# An Introduction to the Management of Inland Water Ecosystems in South Africa

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Prepared for the
Water Research Commission
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# An introduction to the management of inland water ecosystems in South Africa

## Part I

## General description

### 1. Introduction

The study of inland water resources and their availability is the responsibility of both the limnologist and the civil engineer. The limnologist practices the science of Limnology which describes the properties of raw water supplies and how they are likely to respond to natural or manmade changes. The civil engineer is responsible for designing and building the engineering structures such as dams and reticulation networks which ensure that the resource can be tapped and distributed to a demanding public.

For the past fifty years there has been, in South Africa, a determined effort on behalf of freshwater ecologists, chemists and physicists, collectively known as limnologists, to understand the way in which freshwater ecosystems function. The rich scientific record that has been built up is unfortunately not always readily available to managers so that it is reasonable to assume that its message is unknown to them.

I have attempted to translate this scientific record into a readable account of the properties and functioning of freshwater ecosystems. In so doing I hope it will assist managers of local or wider responsibilities with respect to water resources and supply in their communities, to appreciate the deeper structure and functioning of this resource; and in so doing help to restore damaged river systems or parts of such systems and so conserve (in the sense of making *wise* use of) this vital resource. Its relevance to the current Restoration and Development Programme (RDP) of central and provincial governments is immediate, and those responsible for the supply of potable water to our diverse communities should find this contribution of use in both individual and corporate efforts to provide input to the RDP.

There are perforce a number of terms which may be new to the reader. Where possible they have been explained in the text at the point of introduction. In this way we have avoided the compilation of a glossary. There is however one term which does need understanding right from the start, namely the word "ecosystem". While "ecosystem" is widely used, its precise meaning tends to become blurred with usage. For this reason it is important to emphasise the meaning of the term and the concept it describes early in the text.

The term "**ecosystem**" was introduced into the vocabulary of ecology in 1935 by a British plant ecologist, H.G. Tansley, to describe a community of plants interacting with their non-living or abiotic environment. In the case of animals, including Man, the interaction results in the flow of energy from the energy fixing processes of plants through trophic or feeding levels, and the establishment of material cycles which are the exchange of materials between the living and non-living parts, for example the nitrogen and phosphorus cycles. The value of this term was quickly appreciated in the developing science of **ecology** as it neatly brings together the living and non-living components of the wide diversity of environments which together make up the **Biosphere**, i.e. all the earth's living organisms, and the way they interact with the physical environment. There are obviously a large number of ecosystems in the Biosphere of Earth.

What we must recognise is that, almost without exception, human beings have made material inroads into these ecosystems and with considerable impact. A low level flight over any part of southern Africa confirms the intensity of *our* impact. Thus we cannot properly describe the freshwater components of South Africa without appreciating the role of Man as an ecological agent.

Figure 1a. The Drakensberg escarpment in the vicinity of Graskop, Eastern Transvaal.

Figure 1b. Blyde River Canyon, Graskop, Eastern Transvaal.

Figure 2a. An aerial view of the south basin of Lake Sibaya showing incipient segmentation and proximity to the sea.

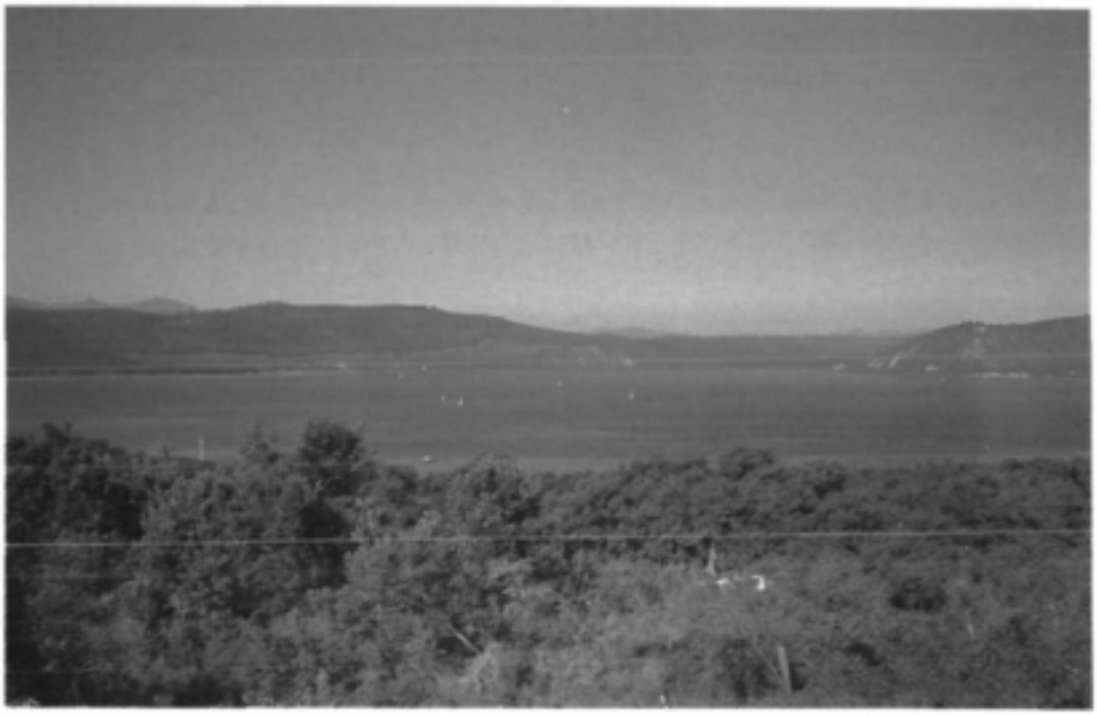

Figure 2b. The barrier lakes of the Wilderness embayment.

## 2. The nature of the freshwater ecosystems of South Africa

South Africa is a semi-arid country. The low average rainfall and the low mean annual runoff (MAR), 8.6%, of mean annual precipitation has forced the construction of an array of major and minor dams in the continental rivers and the planning, design and construction of a variety of inter-basin transfer systems.

But apart from the semi-aridity of the continent, those very pronounced sculpturing agents of the landscape, such as glaciers and coastal rifting, have not been significant geomorphological aspects in southern Africa in comparatively recent geological time. Indeed the great pediplain of southern Africa remained free of major tectonic activity for very long periods of time (some 80 million years), but during the closing stages of the Pliocene it was subject to considerable tectonic upheavals which elevated the interior plateau and escarpment (Figures 1a & 1b) to the levels with which we are familiar today.

Since the separation of Africa from Gondwanaland, the coastal rimland of the southern subcontinent has been subject to successive elevations and subsequent coastal abrasion or wearing down. This coupled with the major tectonic uplift of the Drakensberg to the east, the Cape Fold mountains in the south and the Namibian massif in the west all combined to define the pattern of river drainage in the subcontinent.

A particular feature of these events was that none was responsible for lake building processes on the subcontinent. Rivers dominate the hydrological scene. There is in fact only one lake of fluvial origin, Lake Fundudzi in the Zoutpansberg mountains, which was formed by faulting in the Mutale River valley. All other lakes (Figures 2a & 2b) are to be found in the coastal rimland and are of either ancient or modern estuarine origin.

The "Highveld" plateau apart from the extensive meanders of its traversing rivers is also characterized by numerous wind-blown basins called "pans" which are ephemeral, being filled during periods of high summer rainfall.

Two major geomorphological features of the coastal rimland define to a very large degree the nature of the coastal rivers. The first are the ancient Cape Fold mountains (Figure 3a) of the Cape South Coast, which lie parallel to the coast and result in a series of rainshadow areas increasing in severity as one moves away from the coast. The semi-arid Little Karoo and Great Karoo are the result of the impact of the Cape Fold Mountains upon the rainfall (Figure 3b). The second is in Natal, where the elevation of the coastal spine (the Natal Monocline), and the subsequent rejuvenation of the coastal rivers has resulted in deep valleys and rivers the quality of which has become materially influenced by the activities of Man in their catchments.

The present geomorphological structure which these events created emphasises the rivers as the principal and dominant feature of South Africa's limnological landscape. This riverine-based inland freshwater ecosystem (Figure 4) is constructed from two components: (1) the river channel and its flowing water, and (2) the associated wetlands. Together they form a structural and functional entity, the physical, chemical and biological interactions of which define the ecological processes of this dominant freshwater ecosystem.

Even within the comparatively steep coastal river systems of, for example, Natal or the Cape South Coast, wetland fringes are frequently found associated with the short coastal floodplains where they occur. Where coastal lakes occur at the heads of estuaries, e.g. Swartvlei, Wilderness, the peripheral wetlands (Figure 5) are (were naturally) more extensive.

Because glacial activity during the Pleistocene (45 000 y BP) did not influence the subcontinent directly, extensive floodplains as found in Europe, North America and Russia are absent. And while the rivers meander across the ancient Gondwana-derived landscape, the Highveld, they do so in deep channels. Nevertheless, the episodic nature of river flow in southern Africa, particularly where catchments are substantial in area, e.g. the Zambezi River and even the smaller Pongolo River, results in summer or winter flooding of the adjacent

Figure 3a. The ancient Cape Fold mountains. Meiringspoort, Swartberge.

Figure 3b. The Outeniqua mountains in the vicinity of Oudtshoorn. Note the aridity of this rain shadow area.

Figure 4. Stream and its wetland.

Figure 5. Wetlands of the estuary.

wetlands and pans. This episodic event is of major significance to fish breeding and human subsistence agricultural activity, e.g. in the Zambezi valley upstream of the Kariba Gorge. The infrequent flooding of the Orange River valley is often disastrous as it was in the summer of 1989 following a series of initial cut-off low pressure cells over the subcontinent.

### 3. Climate and its imprint upon the hydrology of the subcontinent

The mean circulation of the atmosphere over southern Africa is anticyclonic throughout the year. This circulation establishes the south-easterly flow over the subcontinent in summer and as the high pressure cell moves northwards with the translocation of the intertropical convergence zone in winter, there is an equatorwards shift of the westerlies which brings a Mediterranean climate to the south-western Cape with pronounced winter rains.

