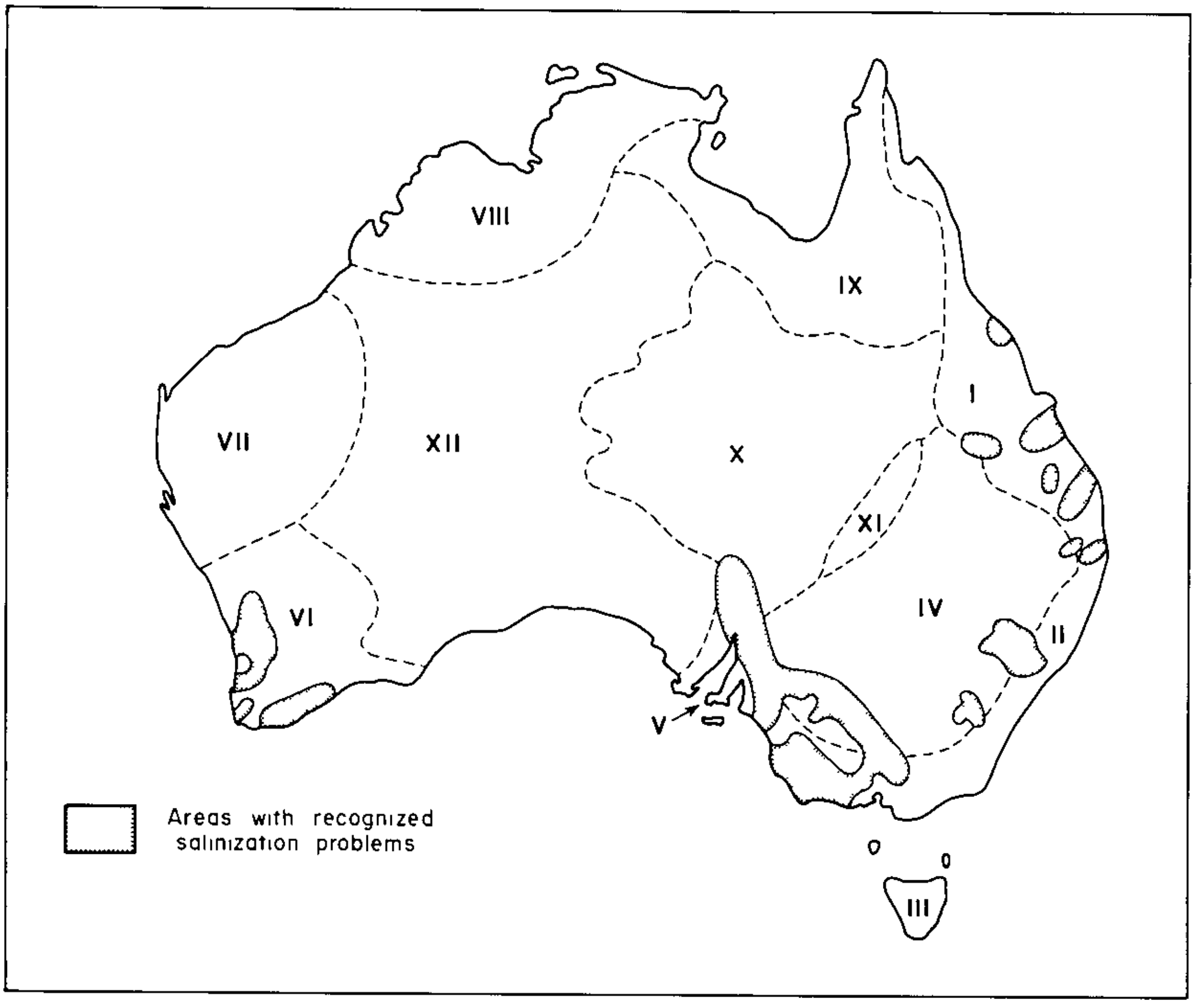

FIGURE 4.2 Drainage divisions and areas with recognized salinization problems in Australia. Roman numerals refer to Drainage Division (see Table 4.2 for names). Map based on data derived from Brown (1983) and Garman (1983). Note: problems do not necessarily apply over the whole of the areas shown.

In the Middle East, almost all countries experience salinization problems. Such problems are known from Pakistan, Afghanistan, Iran, Iraq, countries of the Arabian Peninsula, Syria, Egypt, Sudan and Libya. They are closely related to inefficient use of irrigation water, lack of adequate drainage, and low water quality. Very large areas may be involved: in Iraq, for example, the percentage of salt-affected (and waterlogged) area amounts to 50% of total irrigable land.

In North America, a number of states and provinces of the U S and Canada have salinization problems. Several western states do, especially California, Colorado and Arizona. Several central states also experience problems (eg Oklahoma). Additionally, saline seeps (saline soils in dry-land farming areas that remain wet some or all of the time) are now a major problem in most of the northern plains states of the U S and large parts of the prairie provinces of Canada (Figure 4.4).

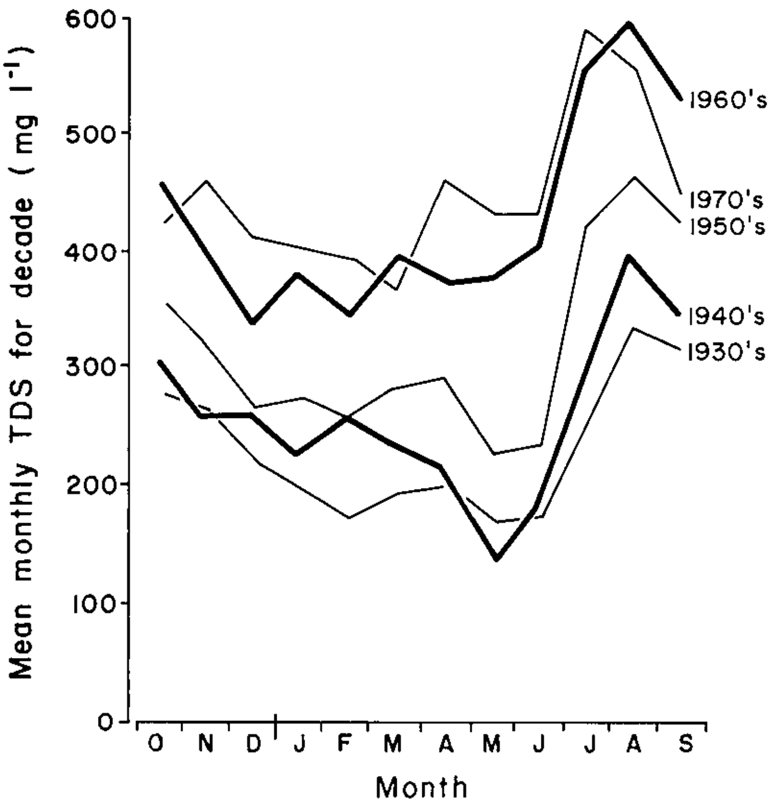

FIGURE 4.3 Mean monthly TDS for San Joaquin River at Vernalis, California, by decades, 1930 to 1979. Redrawn from Orlob and Ghorbanzadeh 1981.

4.3.2 IN TIME

Problems resulting from salinization date from historical times and it has been claimed that the demise of at least some ancient civilizations resulted from the degradation of irrigated land and water supplies by salt.

Fully documented evidence of the increase in river salinities brought about by man's impact is not as plentiful or as comprehensive as is desirable. However, there can be no mistake in the direction of discernible trends: they are always towards increased concentrations.

For South Africa, the evidence includes some good historical records of a gradual increase in the salinity of the Vaal River, and other major rivers following socio-economic development.

In the United States, records of the salinity of the San Joaquin River are particularly complete (Figure 4.3).

For Australia, salinity records for the Kent River and Blackwood River are amongst the best available for the continent (Figures 4.5 and 4.6). Records for the Murray River in south-eastern Australia are rather equivocal (Figure 4.7). Although a number of people claim that the salinity of this river is gradually rising, and indeed some rise does seem to be indicated by Figure 4.7, statistical analysis of past records has led others to suggest that recent salinity rises repeat similar rises in the past. Whatever the case, considerable uncertainty does surround the magnitude of future changes in the salinity of this river.

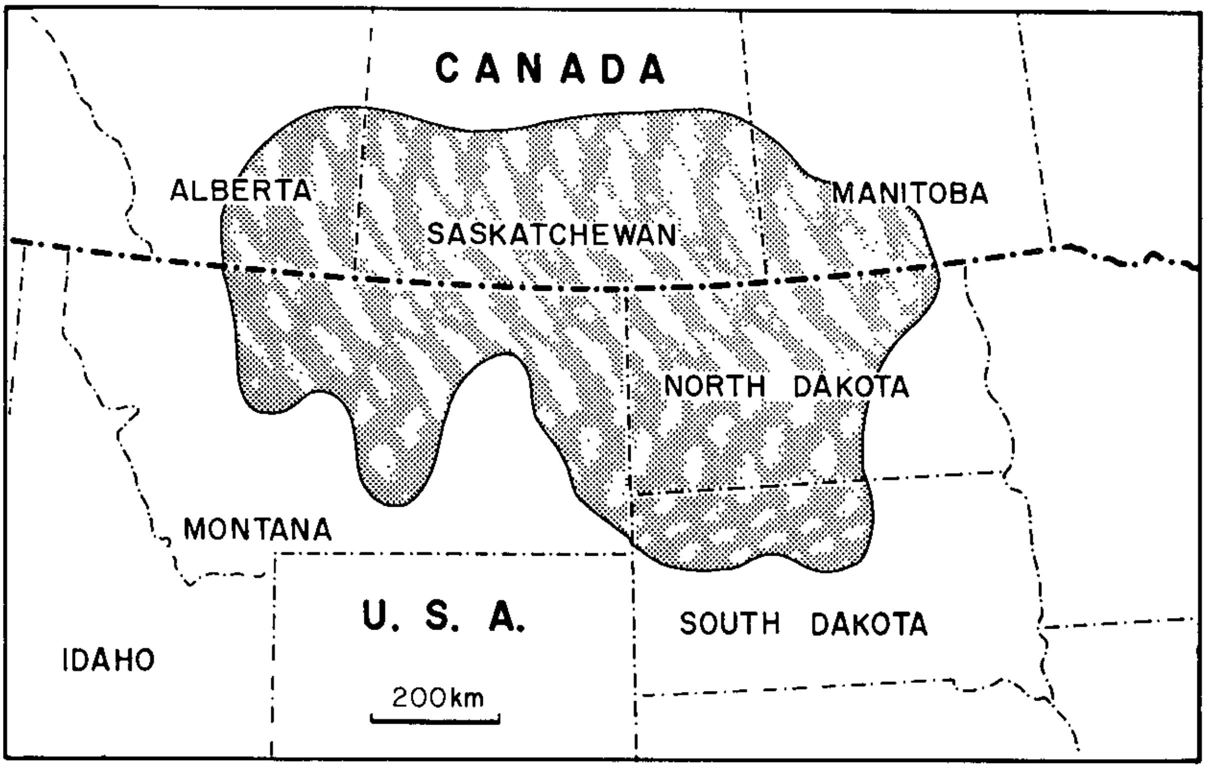

FIGURE 4.4 Area of potential or actual saline seep development in the Northern Great Plains of America. Redrawn after Miller et al 1981. Stippled area is area of potential or actual seep development.

4.3.3 TRENDS

With increasing utilization of water resources in semi-arid and low-rainfall areas, the extent of salinization will increase unless better management and mitigating procedures are invoked.

Some predictions for salinity values likely and potentially possible in various rivers in Western Australia illustrate the seriousness of the problem for at least some Australian rivers (Table 4.3). As the table illustrates, unless preventative measures are undertaken to discontinue the clearing of natural vegetation from land, salinities in some rivers of the area could rise twofold! For the Australian continent as a whole, Peck et al (1983), in their recent comprehensive review of Australian salinity issues, state: 'In general, stream salinities are expected to continue to increase in the immediate future as a result of past and future agricultural development'.

Alexander (1980) is more direct so far as the situation in South Africa is concerned. In some concluding remarks to a workshop on understanding salinization processes in South Africa, he ended: 'There is no doubt that mineralization [salinization] is a serious problem in South Africa - and it can only get worse!'.

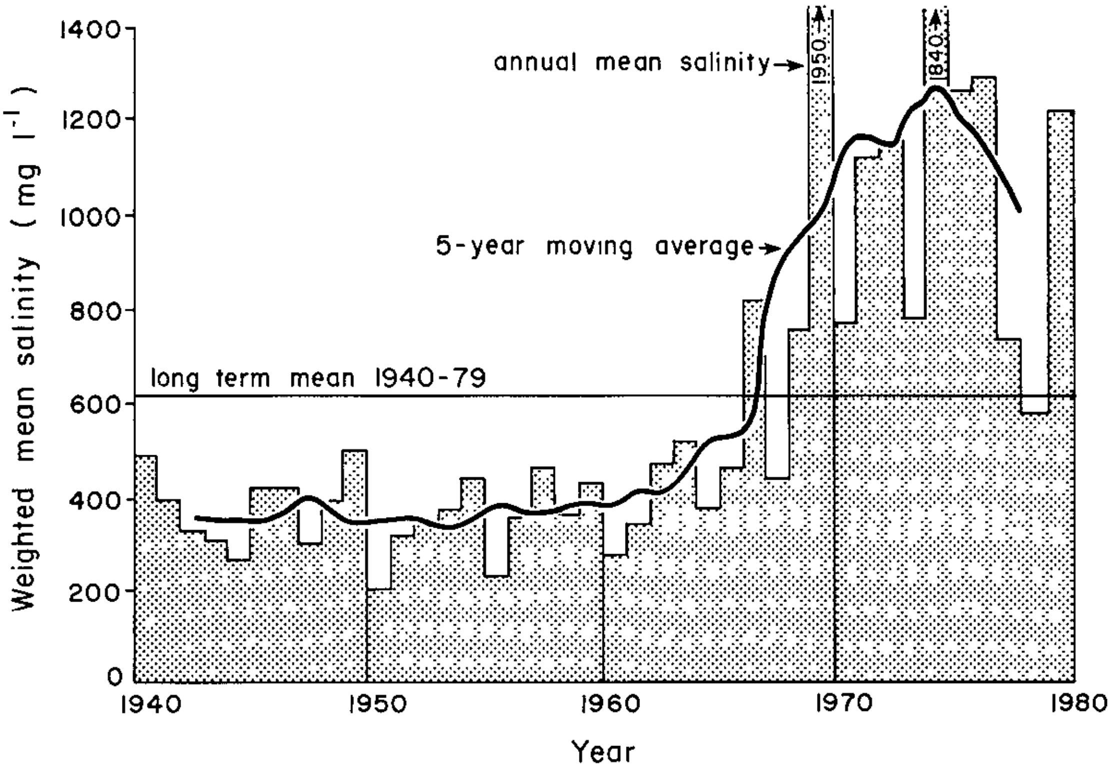

FIGURE 4.5 Salinity of Kent River, Western Australia, 1940 to 1979. Redrawn after Collins and Fowlie 1981.

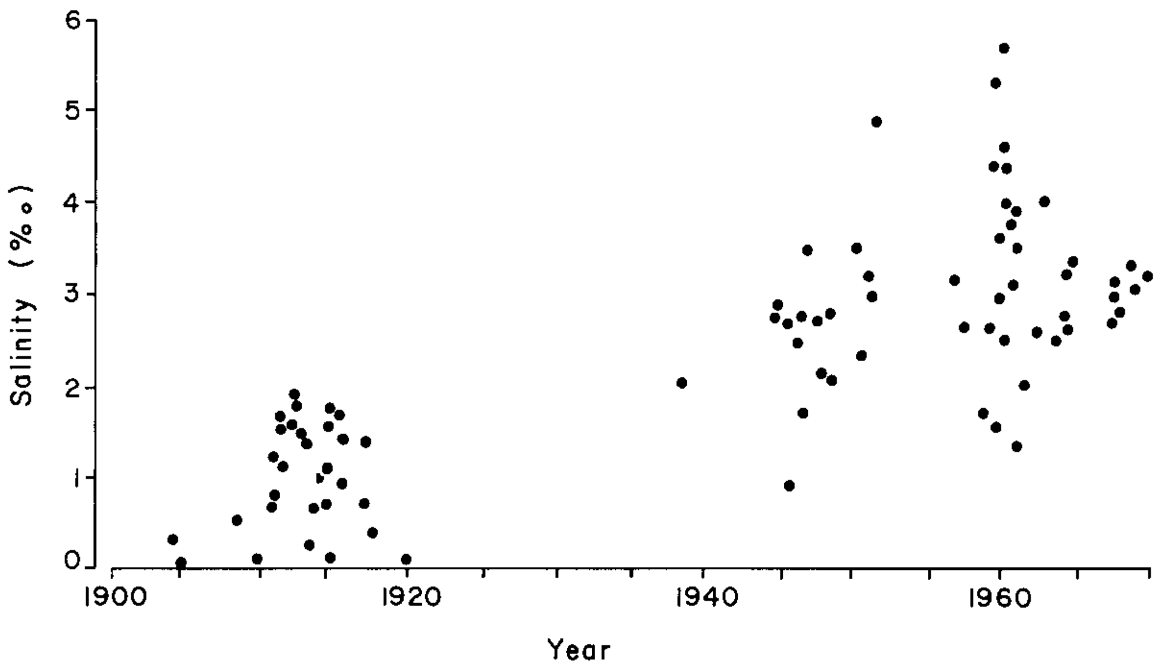

FIGURE 4.6 Salinity records for Blackwood River, Western Australia, at Bridgetown, 1900 to 1970. Redrawn from Hodgkin et al 1979.

FIGURE 4.7 Salinity of River Murray, South Australia, at Mannum, 1945 to 1980. Data expressed as a 5-year moving average. Figure redrawn and modified from Peck et al 1983.

TABLE 4.3 Salinity predictions for some rivers of Western Australia. Table from Sadler and Williams 1981

River	Catchment area (km^2)	Landuses in catchment			Mean annual salinity level ($mg\ l^{-1}$ TDS)		
		State forest & reserves %	Private land		At present	As a result of clearing to date*	If all private land were cleared*
			Uncleared %	Cleared %			
Collie	2830	65	12	23	750	1100	1700
Helena	1470	95	2,5	2,5	360	360	700
Denmark	650	79	5	16	570	640	850
Warren	3890	54	14	32	725	1000	1400
Kent	1650	45	15	40	1100	1500	2500

*Ultimate figures allowing for natural time lags.

Similar expectations of increased problems as a result of salinization are also held for North America and the Middle East.

With regard to the question of whether salinization is of special significance in the Southern Hemisphere, two points may be made. Firstly, it does not appear that there are any special features which are responsible for an enhanced vulnerability of Southern Hemisphere areas. Secondly, the relatively large proportion of land in the Southern Hemisphere which falls into the semi-arid zone does mean that water-courses in various countries of the Southern Hemisphere are especially at hazard to salinization.

4.4 IMPACT

Salinization has already seriously degraded the quality of many waters used for domestic, industrial and agricultural supplies, and there are early indications that salinization is also beginning to have an adverse environmental impact.

4.4.1 ECONOMIC IMPACT

Detailed documentation of the economic impact and cost of increased salinity in water supplies is not an appropriate endeavour in the present context. However, to indicate the diverse nature of this impact, and the magnitude of costs involved, it will be helpful briefly to comment on at least some of the more important economic impacts and tabulate particular criteria.

The most desirable water for domestic use is water of salinity less than 300 mg l^{-1}. Not infrequently, however, this concentration is exceeded in semi-arid areas (and elsewhere). Criteria for a number of constituents in drinking water have been established by the World Health Organization (Table 4.4) (WHO 1971), and increases beyond recommended levels result in additional soap and detergent use, plumbing damage, and, beyond certain levels, a variety of medical problems (such as hypertension).

The actual costs of increased salinity in water supplied to households has been investigated most thoroughly in the USA. Considering concentrations between 300 and 900 mg l^{-1}, cost estimates per 100 mg l^{-1} TDS ranged from US$14,3 yr^{-1} in Los Angeles to US$5,1 yr^{-1} in the USA as a whole. Extrapolation of such estimates indicates that the cost of increased salinities in domestic supplies of water runs into millions of dollars per annum both in the USA and elsewhere.