These broad climatological patterns imply an eastern area of summer rainfall, a south-western winter rainfall belt, a southern coastal belt of less specific nature and an arid western region. This pattern is illustrated in Figure 6. The data from which the means were derived have been subject to appropriate analyses by the Climatological Unit at the University of the Witwatersrand. Analysis of these rainfall patterns has shown the existence of at least three rainfall patterns, each with a different periodicity of peak values. The strongest spectral peak is associated with a wavelength of 18-20 years and has been found in summer rainfall areas subject to anticyclonic disturbances and shown as Region 1 in Figures 7 and 8. Region 2 has a mean wavelength of 10 years and the winter rainfall Region 3 has a completely different spectrum from those of the other regions. Here a 40-year peak is dominant, but at present this major peak is difficult to interpret as the data series is too short, so it is not resolved.

Returning to the summer rainfall region, it has been shown [1] that runoff and rainfall show the same oscillating feature or character with a wavelength of approximately 20 years. The implication for drought and flood prediction is obvious provided that the general circulation of the atmosphere over the subcontinent does not materially deviate from the pattern over the last sixty years ! You will see that Figure 7 predicted that the 1980's would be years of serious drought; how serious may be judged from this figure where, for example in 1982, the actual rainfall was 65% of normal.

Not only have the 1980's seen one of the most crippling droughts of this century in the summer rainfall region of the subcontinent, but we have also witnessed, during the summer of 1987/88, the devastating consequences of two major rain-producing synoptic systems. The first is the more intense form of westerly trough, the cut-off low which is associated with strong convergence and vertical motion; the second and easterly low pressure system in which surface convergence occurs to the east of the low with strong uplift resulting in heavy rains to the west. This system caused extraordinary floods over the catchment of the Orange River resulting in unprecedented flooding over the southern Orange Free State and northern Cape Province.

These cataclysmic events, occurring as they did towards the end of a "dry" decade, will contribute new information about the *real* existence of climatological cycles of the subcontinent and emphasise the inherent within-cycle variability (Figure 9).

From this sort of evidence, the climatologists are continuing to build a picture of the changing weather patterns over southern Africa. And from their work involving extended data series there is little good reason to accept the often held view that the subcontinent is experiencing a decrease in rainfall which is responsible for "progressive desiccation". Other causes must be sought for desert encroachment from west to east among which is the impact of Man himself upon the fragile plant communities of arid regions.

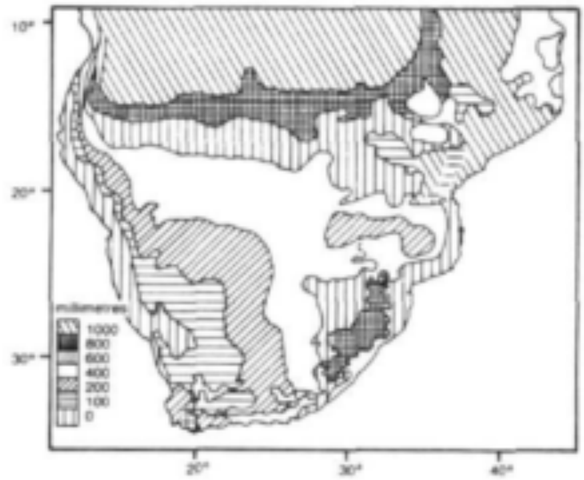


Figure 6. Mean annual precipitation over southern Africa.[2]

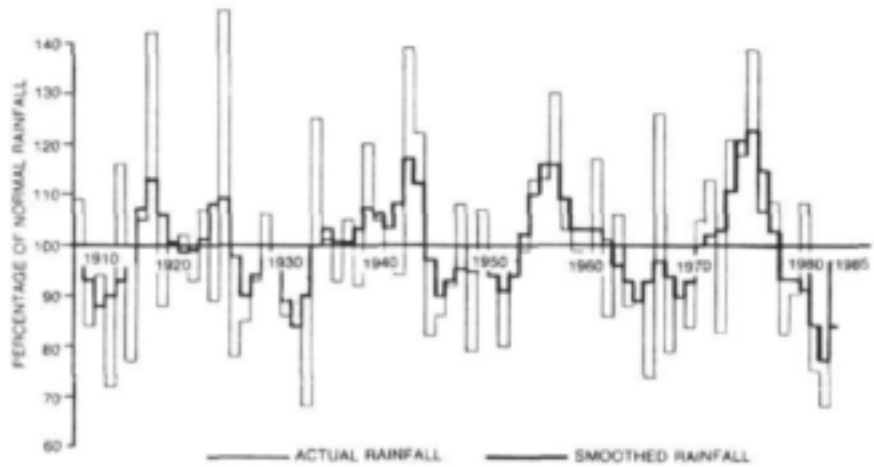


Figure 7. Rainfall patterns over southern Africa by various appropriate filtering techniques. Areally-averaged rainfall zones for the October to September year in the summer rainfall region (1910/11 to 1983/84).[3]

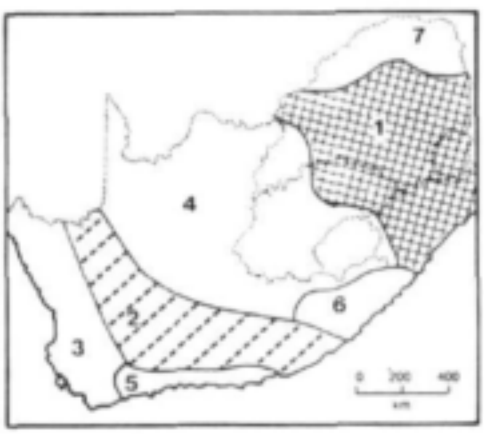


Figure 8. Rainfall regions derived from a principal component analysis of the annual rainfall totals for 157 recording stations over the period 1910-1972.[1]

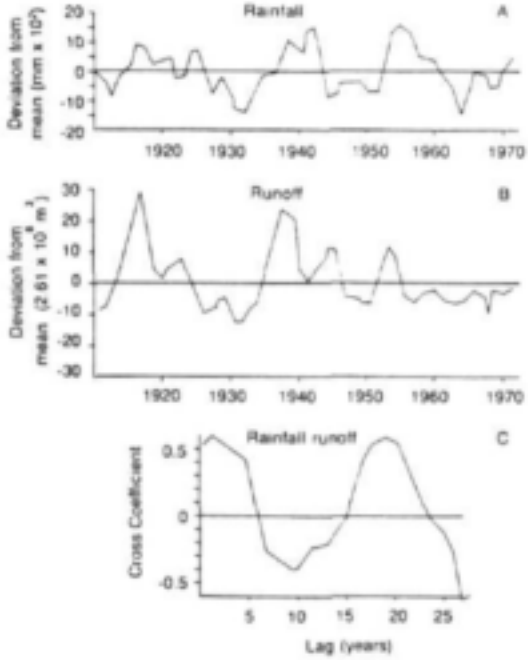


Figure 9. Concordance between deviations of runoff and rainfall in the summer rainfall region of the subcontinent.
A: mean percentage deviations for smoothed rainfall over the summer rainfall region of South Africa;
B: mean annual percentage deviations for smoothed runoff data;
C: the cross-coefficient between rainfall and runoff data which contains a wave with a period of the order of 20 years.[4]

Figure 10. Karoo encroachment over South Africa.[5]

Thus desertification and its camp followers of declining biological productivity, deterioration of the physical environment and increasing instability of human settlements and life affect southern Africa in very much the same way throughout the whole of Africa to the north of us. These authorities report that the whole of Namibia and Botswana and more than half South Africa are rated as potential desert. Large areas of the Cape Province and the Northern Transvaal are at very great risk !

Clearly the management of river catchments and their constituent aquatic ecosystems in these regions of the subcontinent is of paramount importance to stem the advance of the desert which has been assessed at some 1.6 km per year. Figure 10 illustrates how extensive is the main Karoo encroachment closely followed by desert.

We continue to ignore these real events at our peril. Thus the purpose of this introduction is to make us more aware of the urgent need for sensitive management of the freshwater ecosystems of South Africa. Later (in Part II) we will examine our influence on these ecosystems and how we may restore and maintain ecological viability.

## 4. The riverine or lotic (flowing) ecosystem

The water which flows down the river channel is a unique substance. It is chemically a hydride of oxygen, i.e. an atom of oxygen to which two atoms of hydrogen are attached. It is the only hydride of all the gases which make up the atmosphere of Earth which is liquid at the average or mean temperature of our planet. The other common hydride is of nitrogen, namely ammonia, which is a gas at the mean temperature of Earth. Water is the universal solvent with low viscosity and possesses a high specific heat: properties without which life as we know it would be unsustainable. The thermodynamic properties of water are such that chemical reactions can take place at ambient temperature at sufficient velocity or speed. All living things depend upon these properties to exhibit the uniqueness of life.

It is perhaps the universality of this fluid which so severely restricts our appreciation of its remarkable nature and our utter dependence upon it! But, notwithstanding, the treatment by human beings of the River and its valley remains the most serious threat to the sustained supply of potable water to the world's increasing populations.

The way we look at rivers depends very much upon our understanding and needs. We might expect a water resource manager, acting essentially as an applied ecologist, to see a river as part of a drainage network subject to the behaviour of physical, chemical and biological elements characteristic of the system. Thus central to all water supply remains the river and its valley, other than in the areas or countries which depend almost solely upon underground sources. As managers of natural or raw water resources the primary criterion of management must be to ensure that the flow down the river channel is sustained and of good quality. A feature of this hydrological parameter is the "base flow" of the river. Up until quite recently the wider ecological and environmental implication of the base flow of a river was poorly understood. River ecologists at the University of Cape Town and Rhodes University have established the dependence of a wide variety of river plants and animals upon this base flow. Recently EMATEK, Stellenbosch, have confirmed the absolute necessity of baseflow in rivers to maintain an open mouth condition in estuaries. These hitherto quite unsuspected findings underline the need for continuing research to uncover the unexpected !

It is from their studies that the river and its living systems have been recognised as legitimate users of water and as such these rights have to be respected. It is by no means uncommon to hear in public forums that to see some 90% of the mean annual runoff of a river flow into the sea is wasteful. Such opinions are based on our failure to understand these legitimate needs and the consequences if we ignore them.

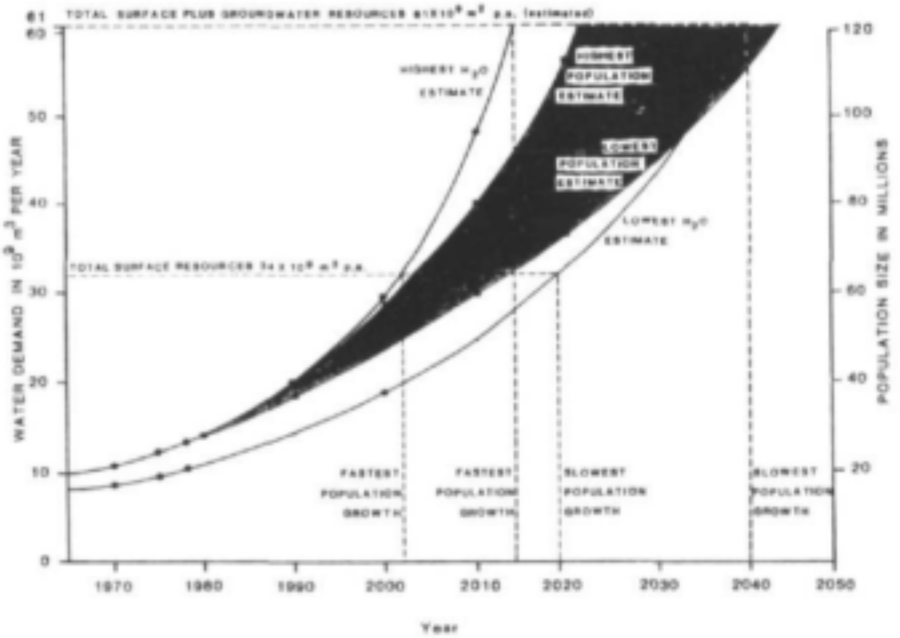


Figure 11. Water demand against population growth over time for South Africa, projected to 2050.[6] These curves illustrate "best" and "worst" water consumption projections and include the current estimates of available surface and groundwater resources for the region (total 49-59 x $10^9$ $m^3$ $a^{-1}$).

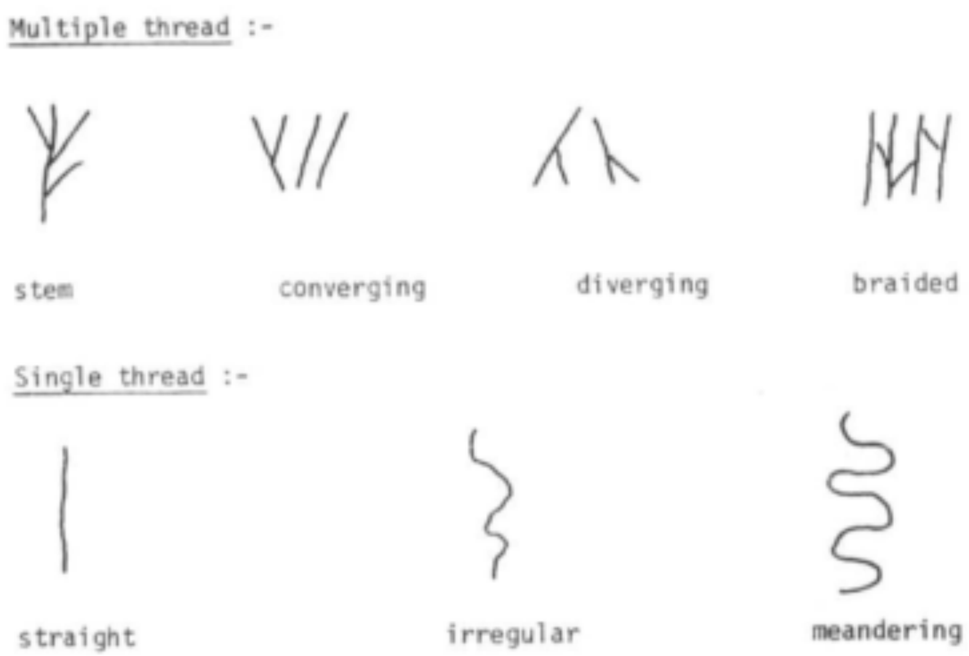


Figure 12. Types of river channel: River channels can be divided into multiple and single threaded water courses.[7]

The supply of surface water in South Africa has a finite limit (Figure 11): by 2020 it is estimated that demand will exceed supply and the resources of neighbours, possibly better watered neighbours, will have to be sought. Already the translocation of water flow from one catchment to another or from one national state to another are essential developments: that of the Lesotho Highlands Water Scheme is the most ambitious to date. It is expected that 2200 x $10^6$ million cubic metres of water per year will be supplied to the PWV area by 1998. Entry of this source into the South African river system is via the Leibenbergsvlei stream, a tributary of the Vaal River.

***River hydrology*** - Let us begin by asking a question to which there is no completely satisfactory answer and which has challenged the human mind for a very very long time:

"Why doesn't a river flow in a straight line ?"

Professor Alexander[7] argues that the answer to this question is that "a straight course is the most unlikely course that a river will follow" ! Indeed, long straight channels are very rare; their lengths when they do occur are rarely greater than 10 times the channel width. Much more common are the types of river channel shown in Figure 12.

Note that where long straight channels do exist, in the Vaal-Orange at their confluence and in the gorges below Victoria Falls, they are usually due to geological controls. Where such controls are absent, as for example on alluvial plains, rivers do not flow in straight, single-thread channels. We know that the flatter the valley type, the more sinuous the river course. Some of the rivers in the Transkei are markedly meandering; the Collywobbles of the Bashee River are a very good example of incised meanders; yet another are the incised meanders of the Great Fish River and of the Grootrivier through Meiringspoort (Figure 13). These incisions are due to the geological uplift which the surface has experienced in past geological time.

Another type of drainage pattern, "consequent drainage", is often found in the elevated plateau of the Highveld. These arise as a result of drainage patterns being laid down initially in the ancient covering of soft erodible rocks of the Karoo system. We may suppose that the rivers in developing their drainage pattern in this soft Karoo sediment which covered the entire subcontinent, when they reached the harder, more durable undermass the established course of the river was maintained and as the Karoo surface was gradually and persistently eroded, the gorges or "poorts" which the rivers had carved became visible. Hartbeespoort is a particularly good example of this event. Without this superimposition of drainage pattern it would be difficult to explain how rivers cut perpendicularly through hard quartzite ridges.

Clearly none of this would be possible without both the supply of energy and its consumption. Thus standing water in a river catchment has an energy potential equal to the height of the surface of the water above sea level. When water commences to flow down a slope some of the potential energy is converted into energy of movement or kinetic energy. This kinetic energy is consumed in a river by a number of processes which are interdependent.

The first and most obvious: *translational movement* which maintains a forward flow by overcoming resistance within the water body, and maintains the net forward movement of sediment by overcoming the gravitational attraction of the sediment particles and their frictional resistance.

The second: *rotational movement*, which overcomes the shear resistance within the water body and results in water rotating in a helical manner. This rotation is caused by factors such as bed roughness, the roughness of the river bank, sudden changes in cross-sectional area of the channel and changes in river flow.

The third energy-consuming process in rivers is the erosion and redistribution of bed material. The material which forms the channel bed is being conveyed downstream. This is a continuous process, for as long as the river flows energy is being continuously consumed through the erosion and deposition of sediments.

Figure 13. Meiringspoort in the Swartberge, near Oudtshoorn.
An example of an incised meander, Grootrivier.

***Chemical properties*** - The chemical properties of river water vary widely in South Africa. All are dependent upon the geological strata over which the rivers flow, and in South Africa we can divide the water quality of rivers between two main categories: (a) those which arise from the calcium-poor rocks of the Table Mountain Sandstone subject to winter rains and (b) those principally of the summer rainfall eastern areas. The rivers of the western Cape are acid (pH 4.5 - 6) and peat stained, while those of the east are usually turbid and alkaline with pH > 7.

Set within this broad environmental scenario is the inescapable truth that:

> "in every aspect the valley rules the stream. Its rocks determine the availability of ions, its soil, its clay, even its slope. The soil and climate determine the vegetation, and the vegetation rules the supply of organic matter. The organic matter reacts with the soil to control the release of ions, and the ions, particularly nitrate and phosphate, control the decay of litter, and hence lie at the true root of the food cycle". [8]

Notwithstanding the fact that Professor Hynes was writing for an international audience - or because of it - we recognize our common experience of the river system(s) and the valleys in which we live. As we increase the availability of soils through soil erosion so the suspensoids and turbidity of the flowing water increase. Likewise sewage and other organic effluents increase the organic matter to levels which rapidly exhaust the dissolved oxygen and the ability of water plants and the physical exchange coefficient to recharge the flowing waters. But by far the largest impact of Man's activities is upon the salinity of our rivers. Increased levels of total dissolved solids (TDS), a process known as salinization, is caused by irrigation and clear-felling in addition to the discharge of large volumes of sewage and mining effluent. In South Africa salinization is a hazard or potential threat in most areas west of the Drakensberg.

As Figure 14 illustrates, most of these areas have salinities in excess of 300 mg$^{-1}$, which in the management of water supplies is approaching unmanageable levels and is one of the reasons why translocation of large volumes of high quality water is so essential to the survival of the Witwatersrand complex ! Disregarding the impact on Man, the tolerance of aquatic animals to TDS is species-specific and a good deal of evidence is accumulating which suggests that alterations in the distribution patterns of individuals, species or communities are a result of changes in salinity. For example, a salt-tolerant amphipod (beach hopper), *Afrochiltonia capensis* has increased in numbers in the lower reaches of the Berg River presumably as a result of a permanent increase in the salinity of the lower reaches of the river, and changes in mayfly species distribution have occurred over the past 40 years.