The cost of increased salinities in water supplied to industry varies according to the type of industry served. Those with stringent salinity criteria, eg electronic, textile and paper industries, are the most adversely affected (Table 4.5). Whatever the case, the cost of any increase in salinity, again, is very high. To take one example, a study undertaken in 1981 to establish what additional costs would be involved for both industry and power stations of the Pretoria-Witwatersrand-Vereeniging complex in South Africa if the salinity of water supplies rose from 300 to 800 mg l^{-1}, provided an annual estimate of R57 million. The present cost of salinity in water supplies for mining, industrial and commercial enterprises in Australia is currently estimated at A$10 million per annum (Peck et al 1983).

TABLE 4.4 World Health Organization criteria for water to be used domestically*

Mineral constituent	Highest desirable level (mg 1^{-1})	Maximum permissible level (mg 1^{-1})
Total dissolved solids	500	1500
Calcium	75	200
Magnesium	150 (30)**	150
Sodium	- ***	-
Sulphate	200	400
Chloride	200	600
Bicarbonate	-	-

* Source: World Health Organization (1971).
** Highest desirable level if sulphate level is higher than 250 mg 1^{-1}.
*** No level specified.

TABLE 4.5 Salinity tolerance for certain industries. Data from Todd 1970; Hart 1974

Application	TDS (mg 1^{-1})
Boiler Feed	
Low pressure boilers	1 000-3 000
High pressure boilers	50
Brewing and distilling	500-1 000
Canning	850
Food (general)	850
Paper and pulp	200-500
Rayon	100
Textiles	100

Increased salinities in agricultural water supplies exert an important impact in two ways. First, crop yields are depressed, and second, the hydraulic properties of soils are negatively affected. Three main factors can be distinguished: salinity, sodicity and toxic elements.

The deleterious effects of salinity are generally ascribed to retardation of plant growth as a result of an increase in the osmotic potential of soil water. In extreme cases, the soil might appear to be sufficiently wet for crop growth, although the plants are wilted. However, crop plants differ considerably in their response to salinity (Table 4.6). The salt sensitivity also differs during the various growth stages.

TABLE 4.6 Crop tolerance to increasing salinity in irrigation water. Electrical conductivity (EC) data expressed as $S\ cm^{-1}$

Crop	Expected yield reduction at EC indicated			
	0%	10%	25%	50%
Cotton (*Gossypium hirsutum*)	510	640	830	1200
Wheat (*Triticum aestivum*)	400	490	640	870
Corn (*Zea mays*)	110	170	250	390
Beans (*Phaseolus vulgaris*)	70	100	150	240
Orange (*Citrus sinensis*)	110	160	220	320
Apricot (*Pyrus ameniaca*)	110	130	180	250
Grape (*Vitus* spp)	100	170	270	450
Cabbage (*Brassica oleracea*)	120	190	290	460
Potato (*Solanum tuberosum*)	110	170	250	390
Onion (*Allium cepa*)	80	120	180	290
Alfalfa (*Medicago sativa*)	130	220	360	590

The effects of sodium are largely confined to soil aggregate stability, and to the colloidal properties of clay particles. If the exchangeable sodium level of soil exceeds a certain maximum concentration, dispersion or swelling of soil particles occurs, which in turn will impede infiltration and drainage.

Toxic elements are primarily boron, chloride and sodium, although the quality of certain fruit crops may be affected by carbonates if water is applied by a sprinkler.

Precise figures of the economic cost to agriculture resulting from increasing salinization are not available, but they are certainly immense. In Australia alone, it is estimated that productivity losses due to salinized land and expenditure on salinity control measures cost landholders some $22 million per annum (Peck et al 1983).

4.4.2 ENVIRONMENTAL IMPACT

To a very large degree, water managers have neglected to consider possible adverse environmental impacts resulting from salinization of inland waters. This may perhaps be viewed narrowly as of little consequence. It is important to stress therefore that many of the natural properties of water-bodies determine water quality, as well as their capacity to discharge certain functions. For example, the so-called 'assimilation capacity' of many rivers, ie the extent to which they are able to treat organic waste, is a function of their ecological balance. There are many cogent reasons why water managers should be concerned with environmental degradation caused by salinization.

In the broader perspective, the maintenance of aquatic ecosystems in as natural a state as possible has many values to commend it. There are considerable scientific, educational, cultural, recreational and ecological reasons why natural aquatic ecosystems should not be allowed to degrade as a result of salinization. Certainly in semi-arid regions, one could reasonably assume that the conservation of fresh waters in as natural a state as possible would be accorded a high priority for a number of reasons.

A major problem, still unresolved, concerns the extent to which aquatic ecosystems can absorb increased salt loads without damage or change to their structure, and without gross alteration to such processes as production, decomposition, and mineral recycling. Reports of damage are not plentiful, but now span a range of taxa and continents. It is of value to document some of them. In so doing, however, we draw attention to the paucity of data upon this most important matter, and the urgent need for research.

In <u>North America</u>, Miller et al (1981) noted that numerous fish kills (and the death of livestock) have been directly attributed to salt increases in waters of the Northern Great Plains of the United States and Canada (Montana, North and South Dakota and the Prairie Provinces). Of interest in this connection are the results of research on the impact of salt from road de-icing activities on streams in well-watered regions. Whilst early results suggested little impact at moderate salinities (Cl concentrations below 1 000 mg l^{-1}), they also suggested that effects begin at chloride concentrations above 1 000 mg l^{-1} (Crowther and Hynes 1977).

In <u>Australia</u>, the impoverishment of the fauna in the lower reaches of the Avon River in Western Australia has been attributed to salinization (Kendrick 1976). In particular, the large freshwater mussel (<u>Westralunio carteri</u>) common in the Avon until 1930 has now apparently been replaced by a small brackish-water mussel (<u>Anticorbula amara</u>). Likewise, in both this river and the Blackwood River (south of the Avon), the occurrence of <u>Sulcanus conflictus</u>, typically an estuarine copepod, is regarded as a result of salinization. The disappearance of the crayfish (Cherax tenuimanus) and the marron from the Blackwood may also have been brought about by salinity changes (though nutrient enrichment has also been implicated). In south-eastern Australia, the death of river red gums (Eucalyptus camaldulensis) on the River Murray floodplain has been attributed to salt damage.

In South Africa, it has been shown for the Fish and Sundays Rivers in the eastern Cape that salinity-intolerant diatom species are progressively eliminated with increasing salinity in the range from 500 to 2 000 mg l^{-1}. They are progressively replaced by species tolerant of such salinities and of salinity fluctuations. The aquatic macroinvertebrates of these rivers are also sensitive to salinity. Thus, in the lower reaches of the Sundays River, where total dissolved solids concentrations are generally in the range of 1 000 to 15 000 mg l^{-1} (Forbes and Allanson 1970a), an impoverished stream insect fauna is present, with rather fewer species than in comparable, less saline streams elsewhere. The few species present, for example the mayfly nymph of Cloeon crassi, have been shown to be remarkably tolerant of increases in the osmotic potential of the river water. Forbes and Allanson (1970b) have shown that C crassi is capable of effective osmoregulation over a TDS range from below 1 to 20% . But, however the incidence of nymphs at 15 000 mg l^{-1} (15°/°°) is low, which emphasises the need for extreme caution in any extrapolation of laboratory-determined salinity tolerances to tolerable field salinities.

The paucity of reports on environmental damage caused by salt in aquatic ecosystems partly reflects our inability to dissociate damage caused by salt from that resulting from other causes such as organic pollution or stream regulation. It also reflects the rather long timespan, perhaps several decades in some cases, over which damage of a rather subtle nature can occur. Lack of information on ecological conditions and salinity before possible salt damage is another explanation for the paucity of reports.

With regard to the subtle nature of salt damage to ecosystems, note that aquatic biota are known from inland waters over the entire range of salinity, viz less than 1 000 to more than 200 000 mg l^{-1}. However, so far as salinization is concerned, it is only those plants and animals which are found within the range 500 to ca 3 000 mg l^{-1} that are of principal interest, and, within this range, it seems likely that ecological effects often take the form of different species dominances and altered functional mechanisms in ecosystems.

Thus far, discussion has been confined to biological environmental impacts. However, a variety of non-biological environmental impacts may result from salinization. An interesting impact is displayed by certain rivers in Western Australia. They have reversed longitudinal salinity gradients: unlike the normal situation for rivers, it is their upper reaches which are most saline, their lower reaches least saline. Additionally, river pools may exhibit meromixis during summer. Both phenomena have been attributed to salinization.

Another non-biological impact results from the flocculation of suspensoids in fresh waters to which saline material is added. Greater nutrient availability and an increased photic zone may then lead to increased production of submerged plants.

Finally, attention is drawn to the severe environmental impact, both biological and otherwise, that may result from certain sorts of measures designed to mitigate salinization. The collection and storage of saline flows, for example, has a very obvious impact upon storage areas. The pulsed discharge downstream of saline waters, a form of intermittent pollution, will have strong adverse effects upon the ecology of aquatic organisms well beyond the actual time of discharge.

4.5 MITIGATION: SALINITY MANAGEMENT

Mitigation of salinization is more a matter for hydrologists, engineers and agriculturalists than for limnologists, but since mitigation measures themselves may have adverse environmental effects (see above) it may be useful for limnologists if a brief resumé of principal mitigatory measures is given.

4.5.1 THE ZERO OPTION

Although to 'do nothing' would not seem to warrant discussion, there is some merit in this strategy. By taking no action to reduce salinity levels, water quality itself acts as a regulator of socio-economic development in a catchment.

4.5.2 BULK DILUTION OF STORAGE WATER

This strategy is a very high risk aspect in that it relies upon the availability of large volumes of good quality water. Such water is not always available in arid and semi-arid environments, especially during periods of drought when the salinity of storage water is likely to increase due to surface evaporation. In addition, to dilute an impoundment will most likely involve eventual dumping of some stored water.

4.5.3 RELEASES OF FRESHENING WATER

This strategy is very similar to bulk dilution except that the aim is a short-term improvement in the salinity level of a flowing stream over a specific reach. There is some wastage of water but far less than in the bulk dilution of stored water. This strategy is successfully applied in several rivers of South Africa and elsewhere.

4.5.4 CATCHMENT MANAGEMENT

This strategy is widely used where target areas are defined. Four specific techniques involved are:

(a) Increase the efficiency of irrigation water distribution.

(b) Increase the efficiency of irrigation: By improving irrigation efficiency through the monitoring of the soil-water content, substantial reductions in the amount of irrigation water needed can be achieved. However, a build-up of salts in the soil will ensue. Flushing of these by large applications of water is required.

(c) Scheduled irrigation.

(d) Afforestation: In areas where a saline groundwater-body is present near to or at the surface, agricultural developments can be severely restricted. One solution is to afforest parts of the area in order to lower the ground water table sufficiently to allow shallow rooting crops to be planted. This is an important strategy in Australia.

4.5.5 OFF-CHANNEL STORAGE OF SALINE WATER

This strategy is confined to point sources of saline inflows including industrial effluents and well-organized drainage systems from irrigated land. Saline effluent diverted into an off-channel storage dam can be managed in the following ways:

(a) Stored until totally evaporated;

(b) Pumped to a ground water storage aquifer;

(c) Re-used for irrigating salt tolerant crops;

(d) Released into the river channel during floods or when downstream abstractions are <u>not</u> taking place;

(e) Used for fish farming or recreational purposes (see below).

4.5.6 DIVERSION OF SALINE INFLOWS

Saline streams which threaten the water quality of an impoundment or a sensitive stretch of river can be diverted to a point in the system where water quality is of negligible concern.

4.5.7 DESALINATION

Desalination technology is advancing rapidly. However, its cost and the problem of brine disposal still places this strategy outside the realms of the 'best practicable means' for dealing with saline effluents.

4.5.8 EXPORT OF SALINE EFFLUENTS FROM THE CATCHMENT

The construction of long-distance pipelines to transport saline effluents from specific catchments to the coast has for a long time been considered a management strategy. However, the cost for such a pipeline has never been justified in terms of improved water quality. If desalination becomes a viable technique for ameliorating saline effluent, then a pipeline may be economic.

4.5.9 EFFLUENT DISCHARGE CONTROL

This can be achieved in one of three ways. Firstly, restrictions can be placed on the development of saline effluent producing activities. Secondly, such activities can be abandoned or modified to produce a less saline effluent.

Thirdly, effluent discharges can be controlled by the formulation and enforcement of quality standards. There is, however, controversy on fixed standards and the issuing of permits allowing the exceedance of the standard. It has been suggested that regional or even catchment specific standards should be adopted which reflect the natural background salinities in a river, the economic problems facing certain industries, the water quality requirements of downstream abstracters, and environmental considerations. A balance between these considerations is not easily arrived at.

4.5.10 MULTIPLE LEVEL WITHDRAWALS FROM AN IMPOUNDMENT

In certain deep reservoirs which experience minimum turbulence, a saline inflow may not necessarily mix with the stored water. Saline water (which is more dense) tends to flow underneath the stored water and accumulate at deep points behind the dam wall. In such cases the potential exists to 'bleed' off this saline water and discard it before it contaminates the better quality stored water.

4.5.11 SEGREGATION OF SALINE AND NON-SALINE WATERS

This is a widely adopted strategy which maximizes water distribution and storage efficiency. It can be expensive in terms of canal construction, but the level of productivity resulting from the supply of high quality water often justifies the expenditure. The segregation can be at two stages: distribution and storage.

4.6 UTILIZATION OF SALINE WATER

Salinization is usually regarded as a deleterious phenomenon, and, indeed, this is almost always the case, both from an ecosystem viewpoint and the viewpoint of consumers. It should not be forgotten, however, that saline waters are not without value and suitable management of saline waters can realize this. Only some of the more obvious of these values are considered here.

4.6.1 VALUE FOR AQUACULTURE

Acclimation and breeding in several countries (but notably Israel) has demonstrated that a variety of edible fish can be cultured in waters of slightly higher salinity than those in which they normally occur. Whilst aquaculture is of limited importance in some countries where salinization is significant (USA, Australia), clearly this value may be capitalized on elsewhere.

4.6.2 VALUE FOR IRRIGATION

Likewise, various experimenters (notably Israel), have demonstrated that acclimation and artificial selection can produce genetic lines of several plant species of economic importance which can tolerate considerably higher salinities than they do under natural conditions.

The potential for particularly exciting progress in this area is provided by recent advances in genetic engineering. Geneticists are now able to isolate and transfer genetic material which confers halotolerance from uneconomic halophytes to economic plants which have naturally low halotolerance. Indeed, it has been suggested that a wiser investment of Government finance would be to support biotechnological programmes of this sort than to attempt expensive engineering programmes designed to maintain salinity levels tolerable to present crop species.

4.6.3 VALUE OF HIGHLY SALINE WATER

Several plant and animal products derivable from highly saline waters are of commercial interest and value. They include, most notably:

β-carotene) from *Dunaliella*
Glycerol)
Artemia cysts
Spirulina

β-carotene is of particular value in the food industry as a colouring material and a source of pro-vitamin A. Glycerol, likewise, is of significance in the food industry (but has many other important uses too). *Artemia* cysts are of great value as a food for fish fry, and hence attract attention from aquaculturalists. *Spirulina*, a blue-green alga, has a significantly high protein content. It has been used as a source of food by natives of Africa and Mexico. More recently its value as an inhibitor of appetite has been recognized. The commercial development of biological material in highly saline water probably has particular applicability with regard to certain mitigation measures (see previous section).

Heliothermal ponds are a non-biological use of highly saline water-bodies.

4.7 RESEARCH NEEDS

There is much urgent research needed to enable better understanding and resolution of problems of an agricultural, hydrological and pedological sort. Such research needs, however, require no documentation by us. We confine ourselves to limnological research needs. Four needs are urgent and obvious, and in order not to distract attention from them, only they are listed below:

a) Investigation is needed to determine the nature and extent of environmental damage resulting from the salinization of inland waters.

b) There is an early need to determine salinity criteria to protect aquatic ecosystems so that environmental as well as other beneficial uses of inland waters are protected.

c) Investigation is needed to determine the relationship between salinity and ecosystem function and structure.

d) Research is needed to determine the significance of LD_{50} salinity values derived in the laboratory to the field situation.

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CHAPTER 5 TURBIDITY AND SUSPENSOIDS

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5.1 INTRODUCTION

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5.2.2 Behaviour of particles in suspension

5.3 TURBIDITY AND THE OPTICAL PROPERTIES OF WATER

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5.3.3 Relationship between turbidity and light absorption
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5.1 INTRODUCTION

'Turbidity' is used in a general sense to indicate the extent to which water lacks clarity. Visually, it is perceived as the degree to which the visible underwater light field is either directional, when the water appears clear; or diffuse, when the water appears cloudy. Used in this way 'turbidity' may be regarded as a measure of the extent to which the liquid scatters light. Quantitatively it may be expressed in terms of the scattering coefficient, or some empirical but easily measurable parameter related to it, such as nephelometric turbidity.

Scattering of light in natural waters is due almost entirely to suspended solids (suspensoids), and the term 'turbidity' has sometimes in the past been applied to the concentration of suspended material, as determined by any one of a number of physical procedures. The units of turbidity were originally expressed as parts per million of suspended solids, a suspension of known concentration of some specified particulate material being used as the standard. The shortcomings of this approach result from the fact that while, for a given solid, turbidity readings and concentrations are generally linearly related, quite different turbidity readings may result from the same concentration of different kinds of solid particles. Thus it is now accepted that turbidity should be regarded as an optical property of the medium, rather than a direct expression of the concentration of suspended solids.

Turbidity is of fundamental significance in natural waters, not merely because of its effects on visual appearance but because the resultant light scattering can have profound effects on penetration of solar radiation with implications for the thermal properties and primary productivity of a water body. In addition, an understanding of the processes governing the distribution and transport of suspensoids in lakes and rivers is important in the solution of modern water quality problems. Nutrients, heavy metals, pesticides and other toxins preferentially adsorb to suspensoids; and are transported in this form.

Our aim in this account is to provide the scientific background upon which to base decisions on water management problems involving turbidity. The account does not aim to offer particular solutions since these must be specific to the problems involved.

5.2 THE ORIGIN AND NATURE OF SUSPENSOIDS

We consider here the origin of the suspended particles in Southern Hemisphere inland waters, and those physico-chemical characteristics which are of relevance to both their optical and adsorptive properties. Their behaviour such as sedimentation and aggregation within the water is also discussed.

5.2.1 SOURCES AND CHARACTERISTICS OF SUSPENSOIDS

The watershed, airshed, aquatic organisms and physico-chemical conditions within lakes and rivers all influence the nature of the suspended material. In turn, physical and chemical characteristics of the suspensoids significantly affect the fate of most chemical constituents such as trace metals, nutrients and halogenated hydrocarbons. Mean size, size distribution, specific surface area, surface charge and chemical composition are basic properties required to characterize suspensoids (Huang 1978).

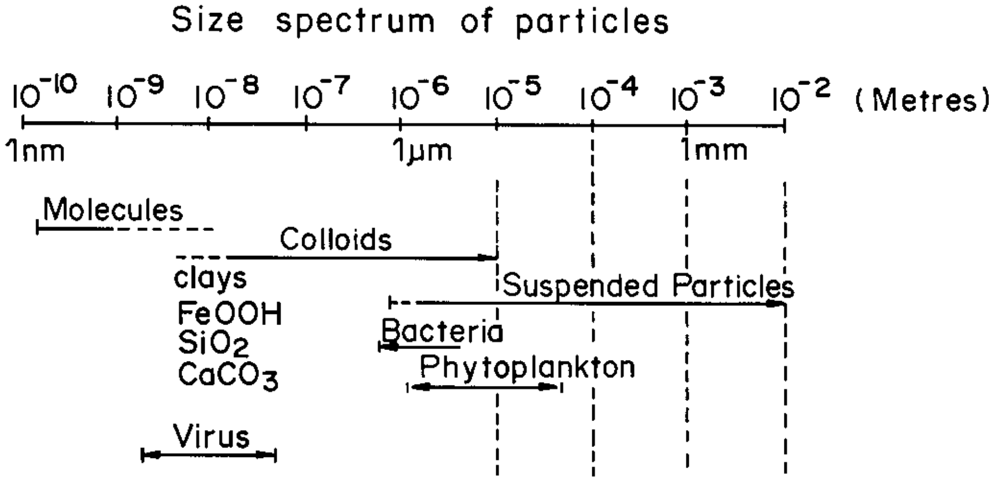

FIGURE 5.1 Size spectrum of particles dissolved or suspended in natural waters expressed as particle diameter in metres (After Stumm 1977).