While these faunal changes are still quite rare in South African rivers, changes due to ecotoxicity are increasing. Failure of controls governing the discharge of toxic water has reached serious levels in many rivers. Often this discharge is the indirect result of mining, and in particular of coal mining where disused or abandoned workings fill with water and the biochemical activity of sulphur bacteria upon the exposed pyrites in the coal seams produces sulphuric acid which is flushed out continuously from the mine and into the feeder streams of the mainstem river, e.g. the Olifants in the Eastern Transvaal! Such river water has a pH as low as 2.4 ! with little or no opportunity of natural neutralization from the surface rocks over which it flows. This already serious condition of some of the headwater streams of major Highveld rivers is being further exacerbated by acid precipitation (so-called acid rain) over the Eastern Transvaal (see also page 52).


Figure 14. Approximate regionalisation of surface water salinity in South Africa. Political boundaries have been ignored. Map based upon data derived from the Directorate of Water Affairs and WATERTEK, CSIR.

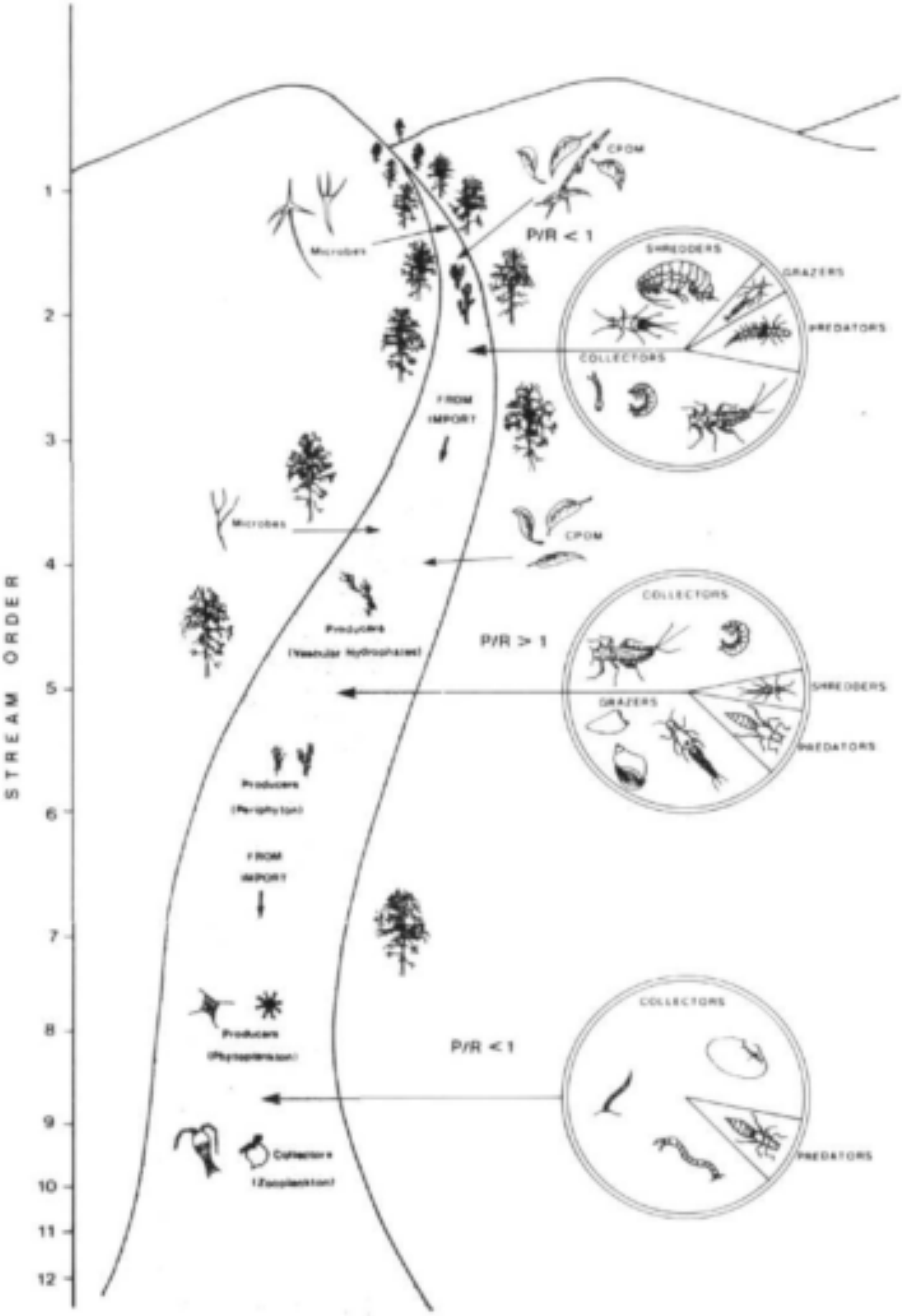


Figure 15. The River Continuum Concept. This refers to biological adjustments that occur along the environmental gradient of a stream. The stream order given along the vertical axis refers to the gradation as a stream flows from its source (low order streams) to where it has been joined by other streams (middle reaches) and finally where all its tributaries have joined to form the main stem river (lower reaches). CPOM = coarse particulate organic matter; FPOM = fine particulate organic matter; P = production; R = respiration.

***Biological properties*** - We see from these examples that river ecosystems are impacted by a variety of physical and chemical events. This raises the question: How do these systems respond to these unwanted events or occurrences? Fortunately the complex physical, chemical and biological structures of river ecosystems (as with many other complex terrestrial systems) possess the means whereby **reaction** to these environmental disturbances, under certain circumstances, may be established. River research both here and overseas has developed a framework of physical and biochemical structure which has generated useful models about how river systems function. One of the most useful suggests that plant and animal communities adjust to spatial resource gradients brought about by downstream changes in environmental conditions.

Essentially what we recognise is that the physical variables within a river system change progressively down the course of the river. Immediately obvious is the change from a shallow, turbulent, mountain stream to a deep meandering, lowland river. These changes, coupled with hydrological cycle and energy inputs, produce a series of adjustments in the biological community which occurs naturally in the river. These, together with changes in patterns of loading, transport, utilization, and storage of organic matter along the river length together form a continuum: the **River Continuum Concept** which is simply and diagrammatically illustrated in Figure 15 proposed by Vannote and his co-workers in 1980.[9] Using this concept we begin to get a better understanding of the way in which the river plants and animals change throughout the river's length and why and how they contribute to the operation or functioning of the river of which they are so intimate a part. To maintain our rivers in ecological conditions as natural as is compatible with Man's legitimate uses, recognition must be given to the existence of different river zones, and in determining river management policies, account should be taken of their different ecological characteristics.

This is an appropriate point at which to introduce the plant and animal groups which compose the living component of the lotic ecosystem. Although rivers receive a good deal of the energy used by animals from natural debris which falls into the river stream, for example leaves of trees and other riparian plants, some parts of the river do possess communities of algae and rooted vegetation which are adapted to live in the river's flow, provided that it is not too strong. River ecologists recognise that the headwaters of rivers are characterised by high current speeds and that under these conditions plants as primary producers are limited to thin films of algae which cover some of the areas of the rocky floor of the river. Figures 16a & 16b illustrate the high current speeds referred to in this paragraph.

Where water speed is reduced, even though the river bed may be pebbly with sand bars built up on the meanders, algal films are very much richer; and in deep water flows, rooted plants such as the sago pond weed *Potamogeton pectinatus* grow. Figure 17a illustrates something of the conditions described. In very large rivers, such as the Orange River (Figure 17b), the community of river plants becomes obvious where the substratum is not liable to severe scour during flooding, e.g. in backwaters.

As the flood plain is reached and river flow slows and deepens the community of river plants comes under the influence of water turbidity; where turbidity is high few plants can survive the low light climate and the community is once again limited to algal films on shallow sandbars and rocky zones.

This ecological scenario is summarised in Figure 15 where the ratio of production (P) to respiration (R) is reported in the form $P/R < 1$ or $P/R > 1$. The former implies that the respiration of the biological community is greater than the primary production available so that in this river zone the community of shredders and collectors depend on an energy subsidy coming from outside of the river flow. The latter tells us that the energy fixed by the plants is greater than the respiration of the community and little if any energy subsidisation is required. In this region the grazing insects and snails become abundant, reducing shredders, for example, to quite low proportions. In South African rivers this middle reach is the one which is most influenced by organic pollution. Here unstable effluents added to the river rapidly change the P/R ratio and values of $\ll 1$ are often found. This is treated in more detail on page 55.

Figure 16a. A headwater stream, Chapman's Peak, Cape Peninsula.

Figure 16b. Mountain torrent formed from waterfalls and cascades and in which the primary producers are limited to thin algal films on the rock surfaces. Blyde River, E. Transvaal.

Figure 17a. Upper reaches of the Biedouw River in the vicinity of Clanwilliam showing the rich submerged *Potamogeton* beds.

Figure 17b. The wide expanse of the Orange River near Colesberg.

A

B

C

Figure 18:

(A) Blyde River Canyon

(B) Van Ryneveld's Dam, Graaff Reinet

(C) A dry river course !

In the lower reaches, where the river water is turbid so that the light climate becomes inimical for water plants, the P/R of the biological community switches to energy subsidisation such that P/R < 1. You will appreciate that if this ratio becomes very small as a result of the addition of unstable organic elements, the chances of recovery are minimal and in extreme conditions septic conditions arise. The lower reaches of the Black River, Milnerton, are (or used to be) in such a condition! A number of the tributaries of the Vaal and Crocodile rivers flowing north and south of the Witwatersrand often exhibited this extreme. In recent years even the pristine streams of the Cape South Coast have been pushed to these limits!

Changes in the physical condition of a river by the addition of suspensoids, heated water, and conservative solutes (dissolved substances) such as the soluble salts of sodium, magnesium and calcium normally require the addition of fresh water to act as a diluent. Where this recourse is absent or restricted in volume, the effect upon the river is permanent until floods recharge the river flow. Even here we are not entirely free of, for example, increased salinization, because flooding of salt enriched soils does provide for persistent leaching into the stream bed of water high in dissolved solids.