Figure 5.1 illustrates the size spectrum of most particles dissolved and suspended in inland waters; the particles larger than about 0,1 μm contribute to turbidity. The size distribution (n(d)) of aquatic suspensions usually follows a power law of the form:

$$n\ (d) = Ad^{-\beta} \qquad 1$$

where A = a coefficient related to the concentration of suspensoids
d = diameter.

For particles greater than about 1 μm in size, ranges from 2 to 5 (Stumm and Morgan 1981). Measurements of particle size can be made with a variety of optical, gravimetric and electronic techniques.

Most interactions of solutes and suspensoids occur at the surface of the particles, and therefore, their surface area is of special importance. The specific surface areas of some common particles are listed in Table 5.1. Surface charge is another property that influences adsorption of dissolved material, coagulation and feeding by aquatic organisms. At near-neutral pH's the surface charge of suspensoids is negative; changes in pH and ionic strength alter the electrophoretic mobility of those particles. Two measures of the adsorption potential of suspended particles are the distribution coefficient and ion exchange capacity. The distribution coefficient is a ratio of the amount of a solute attached to a solid and the amount in solution. Large differences of this coefficient occur, depending on the individual solute, and are related to the ionic strength and chemical composition of the medium (Lerman 1979; Simpson et al 1980).

Some representative values are given in Table 5.2. Ion exchange capacity varies by almost three orders of magnitude among common materials (Table 5.3).

Suspended matter is usually composed of inorganic and organic fractions which depend upon the source and history of the particles. The inorganic fraction consists largely of detrital rock fragments (eg quartz, feldspar, mica), oxides and clays. The great variety of organic matter reflects its biological origin (Riley 1970; Cauwet 1978; Seki 1982). Natural processes such as weathering, erosion, volcanism and biosynthesis, and human activities such as sewage discharge, dredging and agricultural and mining operations contribute to suspensoid loads. Atmospheric deposition can be significant (Andreae 1983). Sediment suspension (Fukuda and Lick 1980), chemical precipitation (Strong and Eadie 1978) and flocculation (Scholkowitz 1976; Johnson 1976; Paerl 1975) are also important in some situations.

TABLE 5.1 Specific surface area of common suspended particles. (After Huang 1978)

Solid	Specific surface area m^2/g^{-1}
Quartz	5 - 10
Al_2O_3	100 - 200
Fe_2O_3	16 - 35
Calcium carbonate	10 - 20
Smectite	750 - 800
Kaolinite	15 - 25
Sediments (Lake Kinneret)	122 - 242
Organic matter	500 - 750

Data for inland waters of the Southern Hemisphere are insufficient to characterize the suspensoids in terms of the basic properties explained here. Qualitative regional comparisons are possible and useful. In New Zealand an especially large variety of suspensoids occur. Glacial till, an extremely fine, grey material, enters lakes in the glaciated uplands of the South Island. Allophane - rich pumice, common on the volcanic plateau of the North Island, has a very high adsorption capacity, particularly for phosphate. Clays dominate the turbidity in other regions, eg southern part of North Island. Geothermal lakes can contain colloidal sulphur. In Australia, the Amazon and southern Africa inorganic suspensoids are owed primarily to clays. The origin of these clays is primarily sandstones in Australia and the Karoo mudstones and shales in South Africa.

TABLE 5.2 Distribution factor (Cs/C) for some chemical species in oceanic and freshwater sediments (Distribution factor dimensionless, concentration in solids Cs and in solution C are in units of mass per unit volume of solution). (After Lerman 1979)

Chemical species	Distribution factor	Notes
Cs	3 500 - 10 000	^{137}Cs in freshwater sediments
Na	0,3	Sea water and clays
Na	2	Freshwater sediments
NH_4^+ - NH_3	3	Anoxic marine sediments
Phosphate	8	Sea water and clays
Sr	45 - 120	^{90}Sr in freshwater sediments

TABLE 5.3 Cation exchange capacities of natural materials, arranged in a decreasing order of upper-limit values. (After Lerman 1979)

Cation exchange capacity (meq/100 g)	Material
350 - 130	Organic matter
300 - 100	Zeolites
260	Hydrous manganese oxide
150 - 100	Vermiculite
100 - 70	Montmorillonites (typical)
60 - 20	Micas from soils
40 - 10	Illite
15 - 3	Kaolinite
1	Feldspar, quartz

Phytoplankton are very abundant in eutrophic lakes throughout the hemisphere and can make an important contribution to the turbidity.

5.2.2 BEHAVIOUR OF PARTICLES IN SUSPENSION

The length of time particles remain in suspension depends on their settling rate which is a function of their size and the hydrodynamics of the medium. Hydrologic conditions such as floods can have a significant effect in some situations. The size distribution of particles is a basic property of a natural suspension (Figure 5.1), and so must be measured. However, particle sizes can change as a result of aggregation. The electro-chemical environment influences this and it is also time-dependent. This behaviour can, in part, be modelled. The rate of aggregation depends on the frequency of collisions and on the proportion of particle contacts that lead to permanent union. These must be determined experimentally.

The frequency of collisions is largely a consequence of three mechanisms of particle transport: Brownian motion, shear and differential settling rates. Each of these mechanisms can be expressed by a tractable equation with measurable terms (Stumm and Morgan 1981). Hunt (1980) used this system of equations to derive successfully the particle size distribution of natural assemblages. O'Melia, (1980) presented a hypothetical model of the distribution of particle sizes and volumes in a lake receiving a riverine inflow with and without size-dependent coagulation. Although preliminary, O'Melia's example illustrates the potential for a combination of a few measurements with a physical model to predict the distribution of particles in a lake. The most difficult term in the model to measure is the shear gradient. Furthermore, the implications of the turbulence spectrum for the residence time of suspensoids is not included (see Denham and Gargett 1983)

Additional processes can cause aggregation of particles and, in consequence, alter their residence time in suspension. In situations where freshwater inflows mix with saline water, formation of flocs is enhanced (Scholkowitz 1976; Mulholland 1981). Dissolved organic matter can adsorb to surfaces such as bubbles or inorganic particles and then form aggregates several microns to several millimetres in diameter (Riley 1963; Johnson 1976). Furthermore, attachment of microorganisms to small particles can result in their aggregation into larger particles (Paerl 1974). Zooplankton egest between 40% and 80% of what they eat, and fecal pellets are often a significant fraction of detritus and usually sink rapidly (Turner and Ferrante 1979). Incorporation of those processes into models of suspensoids' residence times has yet to be done but is a requirement for an improved evaluation of the distribution and transport of particles in lakes and rivers.

5.3 TURBIDITY AND THE OPTICAL PROPERTIES OF WATER

Although we have defined turbidity as a visual optical property the contribution of suspensoids to the fundamental optical properties of the water is more complex. Since the capacity of suspensoids to both scatter and absorb light has important implications for the thermal properties and primary productivity of a water body, this section will consider how best to measure turbidity, the relationship between empirical turbidity and true scattering coefficient, and light absorption by suspensoids.

5.3.1 MEASUREMENT OF TURBIDITY

Since turbidity is to be used to provide an index of the light scattering properties of water, it should be measured by a procedure which makes use only of light scattering and not of some combination of scattering and absorption as is the case with some procedures (eg use of a beam transmissometer, or the old Jackson candle turbidimeter). A satisfactory approach is that utilized in modern photoelectric turbidimeters which use nephelometry, ie they give a reading proportional to light scattering by the sample at some fixed angle, usually 90°. Figure 5.2 shows a typical experimental configuration. The turbidity value is expressed in terms of the empirical, but now widely accepted, Nephelometric Turbidity Units, or NTU (equivalent to Formazan Turbidity Units, FTU, corresponding to a certain concentration in water of the light-scattering polymer, formazan).

To obtain a simple visual comparison of clarity of different waters the Secchi depth (that depth at which a disc with black and white quadrants lowered into the water just disappears for an observer above the water) has some role. It must, however, be realized that the reciprocal of the Secchi depth is not a linear function of, although it is greatly affected by, turbidity. It is in fact approximately proportional to the vertical contrast attenuation coefficient, K_c, which is the sum of the beam attenuation, $\underline{c}$, and the vertical attenuation coefficient for irradiance, K_d (Kirk 1982).

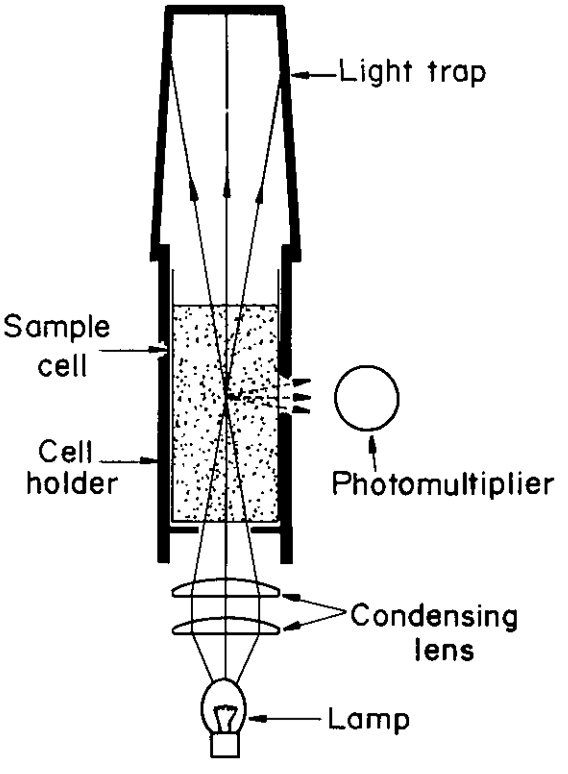

FIGURE 5.2 Schematic diagram of optical system of nephelometric turbidimeter (After Kirk 1983).

5.3.2 RELATIONSHIP BETWEEN NEPHELOMETRIC TURBIDITY AND SCATTERING COEFFICIENT

To understand the effect of a given level of suspended particles on penetration of solar radiation we need to know to what extent the inherent optical properties of the water are modified. Nephelometric turbidity itself, T_n, is a purely empirical quantity which cannot, as such, be used in modelling calculations of the underwater light field. Given, however, that nephelometric turbidity is a measure of the scattering at (usually) 90°, and given also the fact that the volume scattering function (in effect, the angular distribution of single-event scattering) has much the same shape in all except the very purest natural waters, then there are good a priori grounds for expecting nephelometric turbidity to be linearly related to the total scattering coefficient, (an inherent optical property) $\underline{b}$. Thus, if we know the relationship between nephelometric turbidity and scattering coefficient, then the latter can be calculated from the former (Kirk 1981). The significance of this is that to measure the scattering coefficient directly is difficult, whereas measurement of turbidity is easy.

The relationship between the two quantities has not yet been determined by any absolute procedure, but two independent indirect procedures using modelling of the light field have provided values of 0,92 and 1,1 respectively, for the factor by which a measured nephelometric turbidity in NTU should be multiplied to give an approximate estimate of the total scattering coefficient. Conveniently, these average to about 1,0. Thus while direct determination of the relationship is of course desirable, until it is forthcoming, the value of T_n, in NTU, can be taken to be approximately equivalent to the value of $\underline{b}$, in m^{-1}.

5.3.3 RELATIONSHIP BETWEEN TURBIDITY AND LIGHT ABSORPTION

The particles responsible for turbidity in natural waters invariably absorb, as well as scatter, light and in turbid waters this can contribute substantially to total light absorption. This is particularly the case for particles which are brown due to the presence of humic materials, or for living phytoplankton cells containing photosynthetic pigments. To understand, and in particular, to model the penetration of solar radiation into water, values of the total absorption coefficient, (an inherent optical property) $\underline{a}$, across the appropriate spectral range are required.

In the absence of instruments which can directly determine the total absorption coefficient, values of the partial absorption coefficients due to dissolved colour and particulate colour must be separately measured and added to the appropriate known value of the absorption coefficient for pure water, at each wave length. Absorption by the soluble fraction is readily measured on a filtrate (0,22 or 0,45 μm) by standard spectrophotometry, (albeit using long-pathlength, 5 cm or 10 cm cells), but measurements of particulate absorption requires special techniques (Kirk 1975, 1976b, 1980). It will generally be necessary first to concentrate the particulate fraction by filtration and resuspension in a smaller volume. The absorption spectrum of the concentrated suspension must then be measured by a technique which overcomes the errors that inevitably occur in normal spectophotometry of scattering samples. Three suitable techniques (depending on the spectrophotometer) are: use of an integrating sphere, placing the sample cell very close to the photomultiplier, and use of the opal glass procedure (Shibata 1959).

In our typically turbid Southern Hemisphere waters, the particulate fraction will frequently, perhaps even usually, be the major light-absorbing component (Figure 5.3), and so despite the technical difficulties, these measurements must be carried out if understanding is to be achieved.

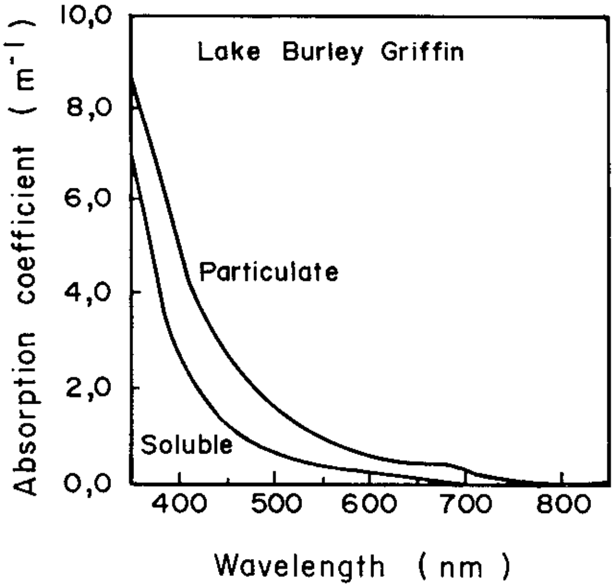

FIGURE 5.3 Spectral absorption properties of the soluble and particulate fractions of Lake Burley Griffin, ACT, Australia. Turbid coloured water; suspensoid fraction mainly tripton. (After Kirk 1980). The curves correspond to the true in situ absorption coefficients for the fractions in question.

5.3.4 CONTRIBUTION OF LIVING SUSPENSOIDS TO THE OPTICAL PROPERTIES OF WATER

The factors that attenuate light in lake water can be divided into four main groups: water itself, dissolved or colloidal (or both) organic coloured substances (gilvin), inorganic turbidity and living suspensoids (mainly phytoplankton except where large populations of coloured bacteria develop, eg photosynthetic bacteria). The influence of these factors on photosynthetically available radiation (PAR, 400-700 nm) is predominantly of interest here. Water itself absorbs mainly outside the PAR region. Gilvin has its major effects also outside this region and mainly absorbs in the ultra-violet region. The effects of inorganic suspensoids on the optical properties of water are given above. Phytoplankton cause light in the blue region of the spectrum to be rapidly attenuated while light in the green (approximately 550 nm) is least attenuated. An additional absorbance peak also occurs at about 680 nm.

Figure 5.4 shows the general relationship found by many workers between the coefficient of the most penetrating component of the light spectrum (green light) and chlorophyll a concentration for systems in which inorganic turbidity is not high. As the attenuation coefficient increases the euphotic zone depth (the depth to which one per cent of the subsurface value of PAR penetrates) decreases. Thus in hypertrophic lakes with large algal standing crops primary production may be contained in very shallow euphotic zones analogous to the situation found in lakes with high inorganic suspensoids (see Figure 5.8). Scatter about the line in Figure 5.4 can be considerable, especially in systems with very high algal standing crops composed of buoyant blue-green algae. Much of this variance can be ascribed to poor estimates of light attenuation since in such systems large variations in algal standing crop can occur over very short time scales. Localized turbulence about a light sensor and lowering harness can also artificially improve light penetration. In addition, variation can occur at low chlorophyll concentrations due to increases in organic turbidity or to dissolved or colloidal organic coloured substances.

Kirk (1975 and 1976a) has theoretically demonstrated that different algal cell shapes have varying effects on light attenuation. Changes in colony size of the blue-green alga, Microcystis aeruginosa, can cause significant changes in the light intensity at a given depth, in the vertical attenuation coefficient, in the increment of attenuation coefficient per unit algal concentration (approximating the slope in Figure 5.4), in the depth of the euphotic zone and in the algal standing crop that can be sustained within the euphotic zone. Recently, Robarts and Zohary (1984) have demonstrated, as predicted by Kirk (1975, 1976a), that even at chlorophyll a concentrations as high as 1 500 mg m^{-3} increasing colony size moderated light attenuation leading to an increased euphotic zone depth and a decreased incremental increase of light attenuation per unit concentration of algae. This is shown in Figure 5.5. The buoyancy mechanism of blue-green algae which allows them to move to higher light intensities in the water column, and the size changes of colonial forms, gives these organisms a strong ecological advantage during periods of low wind induced mixing in natural waters where light is rapidly attenuated by algae. The artificial destratification of a lake may offer a viable management option to reduce the growth of buoyant blue-green algae.

5.4 EFFECTS OF SUSPENSOIDS ON AQUATIC ECOSYSTEM

Having considered the physico-chemical characteristics of suspended particles and the ways in which they change the inherent optical properties of the water, we now examine what effects the particles in turbid waters have on the behaviour of the aquatic ecosystem. In particular, we consider turbidity-related effects on penetration of solar radiation and the consequent changes in thermal behaviour and in primary production. We also discuss the effects of suspensoids on the zooplankton, and the significance

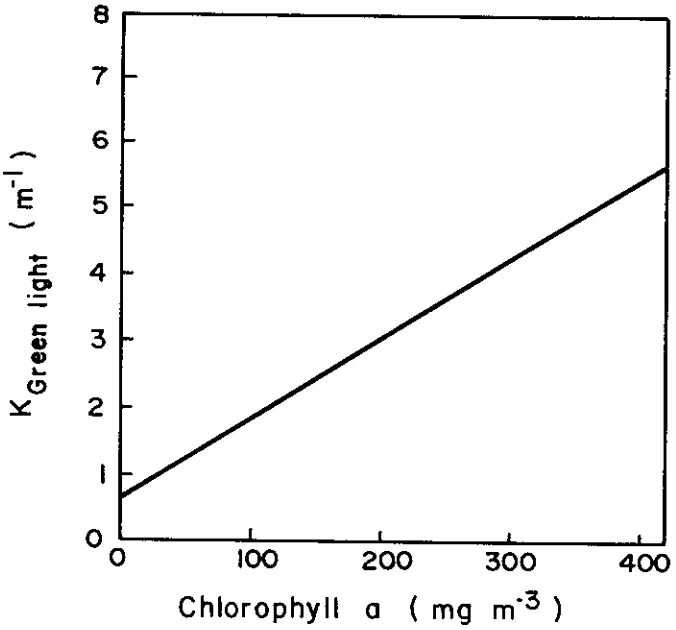

FIGURE 5.4 The relationship between the vertical attenuation of green light (550 nm) and the mean concentration of chlorophyll a in the euphotic zone of a hypertrophic lake. The dominant phytoplankton was the colonial blue-green alga, *Microcystis aeruginosa* (After Robarts and Zohary 1984).