On the other hand organic wastes, which are essentially reduced carbon compounds developed by the autotrophic process of photosynthesis and the heterotrophic metabolism of animals including Man, are, provided the loading of the river is not in excess of its self-purification capacity, oxidized in part by bacterial action to $CO_2$, and allow increases in plant and animal biomass as a result of the increase in nutrients and available food. Because of this reaction, and provided that the organic discharges are not at the same time toxic, the biological response to such inflows is immediate, see page 54. This response has been studied in many river systems throughout the world and, with small variations, is by and large of a similar nature. Thus whether we are asked to examine a stream in Europe or on the Witwatersrand we can recognize the similarity of the biological reactions.

**5. Lakes and reservoirs**

There are no lakes of immediate economic importance in South Africa, ie. used as a raw water supply or for transport of goods. Those that do exist principally along the coastal rimland are used as conservation or recreational foci such as the Wilderness lakes, Swartvlei, Sibaya (Figure 2a) and the Kosi system in Kwazulu. The Panneveld of the Orange Free State is the remnant of a much more extensive system of shallow pans which extended over large areas of the western Highveld some 40 000 years ago. There has been some significant increase in number provided by artificial pans created by the gold mining industry. Lake Fundudzi, in the Zoutpansberg, is the only inland lake of any size or depth on a river in South Africa, and remains a place of tribal significance for the Venda people.

Thus the creation of reservoirs or man-made lakes was an early priority in the agricultural and urban development of South Africa. With the special case of underground resources in significantly arid areas, the total water demand of South Africa has to be met very largely from its impounded supply. The existing major dams in South Africa have a total capacity equivalent to 50% of total mean annual runoff (MAR) and receive virtually the total runoff from the interior plateau.

The Department of Water Affairs and Forestry records an estimated demand of 22438 $m^3$/a by the year 2000 AD and 25888 $m^3$/a by 2010. These represent 44 % and 50 % respectively of the virgin MAR of the primary drainage regions of the Republic. And according to the report of the Department, with our present state of knowledge and technology only some 62% or 33 000 million $m^3$ of the MAR can be exploited economically. Underground sources may add some 5400 million $m^3$.

Clearly, impounded water (Figure 18a) represents the water credit balance upon which the social and economic structure draws. Deficits not only in the shape of dry dams (Figures 18b & 18c) but also due to the misuse of the impounded water are everyday experiences. While little can be done to fill an empty dam, the water quality of those impoundments which are filled is material to the ready availability of supply. Thus the management of impounded waters is becoming increasingly important in our hydrological affairs. Certainly the management of flow from dams is well handled by the engineers: we are on somewhat less certain ground once the properties of the lake behind the dam are brought into an equation of management, although why this should be so is surprising in view of the rich source of research data available for South African impoundments: they are a major man-made influence upon the river ecosystem.

If there are no impoundments on a watercourse, 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 to 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 (e.g. 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 as a result of 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 (e.g. water hyacinths in the Vaal River).
* 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.

Common questions which need attention relate to the quantity and timing of water releases from a dam required to maintain a stable river ecosystem, for example the Pongolo River, and estuary, e.g. the Great Brak River estuary, and the possible appearance of aquatic pests such as water weeds with the commissioning of a new hydrological regime. A first-stage management guide would be to aim for a release pattern which simulates the natural river condition as closely as possible; and with the restricted flows present in impounded rivers every effort should be made to reduce the input of pollutants.

***Physical properties*** - The thermal properties of reservoirs and lakes are governed very largely by events similar to those in rivers, but the very act of decreasing current speed, so increasing retention time and depth, draws into focus the degree of stability within the water column which heating of the surface waters brings about. While in South Africa this is the primary stabilizing agency, stability brought about by saline inflow is an important (and often overlooked) feature of coastal lake systems in which tidal ingression of sea water takes place from time to time, e.g. Swartvlei; Lake Mpugweni in the Kosi system.

Once a river flow is dammed, the properties of the resulting water column behind the dam differ (substantially) from those of the flowing river. It is not that there is a substantive change; it is rather one of degree. While flow is greatly reduced, it nevertheless remains an important feature of the limnology of the reservoir. This greatly reduced flow coupled with the very marked increase in water depth results in the thermal stratification of the water column during summer (Figure 19a). In the Southern Hemisphere the temperature gradients and their seasonal occurrence are more predominant than in the Northern Hemisphere. The temperature range is fixed by the winter inflow of cool water and the rapid surface heating in early summer. The resulting temperature range in quite deep reservoirs, certainly 15 m or more, is 10°C or even 15°C during the peak summer period. Because this is combined with an overall elevated mean temperature, a pronounced warm and therefore buoyant surface mixed layer is developed which characterises these reservoir lakes.

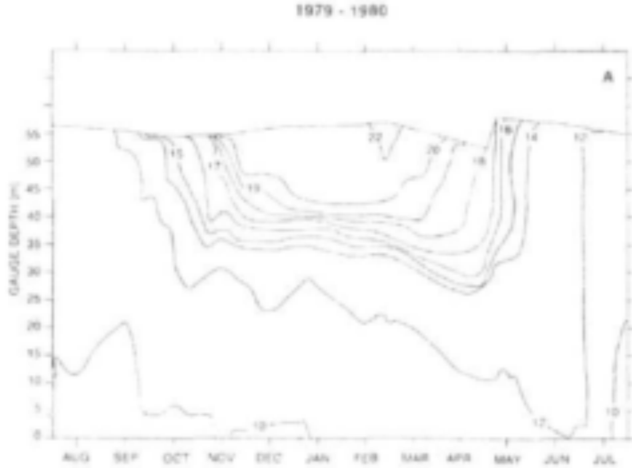


Figure 19a.
The seasonal stratification in a South African monomictic reservoir in which there is an upper mixed layer and a deep hypolimnion below the stratified layer.

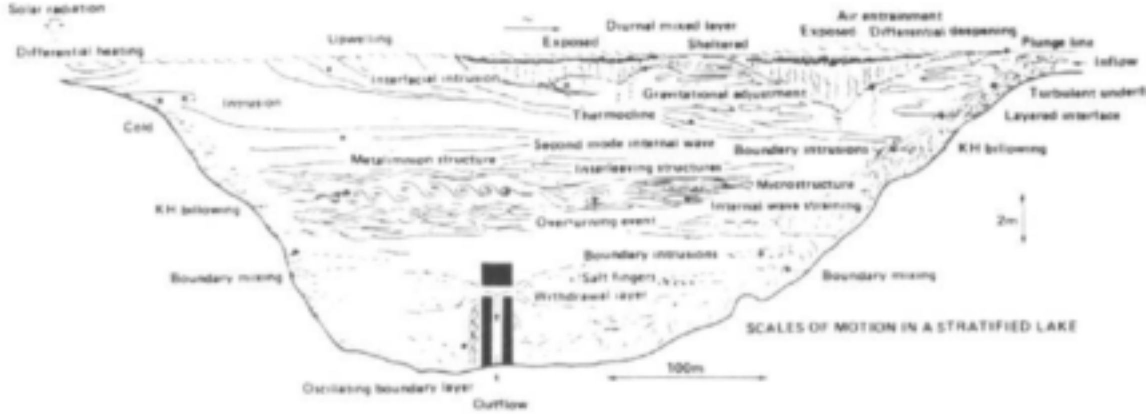


Figure 19b. Schematic showing all known mixing mechanisms operating [10] in a lake exposed to sudden wind stress during periods of strong stratification as illustrated in Figure 19a.

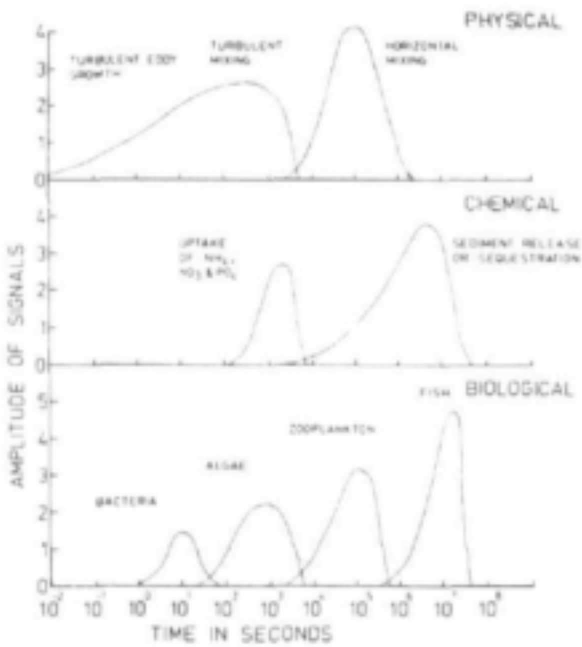


Figure 19c.
Scales of motion pertaining to the three principal internal compartments in aquatic systems. The amplitude scale is arbitrary.

In terms of mechanical energy, this means that a large amount of potential energy is stored in the lake during periods of stratification. This potential energy stabilizes the water column in the reservoir and, except during the severest wind storms, the reservoir remains stably stratified for most of the spring, summer and autumn period. The kinetic energy introduced by the surface wind stresses is in most cases insufficient to overcome the potential energy inherent in the stratification. Only during the latter part of autumn does the water surface cool and the strong density gradient is eradicated at the seasonal thermocline. Under these conditions the fluxes of turbulent energy generated by surface wind stress are able to deepen the mixed layers significantly (Figure 19a).

The reservoirs of South Africa, whether they be situated on the Highveld or on the coastal rimland, all respond similarly to summer heating and autumnal-winter cooling. Thus there is only one period of circulation of the water column, namely in April-May, and stratification set up during September and October. Such reservoirs are termed monomictic. In recent years the resolution of the mixing events in the upper mixed layer of reservoirs has been greatly enhanced by the introduction of temperature microprofilers of high sensitivity and speed of data transmission and precision, which has greatly increased the precision of the computer models used to describe the hydrodynamic events which occur in reservoirs.

We now recognise that the deepening of the surface mixed layer as spring grades into summer, and the generation of this buoyant stability, derive from three sources: surface warming; internal shear production; and the downward flux of surface water associated with surface cooling, particularly at night. These dynamic processes, particularly in a lake exposed to quite sudden wind stress, are illustrated in Figure 19b.

The value of this illustration is increased by placing estimates in seconds of the mixing times in a typical reservoir. By so doing (Figure 19c) we see that the ranges of time scales closely overlap those of biological events within the lake or reservoir, and that consequentially physical and biological events interact, adding importance to decisions about what and how sampling or measuring of events is to be done. Taken together these observations indicate that we should move away from the rigidity of earlier lake stability models and accept that short-term hydrodynamic events can and do take place within the seasonal epilimnion or upper mixed layer and metalimnion which may materially influence the response of the reservoir to rapid changes in flow or wind stress (summer rainfall area) and the availability of sequestration of nutrients such as N and P.

Some important impoundments such as Lake Midmar in the Natal Midlands do not show a simple monomictic system of stratification. Based upon its internal behaviour, it is classified as polymictic, as is Lake Sibaya in Kwazulu. Reservoirs exhibiting this condition undergo brief periods (a few hours or days) of thermal stratification before the kinetic energy of wind or river inflow or nocturnal cooling effectively destroys the buoyancy.

No proper or sensible management of these man-made ecosystems is possible without understanding of the impact the hydrodynamic properties of such lakes has upon their operation in the wider national hydrological landscape.

***Chemical properties*** - In those reservoirs which stratify during spring and summer, the distribution of dissolved oxygen is the first to be affected. There is a range of effect: reservoirs with clear water and poor in nutrients tend to show no or only very slight oxygen depletion of the waters below the seasonal thermocline. Those on the other hand rich in nutrients nitrogen and phosphorus usually exhibit a sharp drop in dissolved oxygen at or slightly below the depth of the upper mixed layer or seasonal thermocline. These hypolimnetic waters become increasingly anaerobic as summer proceeds and under these deoxygenated conditions, hydrogen sulphide is generated by microbial action as the redox falls below -100mv. In polymictic reservoirs this period of lowered oxygen in the deeper water is short-lived as mixing within the water column is frequent and efficient.

The cause of this deoxygenation in nutrient rich impoundments is principally the growth of algae in the warm buoyant surface waters which when they die, fall through the seasonal thermocline and provide the food source for bacteria in the hypolimnion. This process of bacterial decay is in its initial stages oxygen dependent;

thereafter different assemblages of bacteria continue the heterotrophic decay, drawing upon the oxygen in the dissolved sulphate and nitrate ions with the concomitant liberation of hydrogen sulphide and ammonia. As the mean water temperature in South Africa is high, bacterial growth and activity is substantial and deoxygenation of nutrient and algal rich systems occurs rapidly.

Two hydrochemical features modify this process in reservoirs or coastal lakes: the first, input of saline water, either from the sea or from salinization processes in the river catchment. The former is the most dramatic as regards the establishment of water column stratification; seawater allowed to creep over the sill separating a coastal lake from its estuary is rapidly deoxygenated if tidal exchange is restricted (as it usually is). Thus in these coastal lakes there exists a denser layer below or nearly coincident with the seasonal thermocline which reinforces the noncirculating condition during summer and invariably the lake possesses a large volume of deoxygenated, sulphide-rich saline water. This meromictic condition is often long lasting !

The second feature, suspensoids and the consequential turbidity, is a far more common modifier. The watershed, airshed, aquatic organisms and the physical and chemical conditions within lakes and river all influence the nature of suspended material. This material is under normal conditions a significant component of aquatic ecosystems as most interactions between solutes and suspensoids occur at the surface of the particles, and therefore their surface area is of special importance. An indication of the areas per gram of common suspensoids is shown in Table 1, and the size spectrum in Figure 20.

Table 1. Specific surface area of common suspended particles.[11]

| 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 | 122 - 242 |
| Organic matter | 500 - 750 |

In South Africa, the inorganic suspensoids are primarily clays. The origin of these clays is primarily Karoo sandstones and shales. And as these sedimentary rocks dominate the geological scenery principally over the eastern half of the country, the waters flowing over these strata are high in suspensoids which give the grey to orange colour to the rivers. The Orange and Vaal rivers are notable examples.

Within this surface area and the crystalline lattice structure of montmorillonite clays, the inorganic particles possess sorption sites for inorganic and organic compounds, among which are plant nutrients, pesticides, heavy metals and organic molecules, all of which are of considerable concern to the water manager. Thus absorbed nitrate and ammonium are only weakly bonded and are readily available for algal growth; likewise phosphate complexes to form phosphate pools of varying availability to phytoplankton.

While these functions are readily recognised, their quantitative statement is less easy to obtain as little of this complex physical chemistry has been done in South Africa. Preliminary investigations have been carried out in Lake Le Roux and Wuras Dam, both reservoirs with highly turbid water.

in time scales which are short enough to allow them to become effective even in reservoirs with short retention times, e.g. one year or less ! In lakes with very long retention times, as for example Lake Malawi or Lake Tanganyika, the significance of these processes takes on an entirely different dimension.

With the increase in stability and the very marked increase in light attenuation, turbid reservoirs possess some peculiar advantages, hinted at on page 27, over clearer lakes when subject to increases in nutrient loading, nitrogen and phosphorus. It has been demonstrated that some turbid reservoirs possess a higher N and P loading index than do more transparent reservoirs before they are affected (if at all) by nuisance blooms of, for example, bluegreen algae. Clearly the sharp reduction in the light climate in the lake and the absorption of nitrogen and phosphorus into the suspensoid surfaces contributes towards an amelioration of what would otherwise be a serious algal management problem. But as with many things biological, there are important exceptions which prevent dogma. Thus we must be aware of the nutrient status of the surface waters. Those that have a low nutrient status will have the growth of algae limited by nutrient levels rather than by light attenuation. An example is Lake Midmar in Natal. Thus in deciding upon a management strategy for turbid reservoirs such factors and conditions must be taken into account.

***Water quality downstream of an impoundment*** - Where summer stratification is pronounced and algal and phytoplankton growth develops, the deep or hypolimnetic water becomes deoxygenated, enriched with phosphorus and iron and in extreme cases hydrogen sulphide. Thus deep water releases from such reservoirs have a substantial effect upon the water quality downstream of the dam. During the early filling stage of Lake Kariba, deoxygenation of the hypolimnion in the vicinity of the wall and turbine intakes was such that the turbine blades were seriously affected by corrosion and the deoxygenated, hydrogen sulphide-rich water flowing into the river from the turbine discharges was inimical to the fauna of the river for some considerable distance downstream.

On the other hand mild enrichment of an impoundment with the consequential growth in algae provides a measure of water quality restoration. Phosphate and nitrate are lowered because of the algal growth, and if the offtakes are above the seasonal thermocline, the river below may receive a chemically stable water supply in which food particles (algal cells and zooplankton) are suspended. The impact upon the downstream heterotrophs is positive and so contributes to the biotic diversity of the regulated river system. This is very much a feature of the Buffalo River system between King William's Town and East London, along which there are at least three significant impoundments.

In a recent synthesis, published by the Water Research Commission, dealing with the ecological functioning, conservation and management of South African River Ecosystems, Prof Bryan Davies and his co-authors[13] examined the effects of impoundments upon whole river systems, the Buffalo and the Palmiet, and concluded that

- There were no effects common to the dams studied.
- The position of the dam was of overriding importance in governing the types of downstream effects.
- Larger impoundments caused more intense downstream effects, and these impacts took longer to recover.
- Release mechanisms were less important than the position of the dam along the river, *but* bottom releases consistently reduced temperature ranges, increased total suspended solids (TSS), and increased *all* nitrogenous compounds measured.
- Reservoirs were more effective than an equivalent distance of flowing water at reducing the impact of grossly polluted river loads.

The management implication of these conclusions, and particularly the last, is that although regulation of rivers by impoundments has been viewed by conservationists as a degradation of unperturbed river ecosystems, the impoundments often provide protection for the lower reaches from the worst of upstream eutrophication, e.g. the Laing Dam on the Buffalo River which effectively acts as a great settling tank, materially reducing soluble reactive phosphorus (SRP) concentrations, for example.

## 6. Wetlands and floodplains

There are few floodplains in southern Africa below 17°S latitude, but where they do occur they are very important features of the landscape. In many of the large floodplain systems such as in the Okavango Delta and in the Middle Zambezi (before Kariba), their role in the affairs of Man is direct and immediate. Other riverine wetlands (Figure 23) are less important in this respect but retain, as do all wetlands, a central role in the hydrology of the particular river system. Riverine wetlands did occur along long stretches of river channel in South Africa and were influenced by the flood pulse which in the subcontinent can be erratic. Nonetheless, this ecotonal area (an area of structural and functional transition between the river and its valley) should have been quickly recognised as an area upon which the long-term sustainable management of the river depends. Dr George Begg[14] reports that in Natal there existed some 94112 square kilometres of wetlands, many of which were associated with the headwater streams of the major eastward-flowing rivers.

Unfortunately many of these riverine wetlands along South Africa's major rivers, e.g. the Orange, Tugela and Berg, have been materially influenced by drainage by farmers wishing to capitalise upon the rich soils which structure these wetlands. Overgrazing and associated sheet and gulley erosion are the consequences of such invasion. The result in Natal, for example, is that 34% of the hydromorphic wetlands of the Tugela River Basin have been turned over to agricultural production. And while these are not lost permanently as their structure and function can be restored, there are significant areas of riverine wetlands which are permanently lost, namely those which have been inundated by the rising waters behind a dam.

In Africa, Lake Kariba is a paramount example of such loss which included as well the translocation of a human community, the Batonka, who had over the centuries come to terms with the episodic pulsing of the Zambezi River between the Victoria Falls and the Kariba Gorge. They depended upon the flooding of the marginal wetlands to irrigate their crops of maize, and the replenishment of fish stocks of the Middle Zambezi depended upon the river flood cycle.

Similarly, the building of the Josini Dam on the Pongolo River as the river emerges from the Lebombo Mountains altered the flood regime of the Pongolo and with it the cycle of floodplain inundation of the pans and associated wetlands. Given that the geomorphological structure of the floodplain had evolved over millennia and the sustainable utilization by the indigenous people over some 500 years, the building of the dam was a hydrological event of cataclysmic proportions ! Once this impact was understood by the researchers of the University of Natal, notably Professors Heeg and Breen[15], interaction with the operational policy of the dam by Water Affairs and Forestry eventually led to the operation of the dam recognising the seasonal demands of river flooding of the contiguous flood plains and pans and the overall importance of minor flows to sustain relatively low "bridging" levels of fish populations between major flood events.