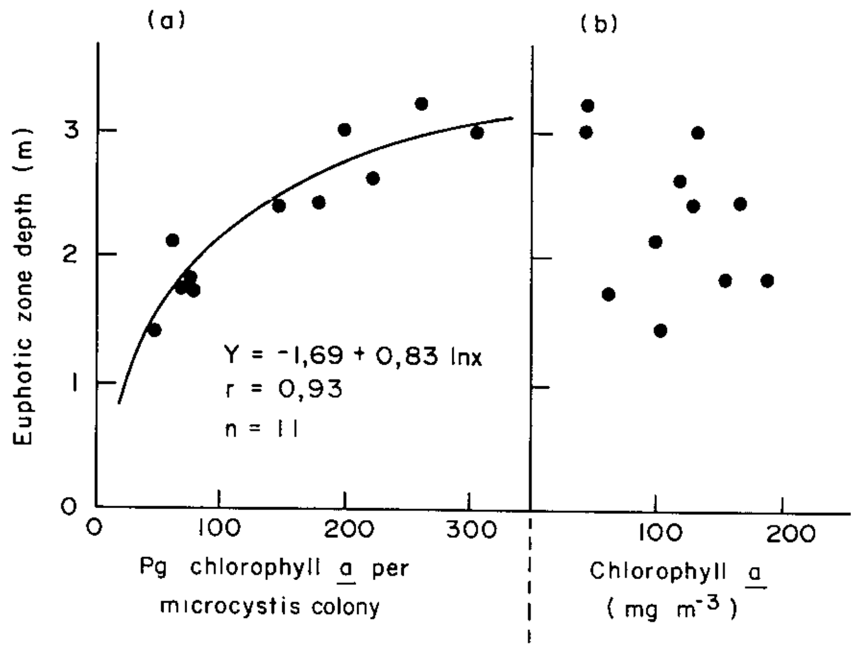

FIGURE 5.5 (a) The relationship between euphotic zone depth and mean *Microcystis aeruginosa* colony size (expressed as chlorophyll a content per colony) in Hartbeespoort Dam, Republic of South Africa.

(b) The relationship between euphotic zone depth and chlorophyll a concentration for the points given in Figure 5.5(a). No significant relationship was found. (After Robarts and Zohary 1984).

of particles for the transport of nutrients, organic compounds and microorganisms within the system. Some specific problems that turbidity presents to water managers concerned in the supply of water for domestic, industrial and agricultural use, or for use in biological conservation are considered.

5.4.1 TURBIDITY AND PENETRATION OF THE SOLAR FLUX

There are only two things that can happen to solar photons within water: they can be absorbed or scattered. The progressive removal of the photons from the downwelling stream by absorption is the main mechanism responsible for the approximately exponential attenuation of downward irradiance with depth. Many of the photons, the majority in turbid waters, are scattered one or more times before they are absorbed. This has two effects. One is to make the solar beam more diffuse, and in this way, increase the average pathlength the photons must travel in traversing a given depth, thus increasing the probability of their being absorbed within that depth. The other is to remove some of the photons from the downwelling stream by scattering them upwards. Thus in turbid waters the rate of attenuation with depth is particularly high, not only because of the light absorption by the suspensoids themselves, but also because of the increased attenuation due to scattering. The scattering effects will commonly increase the vertical attenuation coefficient for the photosynthetic waveband by 20-200% (or more in very turbid waters) above that expected on the basis of absorption alone.

The effects on penetration of solar radiation brought about by changes in the absorptive and scattering properties of the water can readily be calculated by means of appropriate modelling procedure, provided the absorption and scattering coefficients are known (Kirk, 1984). In turbid waters the high attenuation due to suspended particles means that the upper layer (euphotic zone) in which there is sufficient light for photosynthesis, and in which essentially all the solar heating occurs, is very shallow. The far-reaching implications of this for the primary productivity and thermal behaviour of the water are considered later.

The underwater light field within the euphotic zone in turbid waters is more diffuse than in clear water because of the high scattering. In such water, to measure the absolute amount of light available for photosynthesis at a given depth, it is desirable to use a scalar irradiance meter, which integrates the total radiation coming from all angles. However, to determine only the vertical attenuation coefficient for photosynthetically available radiation, then a simple, upward facing, flat irradiance collector will suffice, since the vertical attenuation coefficient for scalar irradiance is approximately the same as that for downward irradiance (Kirk 1983).

5.4.2 TURBIDITY AND THERMAL PROPERTIES

The thermal budget of a lake or stream is determined by the heat fluxes at the surface and bottom, and the advection of heat by inflow and outflow. Losses through the bottom are, in most cases, insignificant, and advective heat transport is unaffected by turbidity; the principal effect of turbidity on thermal behaviour is therefore by means of the surface heat exchanges.

The next heat flux through the surface may be simply expressed in terms of the most important of the surface inputs and losses. Thus the net flux of heat into the water surface Q is given by

$$Q = (1- \alpha)Q_I + Q_A + Q_W - Q_S - Q_E \qquad 2$$

where α = the surface albedo
Q_I = the incident solar radiation
Q_A and QW = the atmospheric and water surface radiation
Q_S and Q_E = the sensible and evaporative heat losses.

Of these fluxes, only the first results in sub-surface heating, with the radiation attenuation being described by the usual exponential decay,

$$q(z) = (1 - \alpha) Q_I e^{-Kz} \qquad 3$$

where q(z) = the radiation flux at depth z and K an attenuation coefficient.

The albedo, α , is a function of sun inclination, wavelength of incident light, and surface wave activity; K is also a function of wavelength. Bulk values of both parameters are frequently used, and will serve to illustrate the effect of turbidity in general terms.

Both α and K are functions of turbidity, but the principal effect of turbidity is on K which increases from values of the order of 0,1 m^{-1} to values of the order of 7 m^{-1} or higher with increasing turbidity. The effect of this is to redistribute the absorption of radiation towards the surface, increasing, in the absence of other effects, surface heating at the expense of sub-surface heating.

Typical temperature profiles resulting from the same incident radiation impinging on the initially uniform water column in both clear and turbid lakes are shown in Figure 5.6. As increases in temperature result in density decreases, the result of this redistribution of radiation absorption is a lowered centre of gravity, or increased stability, of the water column.

This effect is modified by other factors. Both sensible and evaporative heat losses are influenced by surface temperature; the simple bulk parameterization of these fluxes as given by TVA (1972) indicates that with increasing surface temperatures and fixed atmospheric conditions, these fluxes of heat from the surface increase and some of the additional surface heating effect is lost. On balance, however, the net result of increased turbidity is a temperature distribution similar to that shown in Figure 5.6. Because of the increased losses at the surface the total heat content of the water column is less for the turbid case, even though its stability is increased.

The increased stability means that more energy is required to mix a given depth of the water column in a turbid lake than in a clear lake. If only the energy made available from stirring of the surface by the wind is considered, then the wind required to mix a given depth increases with increasing turbidity. Both Q_S and Q_E, however, also increase with increasing wind speed as well as turbidity, and the additional energy may be made available by surface cooling and subsequent convective overturn.

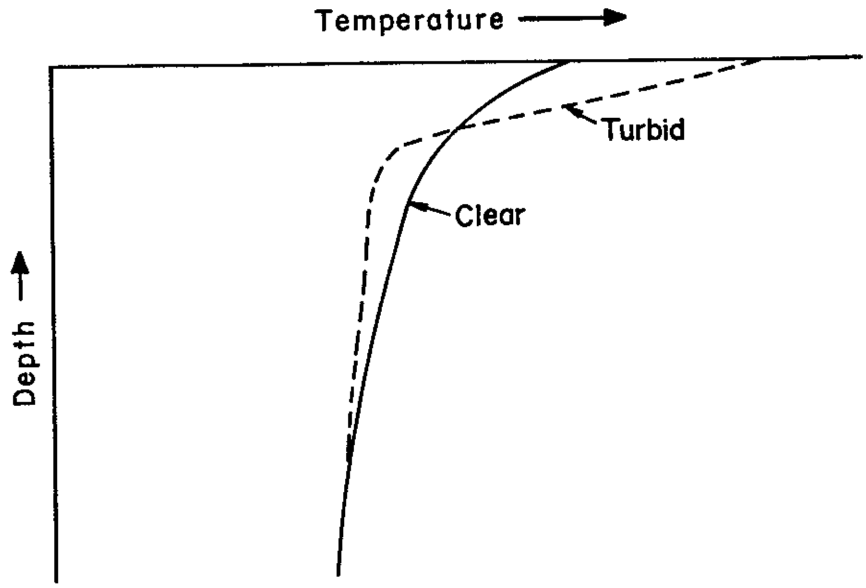

FIGURE 5.6 Typical temperature profiles resulting from radiation penetrating an initially thermally uniform water column of clear (———) and turbid (-----) water.

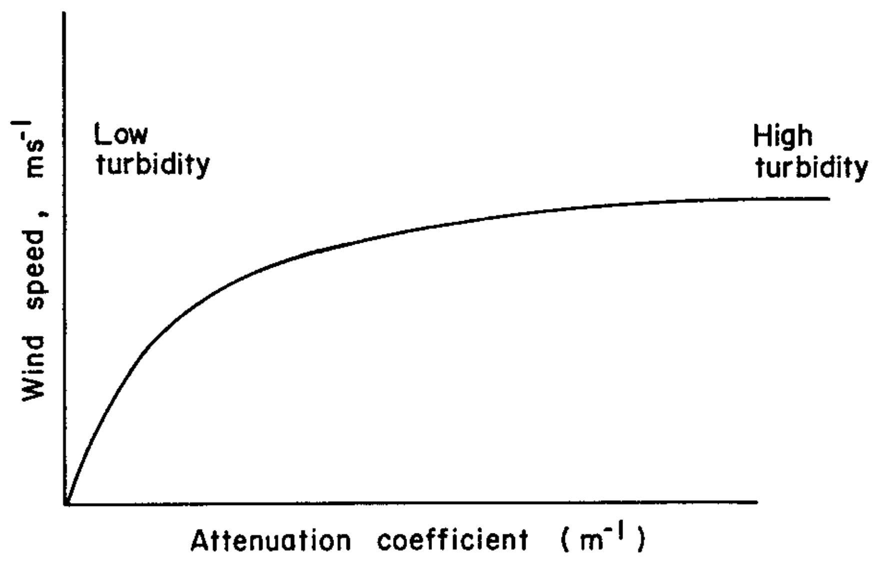

FIGURE 5.7 The critical wind speed required to mix an initially uniform water column of given depth as a function of attenuation coefficient.

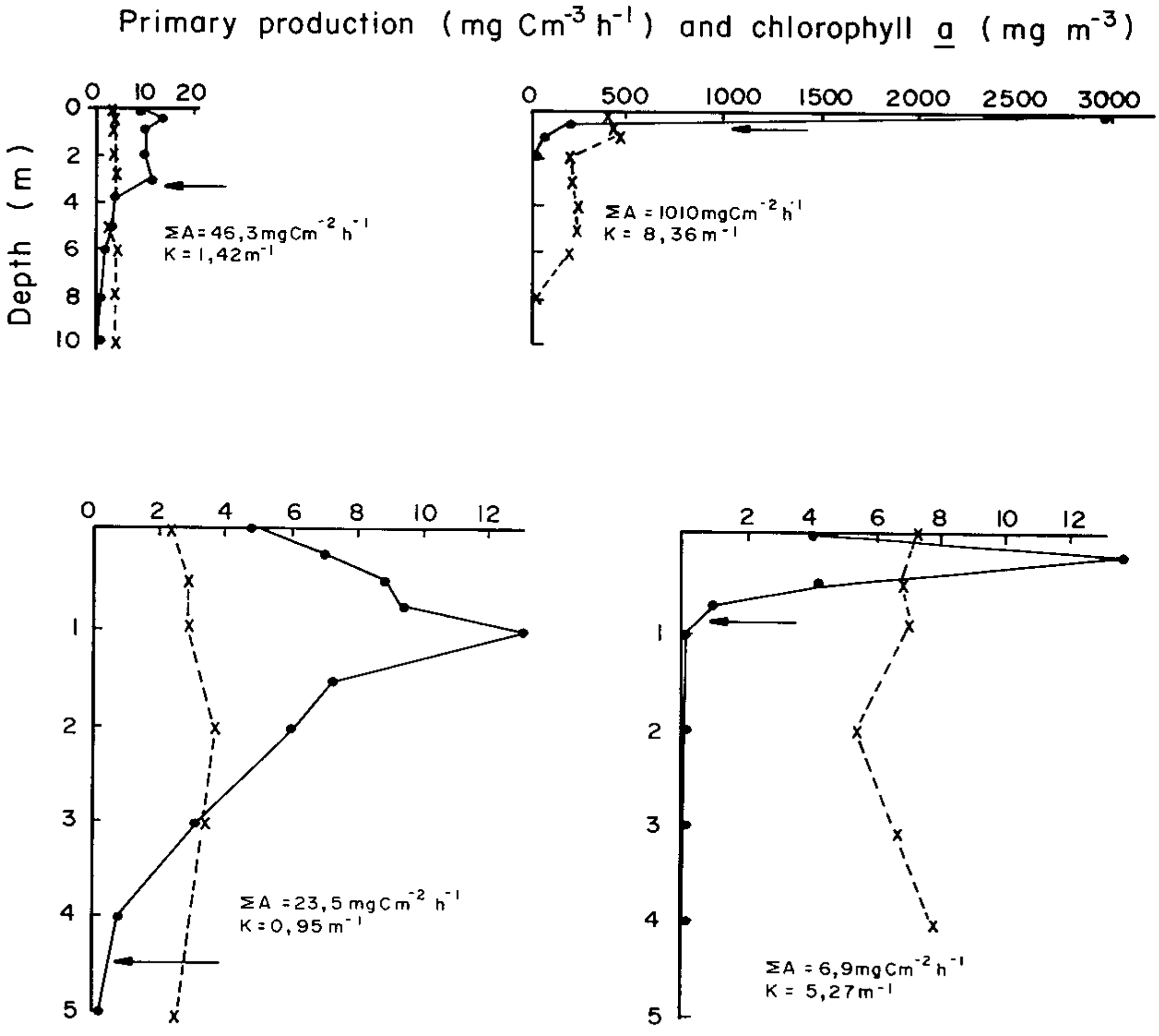

FIGURE 5.8 Primary productivity-depth profiles to show the vertical compression of the profiles with increasing algal biomass (1 and 2) and increasing inorganic turbidity (3 and 4). Arrows indicate the lower limit of the euphotic zone, x = chlorophyll a concentration and • = primary production. Data from Hartbeespoort Dam, 1 and 2 (After Robarts and Zohary 1984), Lake Midmar, 3 and 4 (E G J Akhurst, unpublished data).

This may be expressed in terms of the minimum wind speed necessary to retain a mixed layer at a given depth as a function of K, for fixed solar radiation intensity. Initially, the required wind speed increases rapidly as K increases. With increasing wind speeds the energy made available for mixing from surface stirring, together with the increased influence of Q_S and Q_E, become sufficient to offset the effects of increasing K, and the rate of change of the required wind speed reduces, ultimately becoming asymptotic to a fixed value. This dependence for a typical case is shown in Figure 5.7. Similar behaviour has been documented by Holloway (1980).

Consider now the influence of suspensoid gradients in the lake. The presence of suspensoids affects water density: suspensoid gradients therefore generate density gradients. The relationship between suspensoid concentration and density depends on the type and size distribution of the suspended particles, which also influence the rate at which the particles settle. Thus a density gradient generated by a gradient in suspensoid concentration is continually changing as the suspended solids fall with gravity. This mass transport occurs over time scales shorter than those associated with weak turbulent mixing events with the result that the turbidity gradient, in relatively quiescent conditions, changes more rapidly than other density influencing parameters. Thus the density gradient may shift from one dominated by suspensoids to one dominated by, for example, temperature. The result may be unstable, resulting in mixing.

For example, a turbid river inflow into a lake may be warmer than the lake water, but its suspensoid load may increase its density sufficiently to negate the effect of the increased temperature. The river will plunge below the stored water, depositing some suspended solids but also resuspending others from the river bed. At some point, a level of equal density is reached and the inflow intrudes horizontally into the lake. This flow is considerably less turbulent than the plunging inflow, and the sediment load begins to fall out without being replaced. At some stage, sufficient suspensoids are removed to decrease the intrusion density to the point of instability and vertical mixing results.

5.4.3 TURBIDITY AND PRIMARY PRODUCTIVITY

(a) Phytoplankton: Phytoplankton primary productivity has a direct bearing on the structure and functioning of aquatic ecosystems since it forms the base of most food chains. This section will assess the extent to which suspensoids may influence primary productivity through their capacity to modify light attenuation. Their role in nutrient transport is considered in section 5.4.5.

Turbidity influences both the quantity and the quality of light penetrating water and determines the depth of the euphotic zone. The vertical distribution of algal primary productivity is similar in both turbid and clear waters. However, the rapid attenuation of light in turbid waters vertically compresses the productivity - depth profile (Figure 5.8). Shallow euphotic zones lead to large aphotic:euphotic zone ratios, the 'critical mixing depth', where respiration equals photosynthesis, being reached when the mixed layer is approximately six times the euphotic zone depth. In some systems, in spite of the shallow euphotic zones, high rates of primary production have been measured. In part, this can be attributed to the scattering of light within the euphotic zone by inorganic particles which results in an increase in the quantity of light intercepted by an algal cell. This phenomenon is significantly influenced by the extent to which the inorganic suspensoids absorb light.

In turbid waters of low nutrient status algal productivity is limited by the concentrations of the growth-rate limiting nutrient rather than by light attenuation or temperature, eg Lake Midmar (Republic of South Africa). As a consequence, the response of turbid systems to nutrient enrichment is dependent on whether light or nutrients constitute the growth-rate limiting factor. This has important implications for management.

Assessing primary productivity in turbid waters requires either modifications to existing techniques or the application of new methods. The main problem is to determine rates of production at sufficient depths within a narrow euphotic zone so as to accurately characterize the productivity-depth profile. One alternative is the use of vertical tubes enclosing an integral sample from the euphotic zone (Figure 5.9). In addition, it may be possible to account for the influence of mixing on algal productivity using measurements of fluxes in oxygen or carbon dioxide within shallow water bodies with large algal populations.

Light is a prerequisite for algal photosynthesis and changes in light attenuation will have a direct influence on the trophic dynamics of lake ecosystems. This is particularly important in deep turbid lakes where the shallow euphotic zones restrict the lake volume which can be exploited by algae when compared with clear waters. The management implications of this feature may be favourable with respect to algal-related water quality problems, but unfavourable with respect to fish production (see section 5.4.6).

(b) Macrophytes: Flooding of the littoral zone of lakes by turbid inflows can materially influence the production and, therefore, growth of littoral submerged plants (macrophytes). The marked attenuation of PAR reduces the energy flux to levels which are inimical to the growth of young plants upwards from the rhizomes or root stocks buried in the littoral sediments. The loss of this plant community from the littoral resulted in a decline in condition of two dominant fish species, <u>Monodactylus falciformis</u> and <u>Rhabdosargus holubi</u> juveniles which are normally abundant over the littoral. Whitfield (1984) argues that this effect was largely due to the collapse of invertebrate stocks associated with the plants so that competition between benthic feeding fish increased as a result of the compression of the feeding zone towards the substratum.

This effect is not necessarily universal as the littoral plants of shallow subtropical lakes live in markedly turbid waters. In those cases which have been studied in South Africa, the growing period is maximal during the cool season (as in the case of the pondweed <u>Potamogeton crispus</u>), when turbid inflows are minimal and clarification of the lake water has occurred.

This implies that no hard and fast rule is permissible. But management of inflows must, where possible, take cognizance of these basic light requirements of rooted macrophytes if the diversity of the lentic habitat is to be maintained.