From the management of water quality, there is good evidence that riverine wetlands are able to metabolise the nitrogen and phosphorus load introduced via the influent streams. This property has been the subject of considerable research, and management of water quality often requires the restoration of wetlands or their actual "construction" in stream courses where the enriching loads of N and P would be inimical to downstream requirements.

This function depends upon the states of the storage compartments within the wetland. These compartments are the plant tissue of the standing and floating hydrophytes, microbial cells, detritus, sediments and interstitial water. If the compartments are saturated with for example, phosphorus, then phosphorus uptake and retention will not occur and the wetlands serve no nutrient retention purpose. Clearly uptake of plant nutrients such as N and P is a dynamic process. Hydrophytes act as "nutrient pumps", taking in N and P from the soil and transferring them to shoots and leaves where they are immobilised until the plants die and the complex process of decay returns the phosphorus to the soil and the nitrogen to the atmosphere.

Dense growth of grasses and bulrush *(Typha)*, Bigai Stream, Knysna.

A wetland pool fringed largely by the rush *Juncus kraussi*, Leisure Isle, Knysna.

Figure 23a. The appearance of hydromorphic areas before they are drained.

We are aware of the great significance which should have been attached to the once extensive wetlands to the south of the Witwatersrand, for example Olifantsvlei, which receives the acid drainage from the mine dumps. The extensive contact the wetland allows with calcareous surface rocks brings about the effective neutralisation of this acidic drainage, but it does result in raised total dissolved solid levels. Thus mineralisation is a product of acid drainage in wetlands sited on calcareous dolomite !

Such wetlands possess other attractive functions. Waterborne bacterial pathogens are not returned, but destroyed in the wetlands, emphasising a further positive feature of wetland preservation and restoration.

Thus overall, wetlands in which the biochemical pathways are active reduce eutrophication and bacterial contamination of surface flowing waters significantly. And while we have some measure of these effects, the way in which wetlands actually do their job is poorly understood. Nevertheless in a country where water is a scarce resource, the persistent and continuing destruction of these vital components of our aquatic landscape is foolhardy in the extreme. Much of this ambiguity stems from the legal constraint that the water of wetlands, being areas deriving their water from natural drainage, springs and rainfall, cannot contain public water. This means that the sole and exclusive agents to use and enjoyment vest in the owner of the land where they exist !

Wetland soils, because of their high organic matter, are fertile. They possess relatively high ion exchange capacity and the levels of P and K are usually high. But unless they can be drained, the value of these soil properties is diminished as the permanent wetness lowers productivity of all but a few specialised crops.

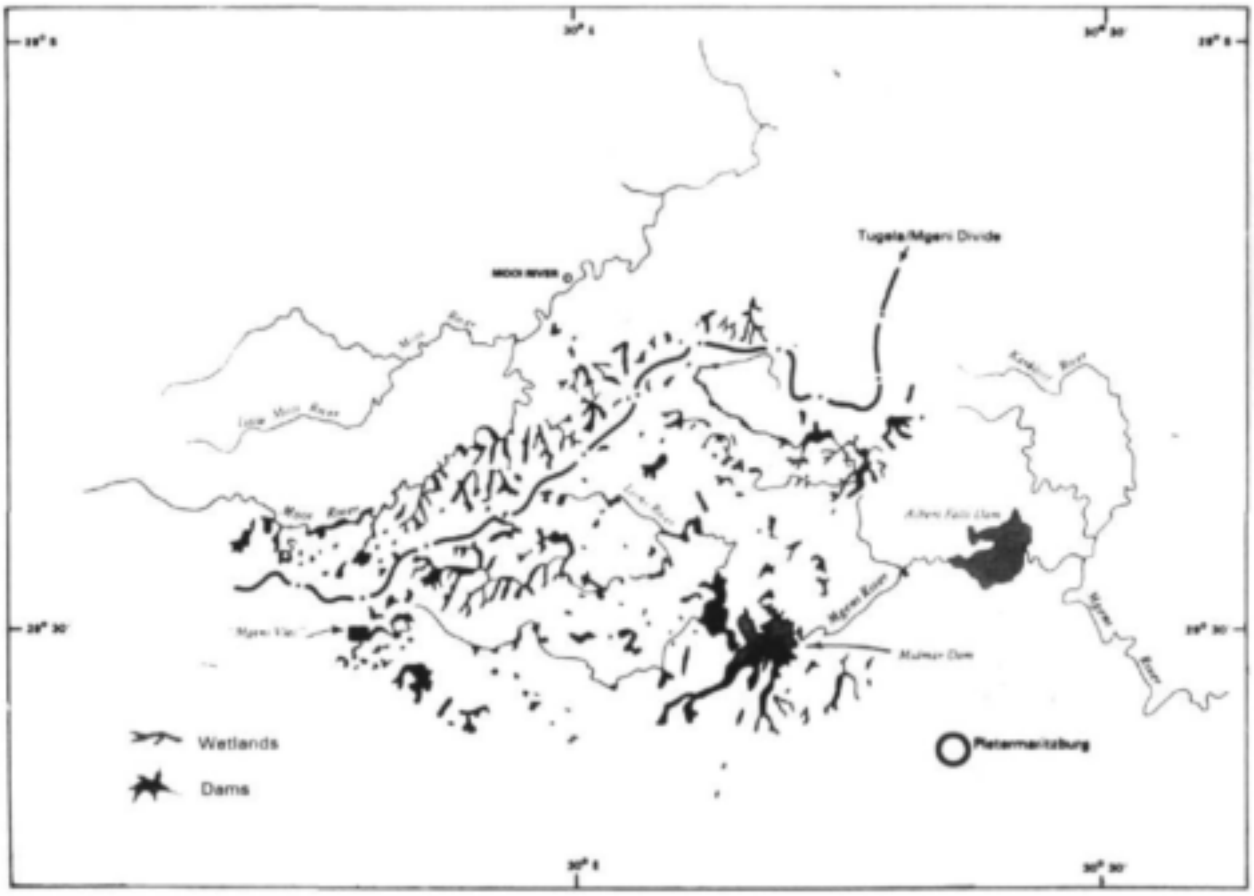


Figure 23b. The distribution of hydromorphic soils on either side of the Tugela/Mgeni Divide, Natal. [14]

Figure 23c. Exploitation of the "Mfolozi Flats" as a prime example of agricultural usage of an area formerly comprised of wetland. The edge of the floodplain is outlined in white.[14]

While the uses to which wetlands are put by farmers, particularly those with a caring approach to the wetlands they own, appear to be least disruptive, there are a number which have major impacts. Timber production is the most controversial. Afforestation results in the drying up of vleis. It is well known how gum and poplar trees are often planted in wetlands to cause a drawdown of water and dry up surface water.

The impact of wetland loss upon the pest status of the stem borer, *Eldana saccharina* is a particularly good example of the influence of Man upon the redistribution of an insect species previously limited to wetland plant species such as *Cyperus immarsus* and *C. papyrus*. Following the encroachment of sugar cane planting into the riverine wetlands, the insect has been forced to change its host plant and outbreaks were first noted on the Mfolozi Flats which had been formerly covered by papyrus, and in the vicinity of Richards Bay, where the wetlands of the Mhlatuze floodplain once comprised a significant portion of the landscape.

Fortunately the *Eldana* infestations are not a serious threat to the sugar industry, but the response by the stem borer underlines the need to properly understand the ecological role of naturally occurring components of the river ecosystem which have evolved over geological time. The interference of Man can be instantaneous and frequently disastrous. Furthermore, it would be surprising if the rich resources of these highly productive subcomponents of aquatic ecosystems were not used by the rural people. Thus in rural areas wetlands are seen as a productive resource-base for hut-building, craftwork and thatching materials.

We might expect that these rural populations in the historical past would have managed this resource in a sustainable manner. This would appear to be no longer possible and in Natal, the Natal Parks Board is required to control to some degree at least the harvesting of the rush *Juncus kraussi* which is used by the Zulu women to make sleeping mats and other useful artifacts.

So far we have stressed the role of wetlands, largely in the affairs of Man. This is a very limited view as current research has stressed their wider ecological significance. The biological diversity of wetlands is high, and we are beginning to understand that vegetative heterogeneity results in high species diversity among the animal communities (Figure 24). This is certainly the case for Nyamithi Pan on the Pongolo floodplain. In most cases, in Natal, however, wetlands are dominated by a single plant species which influences the animal life associated with these wetlands: hence the occurrence of bishop birds, and various weavers in reedbeds; likewise the strong association between wattled cranes and understocked grassland vleis. As these vleis are being seriously impacted by Man, the wattled crane is in danger of extinction.

Thus there is an urgent need to preserve and restore wetlands: Dr Begg reports that of the 114 wetland dependent bird species in Natal, 24 are listed as "red data" species - threatened with extinction. Management of these components of river valleys is an urgent and compelling necessity if we are to prevent their passing, along with a host of less obvious but equally dependent animal species.

> "A nation unable to support the diversity of its wildlife is unable to maintain the standard of living of its people." Tom Lovejoy.[16]

How extraordinarily relevant to southern Africa today : its validity deserves our complete support.