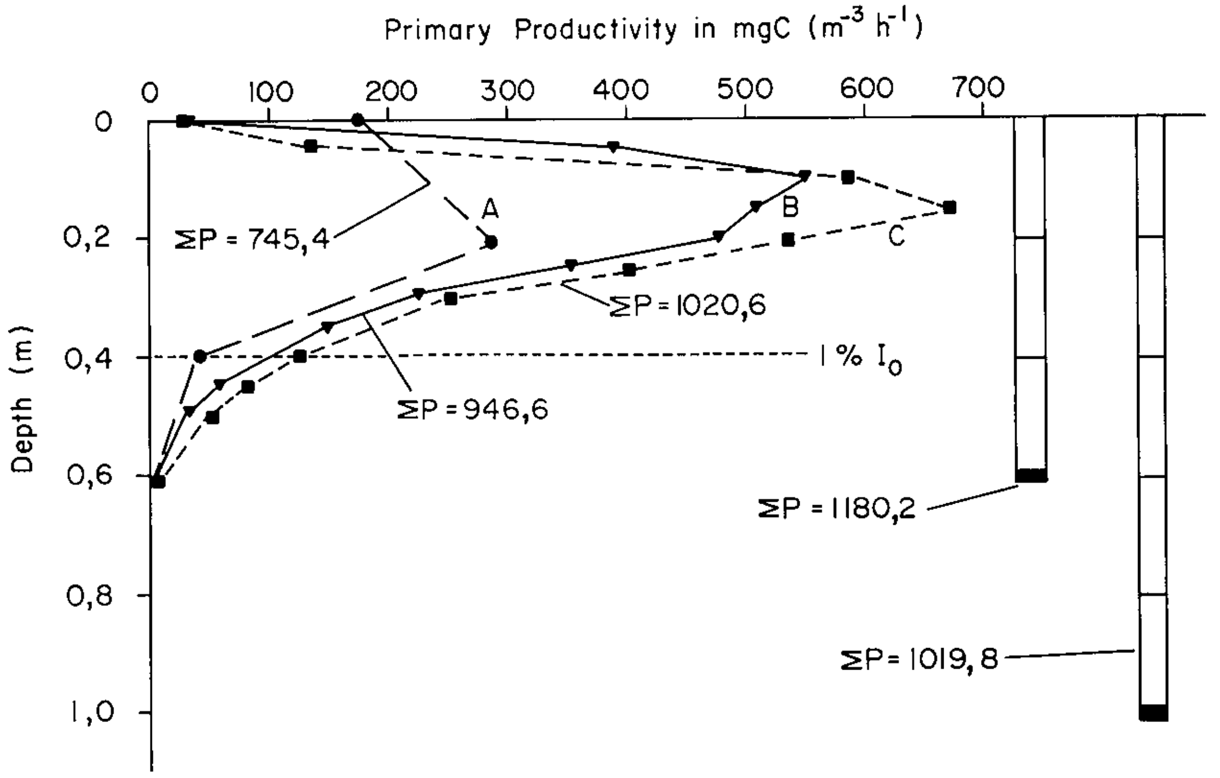

FIGURE 5.9 Primary productivity measured at 50 mm intervals in 30 ml test tubes (A), and tubes of 0,6 m (B) and 1,0 m (c) lengths. Closely spaced discrete samples (A) incubated for one hour had an integral productivity (A) similar to that measured in a tube approximately the depth of the euphotic zone (B), which may represent the maximum possible productivity. Data from Wuras Dam, Republic of South Africa (After Grobbelaar 1984).

5.4.4 TURBIDITY AND SECONDARY PRODUCTION

Suspensoids can aid or abet zooplankton productivity. Organic detritus with or without bacteria can contribute to the zooplankton's nutrition, but the extent of this contribution depends on the size and composition of detritus and the feeding mode of the zooplankton. Laboratory (Saunders 1969) and field (Roman and Rublee 1981) studies have indicated the utilization of organic suspensoids by zooplankton but have not clearly demonstrated the importance of such food compared to other types. Suspended silts decrease ingestion and growth rates of Crustacean zooplankton (McCabe and O'Brien 1983; Arruda et al 1983). Furthermore, altered predation pressures and growth rates can change species composition. The trophic and ecosystem implications of such effects are likely to be of sufficient importance to require further research.

Moderate inputs of suspensoids and associated microorganisms can increase the availability of food to benthic organisms. Sustained high levels of suspensoids, however, have a detrimental effect on the diversity and abundance of the benthos by reducing the depth of the euphotic zone, thereby reducing primary productivity and the availability of food (Bruton, in press). Furthermore, high turbidities cause sedimentation in slow-flowing parts of the water body, which smothers benthos, thus excluding it from the aquatic food web (McLachlan and Grindley 1974; Stephenson et al 1977).

As many inland waters are naturally turbid, many fish species are adapted to withstand or exploit the reduced light conditions which provide shelter from predators. Sustained high suspensoid loads modify pelagic and benthic habitats and may reduce breeding success and decrease food availability and feeding efficiency. As a result, growth rates are depressed, size at first maturity and final size are decreased and fecundity, population size and productivity are lower than under optimal conditions. On the whole, man's manipulation of catchments and inland waters has resulted in increased turbidity levels and decreased fish production (Bruton, in press).

5.4.5 ROLE OF SUSPENSOIDS IN TRANSPORT PROCESSES

Suspended inorganic particles possess sorption sites for inorganic and organic compounds, amongst which are plant nutrients, pesticides, heavy metals and organic molecules, all of which are of considerable concern to water managers. These compounds can be adsorbed or desorbed depending on prevailing conditions. Strongly influential is the particle type which is a function of origin, size, degree of weathering, and adsorption saturation. Essentially these properties define the amount and polarity of the surface electrochemical charge, but the net charge is almost always negative. Sorption activity is thus related to surface area, and clay-sized particles are orders of magnitude more important than the larger particles. Different clays may also influence the quantities which are adsorbed; for example, montmorillonite has a greater exchange capacity than illite per equivalent mass, and allophane is considerably more active than these. Insoluble metal hydroxides, ($[FeOH]_n^+$) mainly of iron, are precipitated over the surface of the particles which results in a net positive charge which allows for the adsorption of a wide variety of anions dissolved in water.

Adsorption bonding strengths vary for different substances, but are, to a large degree, proportional to valency. Adsorbed nitrate and ammonium are weakly bonded and are readily available for algal growth. Phosphate complexes with a wide range of bonding strengths which yields phosphate pools of varying availability to phytoplankton. For management purposes it is not possible to make generalizations about this, and availability can be assessed properly only by separate empirical assays for each catchment. Chemical fractionation of the phosphate bears little relationship with real nutrient availability however, algal growth bioassays have been used to estimate the maximum potential availability (eg Grobbelaar 1983; Viner 1982) and can be considered the most practical approach for management purposes. This procedure is laborious but, as the quantity of adsorbed nutrients may greatly exceed the dissolved fraction, direct assessment is necessary for estimating the nutrient status of turbid waters. It is especially necessary to distinguish the clay sizes in such assays since the clay fraction can remain in suspension in water long enough for plankton to be affected.

Adsorbed organic compounds include toxic man-made substances such as herbicides, insecticides, petroleum hydrocarbons and polychlorinated biphenyl compounds, as well as naturally occurring non-toxic compounds. Concentration of these compounds by surface adsorption can increase availability to microorganisms (Marshall 1980). Alternatively, the adsorption of inorganic and organic compounds could be removed from the aqueous phase to the sediments. By this means a natural sink is often present which can alleviate environmental toxicity. However, subsequent slow desorption after sedimentation can release toxins into the water, and so to the biota and human users. This is particularly so where there are detrital or benthic feeders amongst the fauna. Shellfish industries, in in-shore localities, have been ruined by contaminated sediments.

It is imperative to include the inorganic or organic adsorbed compounds when analysing turbid waters. Without this inclusion, meaningful management decisions are impossible.

5.4.6 INFLUENCE OF TURBIDITY ON WATER USE

The potential of suspended material to increase the costs of production of water for domestic, industrial or agricultural use is largely a function of the nature of the suspended particles. Where the turbidity is due to inorganic particles the following effects can be identified:

(a) Beneficial

- costs of producing high quality water are low as particles are easily flocculated;

- reduction of the potential for algal and submerged macrophyte growth in irrigation canals or small farm dams;

- greater efficiency of heat transfer processes in cooling ponds of power stations;

- increase in fishery potential as a result of associated nutrient inputs, as is the case in parts of Lake Kariba (Zimbabwe) and on the Amazon floodplain;

(b) Deleterious

- increase in the capacity to transport nutrients and toxic substances;

- reduction of storage capacity of reservoirs and impoundments as a consequence of settling out of river-borne inorganic suspended material;

- reduction in fishery potential as is the case in Lake le Roux (Republic of South Africa), due to sustained high levels of turbidity which (i) cause only large zooplankton species to be grazed and (ii) restrict the littoral to a small vertical depth which is frequently exposed when drawdown occurs.

Where the suspended particles are organic, eg algal or bacterial cells or humic detritus, the following effects can be identified:

(a) Beneficial

- in salt works, where water is evaporated in ponds, a dense growth of halobacteria is required to promote heat absorption and consequent heating and evaporation of the water;

(b) Deleterious

- increased water treatment costs due to blocked filters and difficulties in flocculating some algal cells;

- blockage of drip irrigation systems;

- taste and odour problems and the formation of halomethane compounds following chlorination.

While turbid systems may be less appealing aesthetically than clear waters there is little evidence that turbidity has reduced their potential as recreation areas, except in hypertrophic systems with massive algal populations eg Harbeespoort Dam (Republic of South Africa).

5.5 MANAGEMENT POSSIBILITIES FOR TURBID AQUATIC ECOSYSTEMS

High turbidity in inland waters is generally regarded as undesirable, because of its deleterious effects on the biota and on visual quality, and its implications for sediment deposition. However in certain cases, eg when excessive macrophyte or algal growth needs to be reduced, it may be considered as having certain advantages. In either case it is not regarded as a neutral phenomenon, and those charged with the responsibility of managing inland waters would certainly wish to be able to control the levels of turbidity in the water bodies under their jurisdiction. We consider here to what extent it is feasible to minimize turbidity bv control of landuse in the catchment. The alternative approach of adopting in-stream measures, such as sediment settling basins, or adjustment of ionic composition is also examined. Regardless of whether turbidity levels can be controlled, it is of value if they can be predicted. The possibility of predicting the behaviour of suspensoids in turbid reservoirs and other turbid aquatic ecosystems is discussed in section 5.5.2.

5.5.1 CONTROL OF LANDUSE TO MINIMIZE EFFECTS OF TURBIDITY

The suspensoid load of surface runoff caught up in streams and rivers depends upon the varying geological features of the catchment and the manner in which the land surface is disturbed. Erosion by rain and wind is a continuous process which in geological time will denude a land surface and anthropogenic activity materially increases the rate at which this occurs. As a consequence, the suspensoid loads of rivers and lakes, and therefore turbidity, have increased. Acceptance of this viewpoint implies that it should be possible to reduce the rate of suspensoid-accretion in surface waters.

Those landuse practices which depress the optical property of surface waters (rivers, reservoirs and lakes) include inter alia:

- trampling by stock, and ploughing up of the montane sponges;

- clearing of upland forests to the stream edge and replacement by exotic plantations with the concomitant loss of the understorey which materially reduces the erosive force of raindrops;

- ancillary disturbance of surface slopes to provide logging trails and tracks. These are unstable and further contribute to the suspensoid load of runoff from steep slopes;

- the removal of riparian vegetation along the course of the stream or river particularly in the more slow flowing sections;

- overgrazing, leading to destruction of ground cover, and sheet and donga erosion when rain falls;

- unacceptable land preparation techniques such as non-contour ploughing and the pressing into service of unproductive slopes, usually a practice found among owners of small farming units, but not exclusively so.

We argue that these examples are sufficient to show that turbidity reduction is feasible, as each of these malpractices can be reversed by good land husbandry (management). In so doing, the rate at which materials enter the water course will be reduced.

Furthermore, activities within the watercourse itself increase turbidity in the main stream rivers and reservoirs. For example, silt-laden compensation waters taken from levels in the dam near the river bed sustain high turbidities downstream throughout the annual season. Such turbidities have been shown to be inimical to the limnological properties of, and processes within, the river downstream of such discharges. We refer in particular to smothering of rich food resources, the cycling of nutrients and the maintenance of the all important photosynthetic input of energy. All three of the above processes will be markedly depressed by high silt concentrations affecting (i) the sequestration of trace elements and nutrients and the heavy sediment fraction and (ii) the rapid attenuation of light.

By recognizing that the river, its reservoirs and lakes can and do mirror the changing events in the catchment, the measurement of turbidity and the rates by which it changes along the river course may provide one of a number of relatively simple yardsticks against which to measure the environmental health of the catchment.

5.5.2 MODELLING

Although site-specific models of sediment transport in rivers and production in catchments exist, and are described in the engineering literature, these models are largely empirical. There appear to be no widely applicable models of suspensoid distribution in lakes or reservoirs, which are based on descriptions of the actual transport processes and which are in any way linked to hydrodynamic models.

5.5.3 IN-STREAM MEASURES FOR MINIMIZING TURBIDITY

The two best known in-stream procedures for reducing turbidity are settling-basins and flocculation. The object of a settling basin is to bring the stream to a virtual halt by enlarging the cross-section, and thus encouraging suspended particles to fall to the floor. A narrow stratum at the top of the basin is bled over an outlet weir. Settling basins are regarded as efficient until they silt up. At that stage, either the silt needs to be removed or a new tank must be constructed. Due to the particle size distribution, the permeability and specific yield tend to be low, and the silt packs hard, rendering it (quite apart from the presence or absence of nutrients) inappropriate for agriculture.

Flocculation of suspended particles takes place naturally in many water courses (Avnimelech et al 1982). Generally, as the salt content rises, clarity increases. The rate of clarification depends on both ionic strength and ionic composition.

5.6 RESEARCH NEEDS

(i) The effect of high suspensoid concentrations upon vertical mixing processes in, and heat budgets of, lakes and reservoirs.
(ii) Electrochemical and mineralogical characteristics of suspended particles which influence the flux of nutrients and pollutants.
(iii) Turbidity as a factor regulating primary and secondary production and fish yields.
(iv) Adaptations and responses of plankton to turbidity.
(v) Interactions between inorganic suspensoids and microbial activity.
(vi) Modelling the distribution of suspended particles in rivers and standing waters.
(vii) Development of an in situ absorption meter to provide direct measurements of total absorption coefficients at selected wave lengths in turbid waters.
(viii) A continuous study of the effect of turbidity on biological production over several years within a given water body.

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CHAPTER 6 EUTROPHICATION

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6.1 INTRODUCTION

The word eutrophication is used to describe a serious degradation of water quality that has become evident in many countries. The discharge of nutrient-rich effluents and runoff from highly fertilized agricultural lands has been associated with the appearance of nuisance growths of aquatic plants. There are a variety of ways that these nuisance growths can be expressed. Microscopic algae may increase dramatically in number, giving colour and odour to the water, and may also develop unsightly surface scums with a range of consequential impacts on water usage. Other problems have been related to larger plants, macrophytes, which produce extensive growths sufficient to cover the water body completely, block water flow and interfere with water usage. The manifestations of eutrophication are not only evident in lakes and reservoirs, but may also be experienced in streams and estuaries.

Defining eutrophication is a difficult task since the word is used in a variety of ways. Water quality managers tend to use it to refer to excessive inputs of nutrients leading to a stimulation of aquatic plant growth. The classical limnological definition would refer to a scale of trophic status from oligotrophic (meaning low nutrient status), through mesotrophic (an intermediate condition) to eutrophic (well fertilized system). This view of the word implies that water bodies progress along this scale as they age due to natural processes (on a time scale of hundreds of years). The term cultural eutrophication would be used when these natural processes are accelerated to perhaps a few years by activities of man. In attempting a definition of the word it is appropriate that both the process and the consequences should be highlighted. Eutrophication may thus be defined as the enrichment of water by plant nutrients (especially phosphorus and nitrogen) that can lead to excessive plant growth with associated water quality problems.

Much of the literature on eutrophication is based on experiences in the Northern Hemisphere, on lakes that are generally clearer and colder by comparison with those found in land masses of the Southern Hemisphere. Regional differences thus create inherent problems in the use of Northern Hemisphere criteria for the management of Southern Hemisphere lakes. However, recent advances in eutrophication research have led to the development of empirical models for predicting the impact of lake eutrophication. Whereas the direct universal application of these models remains in question, the approaches which have been developed certainly show promise for application in the Southern Hemisphere.

6.2 THE CONSEQUENCES OF EUTROPHICATION

The structure and functioning of aquatic ecosystems becomes modified as eutrophication proceeds. There are predictable shifts in the phytoplankton community (the primary producers) which tends to become dominated by blue-green algae. Phytoplankton is grazed by consumer organisms, especially zooplankton, but as it becomes dominated by blue-green algae this grazing pressure becomes less effective in reducing the algal populations. Blue-green algae frequently exist as large colonies which are inefficiently grazed by zooplankton, and much of the algal material remains to be broken down by decomposer organisms such as bacteria, which accordingly increase in significance in eutrophic ecosystems.

In water bodies which stratify, the microbial decay of plant material can cause deeper waters to become deficient in oxygen. Anaerobic waters promote the release of phosphorus from the sediments and usually contain high concentrations of hydrogen sulphide, ammonia, iron and manganese which may be deleterious to the biota. Accordingly, the habitat available to aquatic organisms, particularly aerobic forms, may be reduced.

Eutrophication can impair the use of water in a number of ways. The commonly reported problems are summarized as follows:

6.2.1 IMPACTS ON WATER USE

6.2.1.1 Table 6.1 outlines some common consequences and implications of eutrophication to water utilization.

TABLE 6.1 Some impacts of eutrophication upon water use

Water use	Problems/manifestations/effects
Domestic/drinking	- Coloured water with bad taste and malodour due to phytoplankton - Methylhaemoglobinaemia in infants resulting from high nitrate levels (10 mg l^{-1} N) in drinking water - Blue-green algal toxicity; chronic and sublethal effects on man, toxicity and death of livestock, pets and honey bees
Industrial	- Biological fouling problems in industrial plants (eg cooling towers) due to biological growth favoured by nutrient enrichment
Irrigation	- Nutrient-enriched waters generally benefit the irrigated crops, but excessive growth of filamentous algae and hydrophytes in irrigation canals obstructs and reduces water flow
Hydroelectric power generation	- Aquatic macrophytes may enter and block turbines, disrupting power generation
Recreation	- Aesthetic and health implications impair recreational uses. Algal scums are unsightly, create odour problems and may induce allergenic responses in bathers. Macrophytes can block access to the water and interfere with swimming, boating and fishing and may create a habitat for disease vectors
Recreational fishing	- Fish production may increase initially in response to eutrophication, but this beneficial effect is eroded by progressive eutrophication which is accompanied by a shift to coarse fish species which are less desirable for recreational anglers

6.3 FACTORS CONTROLLING EUTROPHICATION

6.3.1 NUTRIENT SOURCES

Nutrient loads onto water bodies are determined by climatic factors (weathering, erosion, rainfall, variability of runoff), watershed characteristics (surface geology, land form) and human activities (point source, changing landuse patterns). These are shown diagrammatically (Figure 6.1) in the conceptual model proposed by Reckhow and Chapra (1983). The external nutrient loads are derived from point and non-point sources. Non-point source inputs are highly variable due to their dependence on runoff whereas point source inputs (eg sewage effluents) are much more stable. Other, generally less-important, sources of nutrients are atmospheric inputs (including N-fixation) and internal recycling by means of physical, chemical and biological processes. Since the major proportion of the nutrient load received by a lake is derived from the catchment, the variability of the total input depends on the ratio of point to non-point sources.

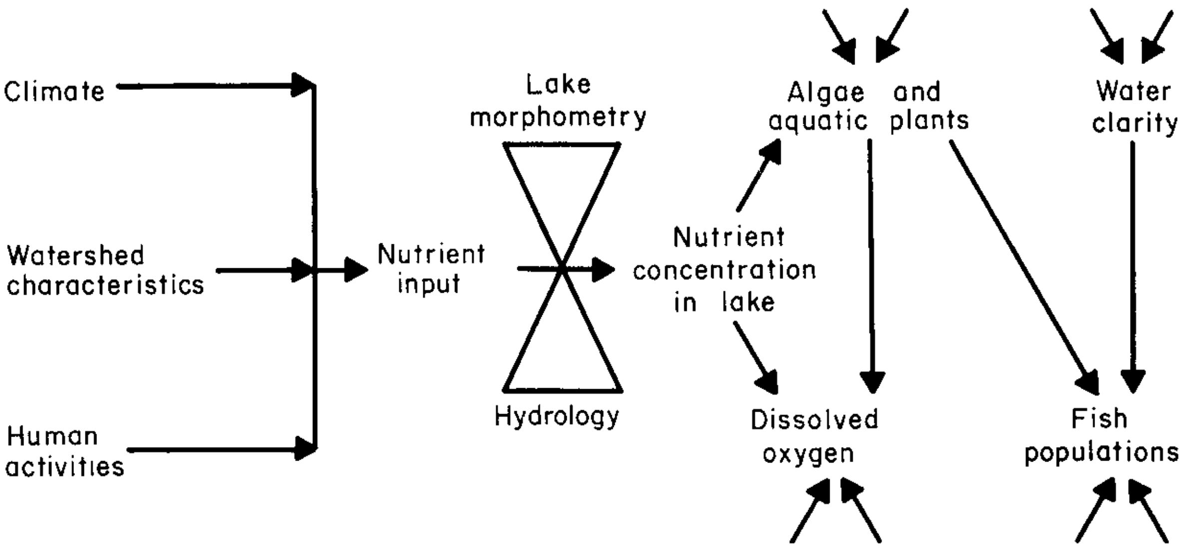

FIGURE 6.1 Some hypothesized variable interrelationships in a nutrient-controlled limnological system.

Nutrient losses from the system consist mainly of mass transfer through the outlet and irreversible sedimentation. In the case of N, denitrification and the volatilization of NH_3 at high pH may also be important.

6.3.2 NUTRIENT LIMITATION

Plants require the presence of certain mineral elements, of which the most important are C, N, P and Si. A concept which holds the key to phytoplankton-nutrient responses is that of nutrient limitation. The growth rate of phytoplankton in lakes is restricted by that element with the least favourable demand/supply ratio. The addition of that element alone will stimulate phytoplankton growth whereas addition of other elements will not. It has been shown that phosphorus and nitrogen are the most frequent growth-limiting nutrients.

The limiting nutrient can be assessed by means of a laboratory based algal growth potential test. The test is an experimental one where the waters of concern are spiked with various concentrations of additional nutrients and then incubated with a test alga. The algal growth response is then measured, and this provides an indication of the relative fertility of the water. The test has also been used for trophic status assessment and for determining the bio-availability of nutrients adsorbed onto inorganic sediments.

6.3.3 LIGHT LIMITATION

Walmsley and Butty (1980) suggested that the quantity of chlorophyll produced per unit of phosphorus was lower in turbid than in clear-water impoundments. Robarts (1984) supported this, stating that the primary limiting factor for algal growth in turbid eutrophic systems is not nutrient availability but light availability. In contrast, recent work by Grobler and Silberbauer (1984a) has shown algal responses to nutrients are similar in both turbid and clear-water lakes. This issue of limiting factors needs further investigation and it might prove necessary to develop predictive methods further should light limitation be shown to be important.

6.3.4 OTHER CONSIDERATIONS

The effect of nutrient loads on nutrient concentrations in water bodies is modified by lake morphometry (dendritic vs bowl shape, deep vs shallow) and hydrology (retention time, variability of flow) and form of nutrient load (dissolved vs particulate), and its bioavailability. The trophic response of water bodies depends on the utilization of nutrients by primary producers (phytoplankton and aquatic macrophytes) under the constraints imposed by the environment (temperature, light, hydrodynamics). Both N and P are implicated in the eutrophication of freshwater systems, but because P is generally regarded as being more controllable, both research into ecosystem response and management strategies have concentrated on P as the controlling nutrient. In isolated cases the trophic response might be linked to other nutrients, eg C and micro-elements (Goldman 1962).

6.4 EUTROPHICATION INDICATORS

As waters become progressively more enriched, the biomass that they are capable of supporting increases. It is possible to qualitatively and/or quantitatively relate the degree of enrichment to a particular characteristic or set of characteristics describing the biomass and/or conditions resulting from the increase. These characteristics, or indicators, can be determined using chemical, physical and biological techniques (cf, APHA 1980; Golterman 1971; Vollenweider 1971; Edmondson and Winberg 1972; Ricker 1971 for suggestions on methodology). Some examples of the major types of indicators are given in Table 6.2 and ranges of values for oligotrophic, mesotrophic and eutrophic systems are presented in Table 6.3.

TABLE 6.2 Examples of Common Indicators

Indicator	Rationale for usage
Causal Indicator	
Total phosphorus concentration	this is probably the most important nutrient associated with eutrophication
Response Indicators	
Chlorophyll concentration	provides a measure of phytoplankton standing crop. Most commonly used response indicator
Hypolimnetic oxygen deficit	decomposition of plant material results in oxygen consumption in the bottom waters of a lake
Secchi Disc Transparency	a change in the phytoplankton biomass results in a concomitant change in water transparency. Also measures turbidity
Phytoplankton cell counts	cell numbers increase with eutrophication
Phytoplankton cell volume	direct measure of biomass
Number of species	enrichment apparently reduces the number of species present; diversity decreases
Observer assessment	obvious colour, scum and odour problems

TABLE 6.3 Trophic status criteria for lakes with some examples from Australia and South Africa

	Mean Productivity mg C m^{-2} day^{-1}	Chlorophyll *a* mg m^{-3}	Total P mg m^{-3}	Total N mg m^{-3}
Oligotrophic	50-300	0,3-3,0	5	250
Mesotrophic	250-1000	2-15	5-30	250-1000
Eutrophic	1000	10-500	30-1000	1000
Lake Burley Griffin* (New South Wales)	-	6,4	45	350
Lake Ginnindera* (New South Wales)	620	4,8	21	370
Hartbeespoort Dam** (South Africa)	400-30900	11-740	509	2500

* data from Cullen et al (1978)
** data from Robarts (1984)

6.4.1 SELECTION OF INDICATORS

Because eutrophication results in a variety of growth and biomass responses at all levels of the food chain, the selection of appropriate indicators will depend on the site and the use to which the water is put. Some degree of knowledge of the water bodies concerned is therefore required. Only a few indicators, such as total phosphorus concentration, can be widely applied. The latter is a universal measure because eutrophication is commonly caused by the increase in phosphorus concentrations.

Some indicators are not universally appropriate. For example water transparency may not be used in situations where inorganic turbidity is high; and hypolimnetic oxygen deficit values recorded in temperate systems are not appropriate for tropical systems where deoxygenation occurs even in oligotrophic systems. The selection of an appropriate indicator remains a matter that is site and use specific.

In general, chlorophyll concentration is presently considered to be the most reliable trophic status indicator for several reasons; namely, it is relatively easy to measure; it gives a quantitative indication of the problem condition which is commonly phytoplankton biomass; and it can be quantitatively related to other eutrophication and water quality measures such as phosphorus and nitrogen loads and concentrations, and primary production.

6.4.2 PROBLEMS WITH SAMPLING AND MEASUREMENT OF CHLOROPHYLL

Phytoplankton populations often show considerable variation in their horizontal and vertical distribution in a lake. These are generally brought about by wind-driven mixing events and are, in turn, modified by the morphometry and bathymetry of the lake. Spatial variations are particularly evident in the case of buoyant gas-vacuolate blue-green algae which can form dense surface blooms and scums. Robarts and Zohary (1984) have shown that up to 40% of the *Microcystis aeruginosa* population in Hartbeespoort Dam, South Africa, can occur in a dense surface scum occupying only 0,01% of the lake's surface area. In some optically-clear Northern Hemisphere lakes, species of *Lyngbya* and *Oscillatoria* often occupy narrow discrete layers at the bottom of the euphotic zone. However, these are seldom found in the generally more shallow and turbid Southern Hemisphere reservoirs.

Variability in the distribution of algae can invalidate assumptions that the lake is evenly mixed and cause problems with the design and implementation of a sampling protocol. Vertical differences in algal populations can, to some extent, be overcome by the use of integrating samplers and here it is essential to standardize methodologies. For example, Walmsley and Butty (1980) recommended a five metre long integrated sampler for use in South African impoundments, although other approaches are used elsewhere. In Sweden a depth of two metres is used whilst in Australia it is common to sample the depth of the photic zone. Horizontal variability is more difficult to overcome and can only be corrected by synoptic sampling of several different points in a lake. In this regard, the use of remote sensing in combination with on-site analysis may prove to be useful.

A further complication is introduced by interspecific variations in chlorophyll content and changes in the chlorophyll content of individual cells in response to different light and nutrient regimes. Chlorophyll extractability varies for different algal groups and introduces further bias. At the analytical level, different extraction and measurement procedures have caused difficulties and the use of in situ fluorometric techniques though cumbersome, may provide a more useful measure of chlorophyll.

6.5 PREDICTING EUTROPHICATION

6.5.1 WHAT DO WE NEED TO PREDICT AND WHY?

Mathematical models are used to predict the likely response of water bodies to changes in nutrient inputs. This is necessary in order to assess the water quality benefits likely to result from various effluent treatment and management options (Rast et al 1983). Models are a useful way for organizing, summarizing and presenting quantitative information (Reckhow and Chapra 1983). Existing models have been developed mainly for long-term planning purposes, but predictions are also needed for short-term operational purposes. Most of the existing eutrophication models predict mean annual chlorophyll concentration in the lake. The spatial and temporal resolution of predictions depends on the type of management and planning issues that need to be resolved. For example, drafting a long-term pollution control strategy may only require an average prediction of trophic status of a system. However, the siting of recreational areas or design of water intake structures may require increased spatial resolution of predictions and in-lake management decisions may require increased temporal resolution of predictions.

6.5.2 MATHEMATICAL MODELS

There are a great number of models available, and these differ in their data input needs and complexity. The prediction error or precision is however not necessarily a function of model complexity (Reckhow and Chapra 1983). For the selection of an appropriate model the following should be considered:

a. Major assumptions
b. Causality
c. Uncertainty
d. Simplicity
e. Sampling design and data acquisition

There is no 'best' model for all applications, but selecting the appropriate model will depend on the particular application. To date the OECD-Vollenweider eutrophication modelling approach (see Figure 6.2) has been the most commonly used for planning and management purposes (Rast et al 1983; Reckhow and Chapra 1983).

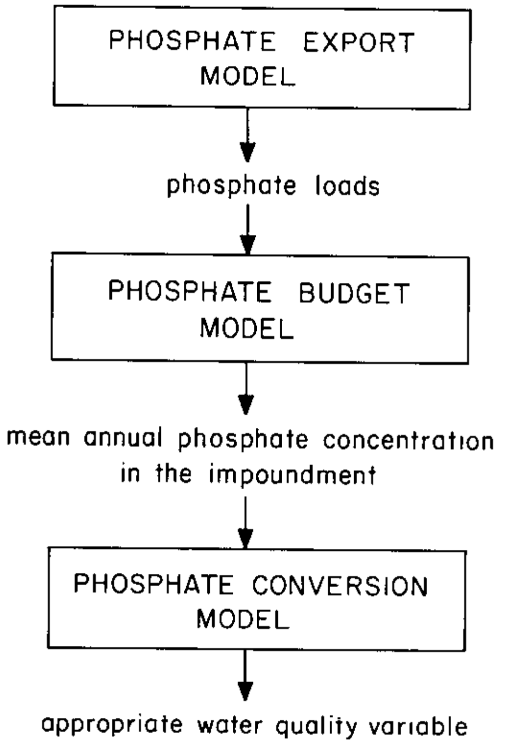

FIGURE 6.2 A schematic outline of the components of the OECD eutrophication modelling approach.

6.5.3 PREDICTION OF IN-LAKE P CONCENTRATION FROM EXTERNAL LOADS

The basis for predicting in-lake phosphorus concentrations from influent water quality is a mass balance approach which can contain as many nutrient compartments as desired (Reckhow and Chapra 1983). In the OECD approach the mass balance equation is:

$$\frac{dP}{dt} = W_i - W_o - S.P \qquad 1$$

where P = mass of total phosphate in an impoundment
W_i = mass of phosphate entering the impoundment
W_o = mass of phosphate in outflow from impoundment
S = phosphate sedimentation rate.

By assuming steady state, dP/dt becomes zero and, assuming the sedimentation rate can be estimated as $1/(T_w)^{\frac{1}{2}}$, equation 1 can be solved analytically to yield the well-known OECD phosphate budget model:

$$[P] = L_p / [q_s(1 + (T_w)^{\frac{1}{2}})] \qquad 2$$

where [P] = predicted in-lake phosphorus concentration (mg l^{-1})
L_p = areal phosphorus loading rate (g m^{-2} yr^{-1})
q_s = mean depth (m) divided by Tw, hydraulic residence time (yr).

Equation 2 has been used with considerable success to predict annual mean phosphate concentration in water bodies, although it has been found to overestimate the P concentration (Cullen et al 1978; Cullen and Smalls 1981; Walker 1982; OECD 1982; Grobler and Silberbauer 1984a). Several modifications to equation 2 have been suggested to overcome this problem. Modification to the sedimentation term in the original equation is advocated.

Equation 2 assumes steady state and therefore does not reflect the large hydrological variability in semi-arid regions. This problem may be overcome by using time-series treatments instead of mean values of the input variable and a numerical solution for equation 1 (Grobler 1984).

It is important to understand the limitations of any model used to predict either chlorophyll or phosphorus. There are a number of assumptions made in the OECD-Vollenweider models regarding phosphorus being limiting rather than light, and a steady state condition with regard to inflows and complete mixing, which may not hold in many water bodies (OECD 1982).

6.5.4 CHLOROPHYLL-P RELATIONSHIPS

The trophic response of water bodies is usually measured in terms of chlorophyll concentration. The OECD modelling approach relates mean annual chlorophyll concentrations [chl] to mean annual TP concentrations [P] by means of a log-log regression, based on a large number of lakes.

$$\log [chl] = 0{,}79 \log [P] - 0{,}35 \qquad 3$$

This relationship has been found to apply to many southern African impoundments (Walmsley and Thornton 1984; Grobler and Silberbauer 1984a).

Some countries of South America (Brazil, Chile and Argentina) have used this relationship with success for reservoirs and some lakes. Australia has had one clear and one turbid reservoir included in the OECD shallow lakes and reservoirs programme. Clear water reservoirs fit the general OECD relationship well, but the turbid lake is treated in OECD models as an outlier since it is considered to be limited by light rather than nutrients. The turbid Lake Burley Griffin also does not fit the OECD relationship. In Australia the OECD relationship has been found to overestimate chlorophyll in turbid situations (Cullen and Smalls 1981).

The confidence interval about the chlorophyll-phosphate regression line spans an order of magnitude which has cast doubts on the utility of this relationship for management purposes. Much of this uncertainty is a consequence of the diversity present in the large number of water bodies used to develop this relationship. Rast et al (1983) and Reckhow (1983) have shown that the response of any particular water body can be predicted with considerably less uncertainty given an adequate data base. The chlorophyll-P relationship is based on the assumption that phosphorus is the primary growth limiting factor. However, both nitrogen and phosphate are known to limit growth. Smith (1982a, 1982b) has developed relationships in which chlorophyll is a function of both P and N. These chlorophyll-nutrient relationships must be used with care in turbid systems when light may be the factor limiting production, and also in systems where grazing by zooplankton populations reduce algal biomass. There also appear to be cases where stocking with fish for recreational fishing has reduced zooplankton populations sufficiently to allow algal biomass to develop to bloom conditions (Cullen et al 1978).

6.5.5 CAN WE PREDICT ECOSYSTEM FUNCTIONING?

Prediction of the type of plant growth (macrophytes or phytoplankton), species composition (blue-green algae, green algae, or diatoms) and food chain grazing efficiency, presupposes the ability to predict ecosystem functioning. Considerable effort has gone into the development of ecosystem models which have given insight into the functioning of freshwater ecosystems. However, large, costly data requirements, model complexity and problems with model transferability, limit this approach. Consequently ecosystem models have not been widely used in the management context.

6.6 WATER QUALITY PLANNING AND POLICY

'Water quality planning' is here used to define activities that have a lead time measured in years such as the construction of storages, the construction of sewage treatment works and land use changes within a catchment of concern. 'Policy' is used to describe regional and national schemes relating to effluent standards, phosphates in detergents and other pollution control strategies.

There are two major elements in such water quality planning. Estimates are needed of the various pollutants that enter the water body of concern and of their impact on the receiving water. In the case of eutrophication the pollutants of particular interest are phosphorus and nitrogen. These considerations are best considered on a catchment basis, but may be used with caution for regional or national policies if information from representative systems is available.

6.6.1 WATER QUALITY CRITERIA

Hart (1982) has discussed the attempts to put water quality criteria onto a firm scientific basis, and his compilation of existing water quality criteria (Hart 1974) has been important in guiding effluent discharges in Australia. Kempster et al (1980) have done a similar study in South Africa.

The rationale behind this approach is that there is some concentration for each pollutant at which the function of the water will not be impaired. Such critical concentrations probably exist in regard to the use of water for industry and both human and livestock consumption, but it is not clear that the approach is justified in relation to the conservation of aquatic ecosystems.

There is difficulty in applying toxicity results developed from standardized laboratory studies to the more dynamic river or lake situation. Because of this, water quality criteria must be seen as a useful starting point, but not as a substitute for understanding a particular aquatic ecosystem and assessing the impact on that system of any particular discharge. The concern must be with the longer term biological outcome of the discharge rather than just with some immediate response.

Given the variable nature of the two determinants of water quality, namely effluent discharge and flow of the receiving water, it is obvious that water quality management should be flexible. The alternative approach is to understand the structure and function of the aquatic ecosystem into which wastes are discharged and measure its responses in order to predict the relationship between waste discharge and ecosystem change. It must also be appreciated that some of the widely quoted criteria for phosphorus levels in eutrophication are value judgements based on people's perception of colour resulting from algal growth rather than on biological grounds. Phosphorus criteria in lakes have commonly been 10 or 20 mg m^{-3} (Clasen 1980) but in some areas 30 mg m^{-3} is now considered an upper limit. The response of people to the resultant chlorophyll concentrations is a learned response based on what they are used to, and thus standards probably need to be considered on a regional basis. For example, in South African impoundments, chlorophyll values in excess of 30 mg m^{-3} created nuisance conditions while values less than 10 mg^{-3} did not (Walmsley and Butty 1980).

6.6.2 ESTIMATING INPUTS TO A WATER BODY

Typical export levels of phosphorus (kg ha^{-1} yr^{-1}) are published for a range of land uses and widely used at the planning level. Since export requires surface runoff to reach a stream, it is a function of rainfall as well as catchment conditions (Cullen and O'Loughlin 1982; Grobler and Silberbauer 1984b). Using such export levels in the more variable flow systems in the Southern Hemisphere needs caution, since average export figures may have little meaning. On average the export may seem minor, but if the one in twenty years flood brings in enough phosphorus to maintain the system in a eutrophic state for the next twenty years, then it may be the occasional extreme event which is more important for planning. Further research is needed in this area.

The stream transporting nutrients from the catchment to a lake will also alter the nutrient input. Under low flow conditions nutrients will be taken up by biota, and particulates will settle to the bed of the stream. These nutrients are likely to be remobilized under higher flow conditions. Consequently the seasonal rainfall patterns are important in assessing the magnitude of nutrient inputs (Grobler 1984).

6.6.3 PREDICTING IMPACTS ON THE RECEIVING WATER

The prediction of phosphorus concentrations and resulting chlorophyll concentrations for lakes dominated by phytoplankton has been discussed in the previous section. As yet prediction of the growth of macrophytes or attached algae is difficult and no widely accepted techniques exist.

6.6.4 UNCERTAINTY

The various predictive models discussed in this report are generalized and have wide error margins. However, these uncertainties can be reduced considerably by using models which take into account variability of rainfall and streamflow in countries which so commonly experience droughts and floods.

Planning predictions under these conditions need to be based on a probability basis in an analogous manner to that used by hydrologists. Planners should consider that a system has, for example, a 10% probability of an algal bloom exceeding a certain chlorophyll concentration in any particular year, rather than to expect specific predictions which are improbable in systems so dominated by rainfall events.

6.6.5 EUTROPHICATION CONTROL STRATEGIES

Eutrophication control strategies often are aimed at either controlling the causes or symptoms of eutrophication. In both cases, the technology exists to overcome water quality problems. For example advanced wastewater treatment plants, such as the Phoredox system, reduce nutrient inputs to receiving waters. Similarly, techniques such as dissolved air flotation and filtration can be used to reduce interference caused by algae in water treatment plants (section 6.7.1). Although treating the causes of eutrophication has the advantage from the ecosystem point of view of being more effective in the long-term, the debate continues as to which approach is the most cost-effective.

6.7 MANAGEMENT OF EUTROPHICATION

Reservoir managers have particular concerns with managing the problem of eutrophication on a day to day basis. The most common concern is with high levels of phytoplankton that cause problems to the users of the water (Table 6.1). There are three basic management strategies to consider: the treatment of water to bring it to an acceptable standard; manipulation within the water body to ameliorate the problem; and management of the catchment to avoid the problem.

6.7.1 WATER TREATMENT

This report will not consider the various technologies available to treat water. For some water managers with limited biological information on their systems, the first indication of a water quality problem may come with shorter filter run times. Additional treatment to cope with algal rich water may include screening, flotation, chlorination and activated carbon treatment, which may greatly increase treatment costs. The pre-treatment of eutrophic water by chlorination is often necessary to allow other treatment processes to function effectively, and this can lead to the formation of potentially carcinogenic trihalomethanes in the treated water.

6.7.2 MANIPULATION OF BIOTA WITHIN THE WATER BODY

It is still common in some areas to control algae in water bodies using a poison such as copper sulphate. There are ecological concerns about using such a long-term poison to treat a short-term biological problem, and better approaches are needed.

With limnological understanding of the particular species involved, and their specific locations within the water column, it may be possible to remove or add water to a storage in a way that will minimize algal problems. In multi-storage systems it may be possible to utilize those storages which are not experiencing water quality problems.

More innovative approaches require a detailed understanding of the ecosystem, but manipulation of the biota is regarded as a promising approach. For example, it may be possible to increase grazing pressure by zooplankton on the phytoplankton by manipulation of fish populations and in this way the algal biomass into organisms that are easier to manage.

Another approach to limiting algal biomass is to reduce nutrients within the water column. This has commonly been done by preventing nutrients in the lake sediments being returned to the water column, by either sealing or oxidizing the lake sediments. No work on these approaches in the Southern Hemisphere is known.

6.7.3 CATCHMENT MANAGEMENT STRATEGIES

The general philosophy of regional water quality planning was discussed in section 6.6, but it may be possible to alter the seasonal load of effluents onto a system in a beneficial manner. Summer irrigation with effluent is used in the Australian context, although this may be a wasteful use of a scarce water resource.

Specific effluent controls on point sources may be necessary in eutrophic catchments, and land use management may need to be stressed by agricultural extension workers and through public education.

6.7.4 AERATION/DESTRATIFICATION

In impoundments where an anaerobic hypolimnion develops it may be beneficial to introduce air into the system to oxygenate the bottom waters and/or destratify the water column. This prevents the development of anaerobic water, reduces phosphate release from sediments, oxidizes Fe^{2+} and Mn^{2+}, prevents the formation of H_2S, expands the volume of habitat for fish and zooplankton, and may bring about a change in phytoplankton species succession from blue-green algae and diatoms. However, these techniques are costly and possibly enhance algal growth by vertical distribution of nutrients into the euphotic zone. This management technique does not solve the problem of eutrophication but may be successful in the amelioration of some of its undesirable symptoms (see 6.7.5.3).

6.7.5 SELECTION OF APPROPRIATE STRATEGIES

Many Southern Hemisphere water bodies have multiple purpose usage (recreation, water supply etc) and hence demand a multi-facetted eutrophication management approach. Seldom is a single approach totally effective in controlling eutrophication. Generally, the selection of an appropriate strategy will be site- and use-specific and will involve:

- identification of the particular problem and its cause(s) and consequence(s);

- generation of alternative approaches to alleviate the problem;

- evaluation of the impact of the alternative approaches in alleviating the problem;

- consideration of the economic, social, legislative and technological requirements associated with the alternatives; and,

- implementation of the selected alternative together with a long-term, pre- and post-implementation monitoring programme that will provide feedback of benefit in assessing the effectiveness of the selected strategy.

Implicit in this process is a basic understanding of the waterbody involved, particularly in terms of defining the problem and evaluating the impact of various alternative approaches. At times, it may be found that doing nothing is also an appropriate strategy. As a rule, it is more effective to treat the causes rather than the symptoms of eutrophication. even though in the short term this may be more capital-intensive. This can be illustrated by reference to several case studies.

6.7.5.1 Hartbeespoort Dam, South Africa (Ashton et al 1980)

a) problem: excessive growth of aquatic macrophytes (*Eichhornia crassipes*)

b) approach: technological

c) conclusion: chemical control successfully eliminated the aquatic macrophytes but nuisance blooms of the blue-green algae *Microcystis aeruginosa* soon returned

6.7.5.2 Hartbeespoort and Bloemhof Dams, South Africa (Grobler and Silberbauer 1984a)

a) problem: excessive algal and macrophyte growth

b) approach: legislative combined with technological point source reduction

c) conclusion: Hartbeespoort Dam is point-source dominated and should respond favourably. Bloemhof Dam is diffuse source dominated and should not respond

d) recommendation: only Hartbeespoort Dam should be subjected to the standard (although it is being applied in both cases)

6.7.5.3 Tavago and Prospect Reservoirs, Australia (Wood 1975)

a) problem: anoxic hypolimnia

b) approach: technological; Tavago Reservoir has been aerated by mechanical means: Prospect Reservoir has been aerated by the hypolimnetic injection of aerated water drawn from an upstream impoundment

c) conclusion: both impoundments responded favourably with a reduction in TDS being recorded

6.7.5.4 Lake McIlwaine, Zimbabwe (Thornton 1982)

a) problem: nutrient enrichment and algal growth

b) approach: legislative combined with technological point source reduction and social education

c) conclusion: Lake McIlwaine was point-source dominated and responded favourably to control. Social education resulted in the creation of green belts. Point source control was by means of irrigating pastures with wastewater. However, land-need pressures have subsequently negated the value of the green belts.

6.8 RESEARCH NEEDS

There remain some important gaps in our understanding of the eutrophication process, our ability to predict how water bodies will respond to an altered nutrient input and our ability to ameliorate the effects of eutrophication. This report has identified several areas which require research.

6.8.1 TOXICITY OF ALGAE

Little is known about the conditions under which certain species of blue-green algae become toxic. The appearance of toxic algae in potable water supplies and the implications of this toxicity to humans at the sub-lethal level need to be evaluated.

6.8.2 IDENTIFYING THE LIMITING FACTOR

There is a need to develop a simple test to determine whether production in aquatic ecosystems is limited by nutrients, light or other factors.

6.8.3 IMPROVEMENT OF RESOLUTION IN THE USE OF CHLOROPHYLL AS A TROPHIC STATUS INDICATOR

Since chlorophyll is the most widely used measure of eutrophication there is a need to assess the validity and reliability of sampling design and analytical procedures. The potential for remote sensing of chlorophyll also needs to be investigated. Criteria for acceptable chlorophyll concentrations for specific water uses need to be determined.

6.8.4 THE MODIFYING ROLE OF TURBIDITY

A better understanding of the conditions under which inorganic suspensoids can modify the impact of a nutrient load is required.

6.8.5 IMPROVEMENT OF PREDICTIVE MODELS

In the further development of OECD models for turbid water bodies, it is necessary to develop better approaches to considering sedimentation losses, light limitation and the stochastic nature of inflows in the more variable Southern Hemisphere climates. In addition the question of uncertainty of prediction needs to be addressed. Criteria for the use of OECD relationships need quantifying.

6.8.6 AMELIORATION OF THE IMPACT OF EXCESSIVE PLANT GROWTH

Further work is needed on techniques of ameliorating the impact of excessive plant growth, and in particular the potential for stimulating zooplankton and fish production (biomanipulation).

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CHAPTER 7 FISHERIES

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7.1 INTRODUCTION

Fish are a source of high quality protein, provide for recreation and are of conservation interest. They are harvested from streams, lakes, wetlands and impoundments using methods varying from simple traditional traps to large efficient trawlers aided by the most advanced technology.

The history of scientific management of the resource started early this century with the simplest stock: catch per unit effort relationships. Subsequent developments have considered the exploited stock as independent of the environment and driven by the recruitment, growth and mortality rates of the individual species. Such methods have met with variable success but have not been widely applied in the Southern Hemisphere.

More recently scientists and managers have come to realise that the fish stock is an integral part of the environment and that the interactions between the fish and their biotic and abiotic environment are crucial to the behaviour, production and maintenance of the fish population. It follows therefore that a knowledge of water quality and an understanding of the response of a given fish population to changes in water quality are essential for effective management of the stock. This principle remains valid for management for commercial, recreational, conservation or water quality purposes.

This chapter therefore addresses the following objectives:

- To state the nature of the interactions between fish production and the aquatic environment.

- To define the principles of fish and fisheries management in relation to their environment.

- To assess the role of fish and fisheries in environmental quality management.

- To identify the research needs for optimal management of the fish resource under different environmental regimes.

7.2 GEOGRAPHICAL ASPECTS OF FRESHWATER FISH UTILIZATION

The utilization of freshwater fish resources varies widely throughout the Southern Hemisphere and is largely governed by the availability of the fish and water resources and the social and economic status of people in the countries concerned. The aquatic and fish resources of the Southern Hemisphere have been widely described (Beadle 1981; Lowe-McConnell 1975; Welcomme 1979).

7.2.1 NEW ZEALAND

This country has abundant water resources but a small indigenous fish fauna with widely distributed alien fish. The human population is small with a low growth rate and adequate protein supplies. Demand for fish as food can be met from marine resources and freshwater stocks are not used for this purpose. Recreational fisheries are important, however, and water quality criteria are likely to be directed towards maintaining the stocks of alien species (eg trout) which form the basis of this fishery.

7.2.2 AUSTRALIA

Australia is largely arid with its water resources heavily committed to agriculture and industry. Its human population density is relatively low with a low growth rate and adequate protein supplies. Marine fisheries are well-developed and freshwater fisheries are most valued for recreational purposes. The indigenous fish fauna is small and threatened by alien species (Walker 1983). The primary management aim is conservation of indigenous species. The potential effects of turbidity, salinization and eutrophication or pollution could lead to a conflict between water users and recreational fisheries.

7.2.3 SOUTHERN AFRICA

Like Australia, this area is largely arid with water resources required by industry and agriculture. Human population growth is rapid, however, and severe protein shortages occur in some areas. Marine resources are well developed but mainly utilized by high-income groups, increasing the importance of utilization of freshwater fish as human food. Recreational fishing is also important, especially near urban centres, and may conflict with food fisheries. Turbidity, salinization and the consequences of industrialization (pollution/eutrophication) pose potential threats to both recreational and commercial fisheries and the survival of certain threatened species.

7.2.4 TROPICAL AFRICA

Extensive water resources occur in this region in rivers, large lakes and reservoirs. Human population growth is rapid but industrial development has been slow. Protein shortages are widespread throughout the region and fish stocks are extensively exploited for food. Overexploitation is already evident in some water bodies. Water quality criteria are thus likely to be aimed at maximizing fish yields. The greatest threat to these resources is probably from the uncontrolled destruction of terrestrial vegetation, poor agricultural practices and the alteration of aquatic habitats.

The African great lakes form unique limnological systems. Their fish faunas are highly diverse and provide an immensely valuable resource. Overexploitation is apparent in some lakes and relatively limited industrial development could cause water quality problems on a large scale, due to very long retention times and the high rates at which ecological processes occur in tropical latitudes. Fryer (1972) argues that these lakes deserve special attention for planning and conservation purposes.

7.2.5 SOUTH AMERICA

Like tropical Africa, this continent has extensive water resources in large river systems and associated lakes supplemented by numerous man-made lakes. Human population growth is high and acute protein shortages exist in many areas. Freshwater fishes are an increasingly important food resource. Industrialization is more extensive than in tropical Africa and water quality problems may increase. The greatest threats to water quality appear to be the destruction of terrestrial vegetation and other poor landuse practices. The construction of impoundments on the great rivers has altered the fish fauna, decreasing fish diversity.

7.2.6 CONCLUSIONS

In the arid and semi-arid areas water is predominantly needed for agriculture and industry, and fish production will have a relatively low priority, even when there are protein shortages. In industrial areas recreational fisheries are frequently well developed.

The regions with abundant water resources frequently have rapidly-growing populations and the importance of managing water resources for fish production is much greater. Eutrophication which is deleterious in arid, industrialized areas might be welcomed in underdeveloped areas because of the increased fish production that follows.

7.3 THE INFLUENCE OF ENVIRONMENTAL FACTORS ON FISH PRODUCTION

7.3.1 PRINCIPLES OF FISH PRODUCTION

Fish production is expressed as mass (kg or tonnes) produced in a unit of time (day or year) for a given water body or area. Production rates are limited by both natural and man-induced constraints, which may be biotic or abiotic.

The basic constraint is that all ecosystems obey the first law of thermodynamics, ie energy cannot be created or destroyed. Fish production is, therefore, dependent on the availability of energy and nutrients. Secondary constraints include:

- climatic factors such as the intensity and duration of solar radiation;
- meteorological factors which affect levels of solar radiation, such as wind and cloud cover;
- edaphic factors, which influence the capacity of the surrounding catchments to supply nutrients to the aquatic ecosystem.

Tertiary constraints are introduced by the morphological characteristics of the water body, (water depth, retention time and shoreline development), and the current velocity of flowing waters. High shoreline development increases the proportion of land-water interface, resulting in increased habitat heterogeneity and providing areas for breeding and feeding (Ryder 1978). The underwater light climate which influences primary productivity is variously influenced by the above tertiary and secondary constraints. Another influence on fish production is the structure of the fish community. Fernando and Holcik (1982) have suggested that the natural riverine ichthyofauna of Africa, South America and south-east Asia is not able to take advantage of the pelagic niche in man-made lakes, and as a result the full production potential of an impoundment may not be realized. This has been shown for man-made Lake le Roux in South Africa by Allanson and Jackson (1983).

7.3.2 NATURAL CONSTRAINTS ON FISH PRODUCTION

Factors which block or interfere with the supply of energy or nutrients will ultimately influence the rate of fish production.

Interference with incoming solar radiation is usually by shading, excessive macrophyte cover, or by reduction in the transparency of the water by organic or inorganic suspensoids. High suspensoid loads may be due to the inflow of allochthonous matter, shoreline-erosion, sediment resuspension or standing stocks of phytoplankton (see Chapter 5). A reduction of solar radiation will not only reduce the rate of photosynthetic production, but will also reduce the size of the photic zone and influence water temperature and stratification (Kirk 1983).

Nutrients enter the aquatic food web in dissolved and particulate fractions. Both allochthonous and autochthonous sources are involved. The input of allochthonous detritus is dependent on normal and flood runoff and the quality of this resource to fishes will depend on the condition and geology of the catchment. Stable, climax vegetation cover will generally produce allochthonous material which is richer in nutrients than runoff from barren, eroded substrata (Balek 1977). Fruit from riparian vegetation provides a major food source for many fishes in the Amazon system (Goulding 1980).

The quality and availability of autochthonous detritus to fishes will be dependent on the nature of the benthic microenvironment. Low oxygen tensions, high salinities, extremes of pH or the presence of hydrogen sulphide will depress the growth rates of microorganisms, which are the main source of food in detrital matter. Nutrient-rich detritus and its associated microflora and fauna can be lost to the aquatic food web by being smothered by sediments.

Wind-induced seiches and upwelling events may have a profound influence on the availability of nutrients to fishes. In shallow lakes with gradually sloping shorelines (eg Lake Ngami, Allanson 1980), seiches cause nutrients from the terrestrial environment to enter the lake. In Lake Malawi highest fish yields occur in the south-east arm as a result of nutrient upwelling in this region caused by wind (Fryer and Iles 1972). The seasonal flow of nutrients from tributary rivers into Lake Kariba influences the yield and annual cycle of productivity of the pelagic sardine *Limnothrissa miodon* in

Lake Kariba (Marshall 1982a; Cochrane 1984). Conversely, several authors have reported fish kills when wind-generated turbulence or seiches have resuspended sediments or brought deoxygenated water to the surface (Marshall 1982b; Bruton, in press).

Floodplains, wetlands and estuaries have a natural cycle of water level fluctuations which result in a regular input of allochthonous detritus into the system, especially during floods. This detritus results largely from the decomposition of terrestrial vegetation at high water levels. Rivers and lakes also flood their shores more or less on a seasonal basis. The wide, aseasonal fluctuations which generally occur in man-made lakes and regulated rivers may decrease aquatic production by alternately draining and drowning the littoral phytobenthic zone. This has been shown to have a detrimental effect on fish production in Lake le Roux, a turbid impoundment with a narrow photic zone (Allanson and Jackson 1983).

Many terrestrial and aerial predators and scavengers, including invertebrates, amphibians, reptiles, birds and mammals, are responsible for nutrient export from aquatic systems, but only a few eg hippopotamus, water-nesting birds and some frogs transport nutrients from land to water.

7.3.3 MAN-INDUCED CONSTRAINTS ON FISH PRODUCTION

Man reduces levels of fish production in inland waters by interfering with levels of incoming solar radiation, by increasing water turbidity, altering the quantity and quality of incoming nutrients, changing species diversity and composition, changing habitat structure and by influencing (usually dampening) fluctuations in environmental variables. Reduction in quantity of water and increases in the variability of levels by water abstraction apply further constraints.

High sustained suspensoid loads may decrease food availability and the feeding efficiency of fishes (Bruton, in press). As a result, growth rates, size at first maturity and fecundity are decreased, ultimately reducing fish production rates. Suspensoids may also have a direct effect by reducing habitat diversity and egg and larval survival, and interfering with respiratory efficiency of fish. The transport of toxic substances by suspensoids, especially herbicides and insecticides from agricultural lands, may be a serious threat to fish production rates (Sorenson et al 1977).

Pollution of the aquatic environment and destructive habitat alterations, such as dredging, the construction of weirs and bridge ramparts, the canalization of river courses, cutting of riparian vegetation, reclamation of wetlands and floodplains, interference with seasonal flood cycles, placement of engineering structures in the littoral zone, etc pose further threats. They may also interfere with the natural migrations of fishes and prevent anadromous species from depositing their eggs in food-rich floodplains, and catadromous species from breeding at sea. The construction of fishladders and fishways can reduce the impact of man-made structures on fish migrations.

In general, high nutrient concentrations will increase primary and secondary, and thereby tertiary production, but the overall result of industrialization in Japan, the USSR, western Europe and North America has been a sharp decline in freshwater fish catches (Borgstrom 1978). The impact of eutrophication on fishes is discussed further in 7.3.5.

The deliberate and accidental introduction or translocation of alien fishes into natural water bodies can both reduce food availability to indigenous forms as well as result in changes in community structure as a result of predation and biotic competition. The introduction of pathogens and parasites has a more insidious but no less serious effect.

7.3.4 WATER QUALITY AND THE BREEDING STRATEGIES OF FISHES

Fishes have two basic breeding strategies: to produce large numbers of eggs or young which are afforded no protection and are mainly subject to density-dependent mortality, or to produce a few eggs or young which are well guarded and are mainly subject to density-independent mortality. All gradations exist between these two extreme strategies. Although the breeding characteristics of a given species are fixed genetically many species show a remarkable degree of phenotypic plasticity in their breeding behaviour and other life history traits which can be markedly influenced by the environment (Bruton 1979).

The presence of a fish species in a system with poor water quality does not mean that the environmental conditions in that system are optimal for that species. The fish concerned may have a flexible life history strategy enabling it to cope with adversity. The species will continue to survive in the system but its fecundity, size, condition and therefore its production may be severely reduced. Improvements to water quality can result in a marked increase in the value of a species to the natural community as well as to man.

The structure of a fish population and how it differs from a known pristine demography has been used as an indicator of water quality and this concept could be developed. Sensitive, stenotopic species will normally be missing from a population which is subject to environmental stress.

7.3.5 RELATIONSHIP BETWEEN OPTIMAL FISH UTILIZATION AND OTHER FORMS OF WATER USAGE

As fish form an integral and interactive part of the aquatic system, deterioration in water quality will result in a decrease in fish production and species diversity. Thus, in theory, there should be no major conflict in management for water quality and for fish production except in the context of eutrophication where fish production may be increased with a concomitant reduction in water quality.

In practice it has been found that the demands of other water users, degradation of the catchment by poor management, and stream regulation for water storage and hydro-electric power have caused a reduction in the abundance and range of some species. Stream flow regulation has altered or destroyed the habitat of many species in many areas and interfered with natural migrations. The problems brought about by stream regulation have been aggravated by poor catchment management leading to, inter alia, increased salinization, turbidity and eutrophication of many of the Southern Hemisphere water systems.

There are some beneficial effects of stream regulation. The increase in the total volume of water resident in the water course increases the abundance and production of some fish species and can provide a valuable resource for commercial utilization (eg Lake Kariba), or recreation (eg Hartbeespoort and Vaal Dams). Eutrophication, too, will increase fish production up to a point, until anaerobiosis, high pH, blue-green algal dominance and ammonia concentrations adversely affect first fish species diversity and then total production.

It must be accepted that development and utilization of the water resources of the Southern Hemisphere will increase and that, where resources are scarce, the relative importance of fisheries will be a minor consideration if other food sources are available. However with some compromise and communication it is possible to minimize the disruptive effect of water resource development on the fish. In some systems the regulation of discharge from reservoirs to allow simulation of the natural flood regimes may permit the survival of a population downstream. This may have important sociological implications as, for example in the Pongolo floodplain area which supports a large subsistence fishery dependent on seasonal flooding (Heeg and Breen 1982). Allowance for differential release depths of water from impoundments could prevent the discharge of anaerobic, highly turbid or cold water from the hypolimnion of a lake and thus minimize disruption to the biota below the wall.

Finally, in common with the requirements of most water users, the optimal utilization of fish and fisheries requires adequate catchment management to prevent the deterioration of fish production through excessive pollution, enrichment, turbidity or salinization.

7.4 MANAGEMENT IN RELATION TO WATER QUALITY

7.4.1 INTRODUCTION

Human impacts on aquatic ecosystems necessitate the development of management strategies that will protect fish stocks and maintain the quality of their habitats. The diversity of aquatic habitats means that no single strategy can apply to all situations.

Fish are valued for many reasons, including

- food
- recreational fishing
- conservation and educational purposes
- aquarium purposes
- control of undesirable organisms
- improvement of water quality

Fisheries management aims to meet a variety of needs, often from the same fish population. There may be frequent conflicts between the main water users and the resolution of these, without overexploitation of the stock, is a major objective.

7.4.2 HARVESTING

Before developing a commercial fishery the demand for the product and the economics of the fishery should be evaluated. The basic information requirements for management include:

<u>Abiotic</u>

- Limnological data from the water-body concerned. (When actual data do not exist it may be possible to use empirical predictions to establish baseline estimates).

- Catchment usage studies are of particular importance to understanding the limnology of the water-body.

- Hydrological considerations, especially regarding possible modifications to water flow and chemical composition (see sections 7.3.3 and 7.3.4).

Large African reservoirs provide excellent examples of the response of aquatic communities to extensive habitat change. The response of fish populations to changing water quality is well-illustrated by the increased yields that followed enrichment in the filling phase of a new reservoir (Figure 7.1). While the high production of the initial phase of a new reservoir should be utilized, long-term estimates of yield should not be based on early catches.

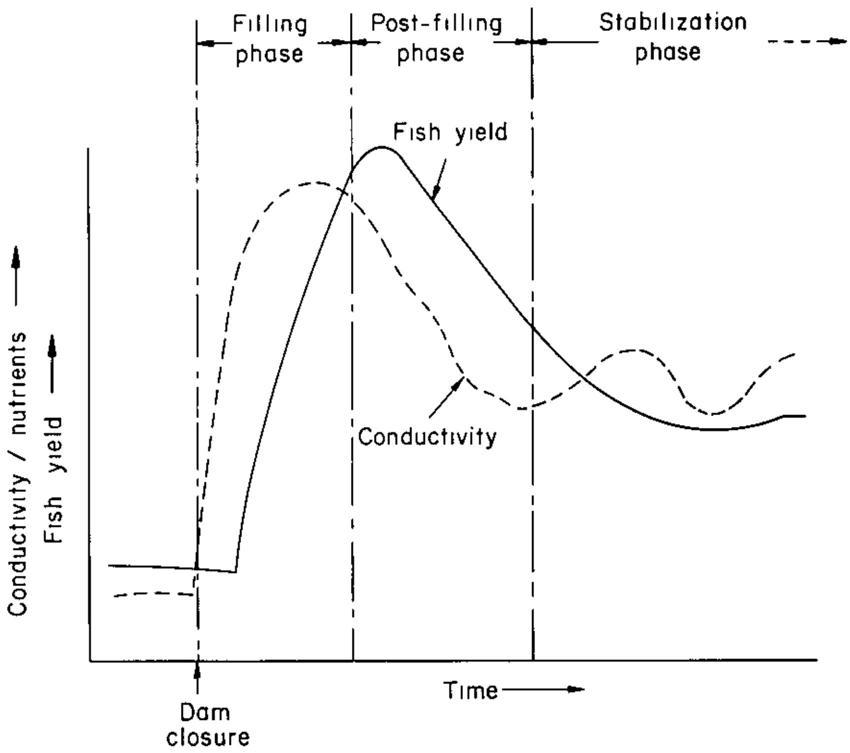

FIGURE 7.1 Diagram of events following closure of a dam and creation of a reservoir, showing the relationship between fish yield and water quality. Reference should be made to McLachlan (1974) and Balon and Coche (1974) for further details.

Biotic

- Fish community structure and species interactions must be evaluated first followed by studies of the basic ecology and life history of the target species.

- The potential yield of the target stocks must be assessed. In tropical and subtropical regions where biological and limnological data are inadequate, management policies need to be conservative, but in better-studied regions predictive models permit a greater degree of precision.

- A number of simple models based on limnological parameters have been derived in order to predict fish yields in lakes and reservoirs. An example which may be applicable to many Southern Hemisphere water bodies is the adaptation of the morpho-edaphic index (Marshall in press) (MEI) in which

$$Y = 23{,}281\ MEI^{0{,}447} \text{ for reservoirs} \qquad 1$$

and $$Y = 7{,}889\ MEI^{0{,}595} \text{ for natural lakes where}$$

Y = yield (kg ha^{-1} yr^{-1})

$MEI = K/z$

K = Conductivity (umhos cm^{-1})

z = mean depth (m).

The morpho-edaphic index and its limitations have been recently reviewed by Schlesinger and Regier (1982).

A second useful predictor based on a number of African waters is the relationship described by Melack (1975) in which

$$\log Y = 0{,}113\ PG + 0{,}91 \qquad 2$$

where

PG = gross photosynthesis
($g\ O_2\ m^{-2}\ d^{-1}$).

These models may assist fishery managers to obtain first-order estimates which are useful in initial planning. Some similar models have been developed for flood-plains but their application to rivers and streams is uncertain. The major limitation on the development of these models is the poor quality of fisheries yield data from tropical and sub-tropical areas.

Technological

The efficiency of different gear types for capture of target species and the potential impact of any proposed gear on the stocks themselves, non-target species and environmental quality must be evaluated.

These data provide only a short-term solution to management problems.

Prediction can be improved by relatively advanced dynamic pool and surplus yield models (see Ricker 1975) if detailed fish population parameters are available. Constant monitoring of environmental conditions and of fish abundance, biology and community interactions will increase understanding of a system and assist in management. No comprehensive models exist which relate the characteristics and behaviour of fish stocks to their biotic and abiotic environments. The development of such predictive models would represent a major advance in fisheries biology.

7.4.3 CONSERVATION

An ideal conservation management philosophy would advocate the protection of every species (irrespective of its conservation status) in a variety of natural habitats which are free from unnatural influences. As a result of agricultural, industrial and urban pressures on many catchments this is seldom possible. Management for conservation requires a thorough knowledge of the distribution and environmental biology of fish as well as the presence of potential threats such as turbidity, siltation, water extraction, salinization, eutrophication, pollution, change in allochthonous input, alien species (predation, parasitism, hybridization, competition) and stream regulation.

The Southern Hemisphere has several systems with unique endemic fauna which should be conserved For example 90% of the 500 species occurring in Lake Malawi are endemic to that system. The balance of the community structure and the existing fisheries could be destroyed by large scale effluent discharge into the lake or by the proposed introduction of *Limnothrissa miodon*. The Olifants River system in the western Cape contains 10 species of which nine are endemic. Five of these are listed as threatened in the South African Red Data Book on fishes (Skelton 1978). In Australia there are approximately 200 indigenous species and the native fish fauna is already threatened by introduced alien species. One quarter of the fish species occurring in the Murray-Darling is made up of alien species (Walker 1983), indicating the need for caution in proposing introductions to increase yield.

7.4.4 WATER QUALITY

The consequences of water quality changes on fish are well documented and referred to earlier (Section 7.3.4). The influence of fishes on water quality is less well known and frequently overlooked. Their role in affecting water quality should therefore be considered in management planning. Some of these effects include:

- Fish act as nutrient reservoirs although harvesting of fish can contribute little to nutrient removal in most situations.

- Studies on the role of fish in waste treatment lagoons generally concluded that they improve the efficiency of these systems. Several explanations have been put forward to explain this but the true mechanism is still poorly understood.

- Grazing by fish can lead to resuspension of nutrients and inorganic particles as well as increasing phosphorus loads by changing phosphorus from an insoluble to a soluble form (Lamarra 1975). This may be ecologically beneficial in oligotrophic waters but a serious problem in eutrophic ones.

- Selective grazing by planktivorous fish can lead to the elimination of large zooplankters. This may permit phytoplankton to increase in abundance and could lead to a deterioration in water quality (Nakashima and Leggett 1980).

- Fish have often been used to control other organisms and so influence water quality. A well known example is the use of Sarotherodon galilaeus to control undesirable blooms of Peridinium in Lake Kinneret, Israel (Gophen et al 1983). Fish may also be used to control macrophytes, not always with beneficial effects (Junor 1969), other fish species or insects and molluscs which affect human health.

7.4.5 SYNTHESIS

The main management aim in natural lakes and rivers may be harvesting of the fish, whether for food or other uses (eg Lake Malawi cichlids and Amazon species for the aquarium trade). If the systems are pristine, management for conservation should also be considered, and the natural species diversity and essential ecological processes maintained.

Artificial reservoirs are constructed with one or more primary aims which do not include utilization of the fish. The construction of a reservoir, however, results in greater fish production which can be utilized. In addition, the system is artificial, preservation of natural status is no longer an issue and greater management and manipulation of conditions, within the impoundment, are possible. Earlier discussion (Sections 7.3.3 and 7.3.4) demonstrated the way in which manipulations of the water system can affect fishes. Early liaison between user agencies and biologists could alleviate many conflicts and optimize fish production with minimum disruption to management for the primary aims of the dam (see Chapter 2).

7.5 SUMMARY

- The Southern Hemisphere may be divided into highly industrialized areas where demands on water are high and fisheries have a minor role, and areas of high water availability but frequent protein shortages where inland fisheries are important in maintaining the quality of life.

- Fish in natural systems are subject to natural constraints by energy and nutrient supply, climatic and edaphic factors and the fish community structure. These constraints are frequently aggravated by man-induced changes such as turbidity, eutrophication, salinization, habitat alteration and over-fishing.

- Management techniques aimed at the optimal use of fishes under varying water quality differ according to the management aims. Species introductions can increase the yields of a newly created habitat or water body which has been extensively manipulated by man but may severely disrupt community structure and production in a stable, natural system. Successful management is dependent on a holistic approach which takes into account the characteristics and present and future use of the whole catchment.

- Parameters based directly or indirectly on water quality, such as morpho-edaphic index and primary production, can be used in conjunction with knowledge of the fish community to indicate potential yield of the fish population.

- Successful long-term management, for whatever purpose, requires a thorough understanding of the biology and population dynamics of the relevant fishes, their relationships with other biota and their dependence on the physico-chemical environment. Rational fisheries utilization is only possible if there is adequate control of the environmental, particularly water, quality. This requires communication and cooperation between all water users and managers.

7.6 RESEARCH NEEDS

- Long-term catchment studies to quantify the relationship of fish production to environmental quality in different kinds of waterbodies.

- Further studies on the impact of salinization, turbidity and eutrophication on fish diversity and production.

- The role of fish in regulating water quality, particularly in waste systems.

- The importance of autochthonous and allochthonous detritus as a food source for fish.

- The effect on fish production of dampening environment fluctuations by stream regulation. Such studies should cover large and small lotic systems and their estuaries.

- The impact of toxic pollutants and acid rain on fish production and suitability for human consumption now and in the future.

- The role of suspensoids as vehicles for the transport of nutrient and toxic materials in aquatic systems and its significance to fish production.

- Methods for long-term management, involving predictive, comprehensive models of the response of harvested fish populations to environmental changes.

- Conservation strategies including the needs for fishways and fishladders to conserve natural fish communities in regulated river systems.

7.7 MANAGEMENT RECOMMENDATIONS

- Water systems which have not undergone major artificial perturbations should be identified and managed to maintain water quality. Where a need can be demonstrated, management should attempt to conserve the indigenous fish fauna and habitats.

- The increased fish production offered by new impoundments should be utilized for commercial or recreational use. Pre-impoundment studies should be undertaken to assess the ability of the indigenous fish population to utilize newly created habitats.

- In turbid systems, reduction of suspensoids should be brought about by more effective soil erosion abatement methods, bank stabilization and in-stream sediment traps (Bruton in press).

- In eutrophic systems, management should be aimed at reducing adverse physico-chemical effects and the abundance of blue-green algae. Optimal conditions for fish production should broadly coincide with the quality requirements of domestic and industrial users.

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GLOSSARY

absorption coefficient (a)	describes an inherent optical property (a), across an appropriate spectral range. Units m^{-1}
adfluvial migrations	migrations up or down a river
albedo	the fraction of incident solar radiation that is reflected at the water surface.
algal growth potential	the potential of a water to support algal growth in terms of the algal mass which can be grown
alien	a species not native to a given geographical area
allochthonous	arising from outside the system under consideration. In streams, allochthonous organic matter is derived from outside the stream itself (see autochthonous)
allogenic rivers	rivers rising in humid regions and flowing through arid regions (eg Nile, Murray, Orange-Vaal)
attenuation coefficient	the fraction of photosynthetically active radiation (PAR) that is absorbed and scattered by water. Units m^{-1}.
anaerobic/anoxic	devoid of oxygen
antagonist	a determinand which minimizes the effect of another determinand
autochthonous	material produced within the ecosystem (see allochthonous)
baseflow	the flow of water entering stream channels from groundwater sources in the drainage basin
beam attenuation coefficient	describes the extent to which light of a particular wavelength is absorbed and scattered while passing through a medium. Units m^{-1}
benthos	organisms living on or in the bottom of an aquatic system
biomass	the mass of living material present in the water; growing from the sediment or living upon or within it at a given time

biota	the array of living organisms in an ecoystem
biotic diversity	either the number of different kinds of living organisms or the evenness of their relative abundance
carcinogenic	cancer causing
catchment	an area from which water runs off to any given river valley or collecting reservoir: the drainage basin of such a river system
chlorophyll	the green photosynthetic pigment found in plants. The most common form is chlorophyll _a_, however, in this document no attempt is made to distinguish between the different forms
collector	an invertebrate animal that feeds by filtering small particles from the water
conductivity	an approximate measure of total dissolved salts or solids. The reciprocal of the electrical resistance at a stated temperature through a cube of stated dimension (usually as Siemens cm^{-1})
conservation status	the state of an ecosystem with regard to the influence of man
conservative/non conservative determinand	a conservative determinand does not lose its character or concentration upon entry into the environment; a non-conservative determinand may lose its character or concentration upon entry into the environment
criterion	a number against which the concentration of a determinand is assessed. It is not legally enforceable (see standard)
determinand	implies that which is determined
detritus	aggregate of fragments of a structure, or of detached or brown down tissues
detritivore	an animal feeding on detritus
diatoms	small, single-celled algae with a silicaceous cell wall which may form colonies

dimictic	lakes or reservoirs which overturn twice a year
disease vectors	organisms, such as mosquitoes, which transmit malaria
ecological diversity	the variety of organisms in a particular habitat
ecosystem	ecological system formed by the interaction of co-acting organisms and their environment
edaphic	pertaining to, or influenced by conditions of soil
elvers	young eels
endorheic basins	closed basins, ie with no exit for run-off to sea. Generally, salt lakes are the termini for rivers and streams in such basins
energy base	the primary source of energy for an ecosystem. This may be photosynthetic plants, as in a lake, or terrestrial leaf material, as in a headwater stream
environmental influence	the action of the sum-total of external influences acting on an organism or on part of an organism
epilimnion	the warm, upper circulating water of lakes and reservoirs
euphotic zone	the upper section of a water mass penetrated by light of sufficient intensity and of suitable wavelength to promote photosynthesis by aquatic plants. For convenience of quantitative definition, that depth reached by 1% of the light passing through the water surface during the period of maximum illumination
exotic (see alien)	
fauna	animals
fecundity	the number of eggs or individuals produced; an index of the reproductive potential of a species
floodplain	that part of a river basin which is inundated at times of high flow

flora	plants
fry	juvenile fishes
functional feeding	groups of organisms with the same functional role in an ecosystem (eg collectors, predators, etc)
halophyte	salt-tolerant plant
heterogeneity	of different kinds of habitats
hypolimnetic	(adj of) hypolimnion: referring to the cold water below the thermocline in deep lakes and reservoirs
hypolimnion	the water between the thermocline and bottom of lakes
indigenous	organisms native to a particular area
instream flow	the minimum requirement for the continued functioning of a stream ecosystem (for example after the construction of a dam)
invertebrate drift	otherwise benthic (qv) organisms temporarily in the water column of streams
lentic	standing waters (opposite of lotic)
life-cycle	the various phases through which an individual species passes to maturity
lotic	flowing waters (opposite of lentic)
macrophyte	large aquatic plants, macroscopic in size which include large forms of algae, mosses, ferns and higher plants
meromixis	a phenomenon seen in standing waters in which the seasonal overturns do not stir the entire water column, but leave an undisturbed mass of water below so that distinct chemical differences (and often pronounced salinity differences) occur
methylhaemoglobinaemia	disease, especially of infants, produced by high nitrate concentrations in drinking water
mineralization	the conversion (by microbiota) of organic material to mineral salts [sometimes used as a synonym for salinization, a practice to be discouraged]

multivoltine	insects completing several life-cycles (qv) in a single year
mutagenic	producing genetic change
network design	a process of selection of determinand sampling sites and frequency
oligotrophic	poor in nutrients, and therefore, usually with low abundance and production of living organisms
organic	carbon-containing and, in an ecological context, of biological origin
organoleptic	having a taste and odour effect
pathogenic	disease causing
phytoplankton	the plant portion of the plankton
piscivorous	fish-eating
planktivorous	plankton-eating
plankton	small, free-floating plants and animals with feeble powers of locomotion
primary producers	organisms which are capable of producing organic material by the process of photosynthesis
production	the amount of living material produced by an ecosystem in unit area or unit volume in unit time
reuse of water	reuse implies that the same water is successively used for the same purpose
riparian	frequenting, growing on, or living on the banks of streams or rivers
salination	see salinization
salinity	sum of dissolved ionic material (salts) present in a water mass. Expressed in this chapter as mg l^{-1}
salinization	the process whereby the concentration of total dissolved solids in inland waters is increased
scattering coefficient	the fraction of light of a particular wavelength that is scattered in passing through a medium. Units m^{-1}

secondary producers	organisms which depend on a supply of organic material from the primary producers for their growth
sequential use	sequential use implies successive use of the same water for different purposes
shoreline development	measured as the ratio between the shoreline length of a given water body and the circumference of a circle of the same area. Gives a measure of the extent of inlet and bay development around the shore
sodicity	pertining to the sodium ion content of soils in particular
species	a reproductively isolated aggregate of actually or potentially interbreeding populations
standards	see criterion. The difference is that a standard is legally enforceable
standing crop	the mass of animal or plant material that can be sampled at any one time
stormflow	the flow of water entering stream channels as a result of rainfall
stream order	refers to a system of classification wherein a first-order stream has no tributaries, a second-order stream is formed by the confluence of two first-order streams and so on
synergistic	a determinand that enhances the effect of another determinand
tailwaters	the segment of a river below a dam, where the physical, chemical and/or biological effects of the dam are detectable
taxonomic	(adj of taxonomy) the study involving identifying and naming species of organisms
teratogenic	causing congenital anatomical abnormalities
thermal stratification	the layering of the water mass as a consequence of a thermally induced density gradient within the water column

total nitrogen	the nitrogen content of dissolved and undissolved material in unfiltered water measured as nitrogen
total phosphorus	the phosphate content of unfiltered water measured as phosphorus
trihalomethanes	trisubstituted methane derivatives by halogens
trophic structure	the structure of the food-web involving organisms of different feeding types
vertical attenuation coefficient (K)	Describes the extent to which photosynthetically active radiation (PAR) is absorbed and scattered by water. Units m^{-1}
wetland	a shallow, fluctuating waterbody heavily dependent on rooted aquatic vegetation for its primary energy inputs
yield	the mass of fish removed, by man, from a given system
zoobenthos	the fauna living in or on the bottom of rivers, lakes and reservoirs
zooplankton	the animal portion of the plankton

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