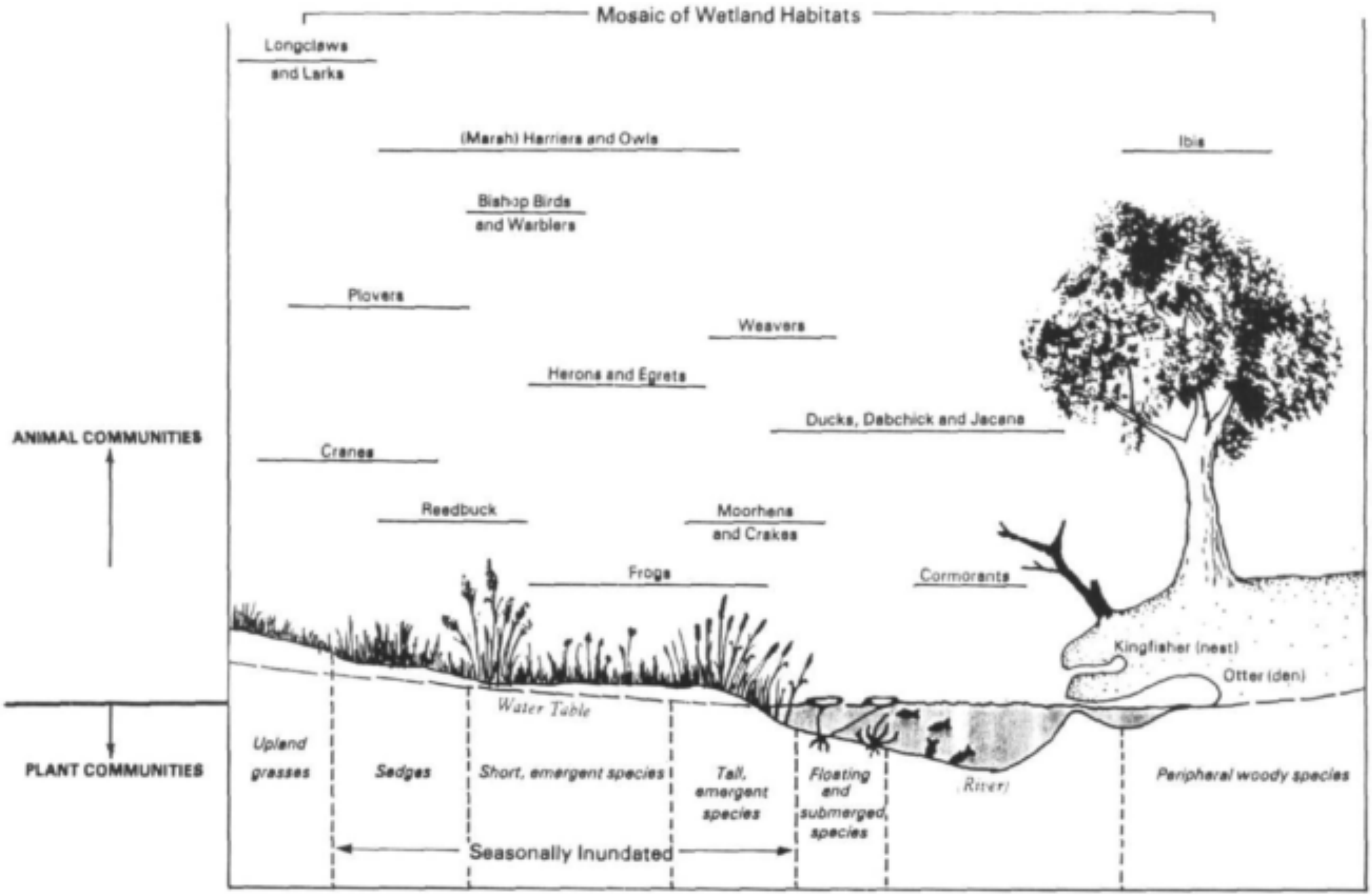


Figure 24. Conceptualization of the inter-relationships between plant and animal communities in a typical wetland area of Natal.[14]

# Part II

## An ecological approach to water resource management

### 1. Introduction

The purpose of Part I was to provide a background to bring the reader who is acknowledged not to have a specialized knowledge of the properties of freshwater ecosystems to a level of understanding which will make the following ecological approach to management that much more relevant, and therefore acceptable.

As a basis for necessary categorization, we have chosen to use the simplified zonation prepared by Drs Dallas and Day[17] of the University of Cape Town and shown in Table 2. Its usefulness lies in its uncomplicated accuracy.

Table 2. Generalised characteristics of each riverine zone. The extent to which specific characteristics change down the course of a river is dependent on land-use practices and pollution sources along its course, and changes are relative with respect to each zone.

| CHARACTERISTIC | Headwater Zone | Middle Zone | Lower Zone |
|---|---|---|---|
| **Physical** | | | |
| Slope | Steep | Gradual | Gradual |
| Velocity | Fast, erosive | Slower | Slow, depositing |
| Substratum | Mainly boulders | Mixed boulders and sand | Sand and mud |
| Temperature | Normally low | Slightly warmer | Warm |
| Turbidity | Clear, low | Intermediate | High |
| Solar radiation | Low | Intermediate | High |
| Riparian vegetation | Canopy-like | Concentrated on banks | Only on banks; often exotic species |
| **Chemical** | | | |
| Dissolved oxygen | High | Intermediate | Low |
| Nutrients | Low | Intermediate | High |
| Conductivity | | Generally increases down the river | |
| pH | | Generally increases down the river | |
| **Biological** | | | |
| Energy input | External | Internal | Internal |
| | CPOM [1] | CPOM and FPOM [1] | FPOM |
| Plankton [2] | Mostly absent | May be present | Often present |
| Dominant invertebrates | Shredders, collectors | Collectors; grazers | Collectors |

1: CPOM = Coarse Particulate Organic Matter; FPOM = Fine Particulate Organic Matter.
2: Plankton consists of the small plants (phytoplankton) and animals (zooplankton) that live suspended in the water column.

There is absolutely no doubt that if we continue to despoil the natural waterways of the subcontinent in whatever manner, our survival is at stake. We are utterly dependent upon the earth's natural systems. None is of greater or lesser importance so that each of the structural ecosystems of the Biosphere demands equal respect. The RDP so necessary to the upliftment of South African people is essentially a human activity within this biosphere, and must take cognisance of this absolute dependency.

We have seen that lack or absence of natural lakes in southern Africa has had a material effect upon the properties of our rivers. Clearly there was simply no option but to interfere with the originally pristine limnological landscape and cause large and small storage dams to be built. Perhaps we may call this a legitimate mode of environmental interference: it is the sequelae of this interference which are not! During the past decade, the trends in water supply and quality are pessimistic. Thus the demand for water is increasing and will have to be materially increased to upgrade the basic requirements of our previously disadvantaged black population. Coincident with this increase is the effect on quality which is deteriorating in a number of ways, notably by salinization and organic debris littering the catchments of feeder streams. We may expect this to continue as river flow decreases as impoundment and abstraction increase, and the buffering capacities of catchments are reduced by urbanization and devegetation.

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 on slopes of the catchments, there has been the development on floodplains. Apart from the obvious increased likelihood of the flooding of these areas, such development has often involved damage to 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, levée 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. The floods of September 1993 in Knysna illustrated the failure of a so-called "stream clean-up campaign" - the destabilized banks were transported into the estuary ! 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 canalise or cut quick exit channels through reedbeds. Such holding areas can be at a series of elevations with different uses (e.g. the lowest could be sports fields).

We have to recognise that the impact of organic enrichment, salinization, acid pollution and the extensive and continuing loss of topsoil through erosion associated with very material changes to the vegetation of catchments, particularly mountain or upland catchments, will increase the failure of natural vegetation and soil systems to store water and buffer against episodic flooding, thus increasing the "flashiness" of river flow.

Most South African rivers are geologically young, which is characterised by their fast flow. Thus while this immaturity is reflected in sediment yields having regard to the erosive nature of the natural flow, the impact of Man has been to greatly exacerbate this natural process. As a consequence the estuaries (in Natal, especially) are choked with terrigenous sediments, their constituent wetlands have been lost and the estuary has been converted into a river mouth, flowing into the sea only during times of extreme flood.

## 2. Requirements of river system management

The management of river systems requires us to admit the reality of our impact upon the natural physical and biochemical processes "inherent" in stream flow, and that the amelioration of our impact is possible.

Essential to the beginning of the solutions required has been the approach of the Department of Water Affairs and Forestry, which has become increasingly aware of the problems of supplying sufficient water of suitable quality from catchments or groups of catchments. Inherent in this awareness was the recognition that there exist water users over and above the demands of Man - the river community in all its complexity is a legitimate user of the mean annual runoff (MAR). The unsung research of hydrologists, engineers and river ecologists has established unequivocally, over the past 40 years, that permanent disturbance or even destruction of the river's physics and chemistry and the biology of its plant and animal communities inhibits the ability of the Department to deliver this high quality water. This has become built into a wider appreciation of the need to manage catchments and river basins in an integrated way. The Department's long-term strategy is directed towards the regional management of water services, particularly by water boards and thus the development of a total catchment policy (see page 72). A particularly good example of this more holistic view of aquatic ecosystems management is to be found in the actions of Umgeni Water. They have adopted a policy of seeking to protect the quality of water in its rivers and dams by monitoring discharges and actively preventing pollution and facilitating waste water and sanitation treatment.

Many of our water supply problems would be solved if we established an ethic of river conservation. Indeed the term "conservation" as applied to terrestrial systems and in particular large mammals has tended to draw attention away from the ecosystems which support them. Furthermore because rivers are longitudinal ecosystems, they are seen to be difficult systems to manage for conservation. Nevertheless it remains of paramount importance to recognise that the conservation of rivers means in effect to manage them as *renewable ecological resources*. This requires an extension of the currently held view that rivers are considered purely as hydrological systems for which almost any problem can be overcome by engineering solutions.

As regards the supply of water to human communities, this is a reasonable approach: the problems lie with the wider impact upon the river valleys, the structure of the river beds and banks and the inevitable loss of biological diversity and, therefore, the slow destruction of the ecosystem. Fortunately, through the work of researchers at Rhodes, UCT and the Department of Water Affairs and Forestry, incisive methods for assessing the minimum flow requirements of rivers have reached an advanced state of development and application.

The impacts which cause this slow destruction are described here and are the most important of the effects of Man upon the river and its valley and require to be properly understood.

The overall picture in southern Africa and also in other southern sub-continental regions with similar hydroclimatic conditions is that, as the 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. 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.

### 3. Man-induced influences on water export

This loss from the river catchment is **further increased** by Man in several ways.

* *Afforestation and 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 stream flow. Changes in evapotranspiration rates following clearfelling are influenced by the rate of recovery or regrowth of the vegetation. Figure 25 points to the impact deforestation of **natural forest** can have upon runoff and infiltration. In view of the large areas of indigenous forest which have been cut down over the past two hundred years in South Africa, the impact upon the hydrology of the streams and rivers which flow through and from them has

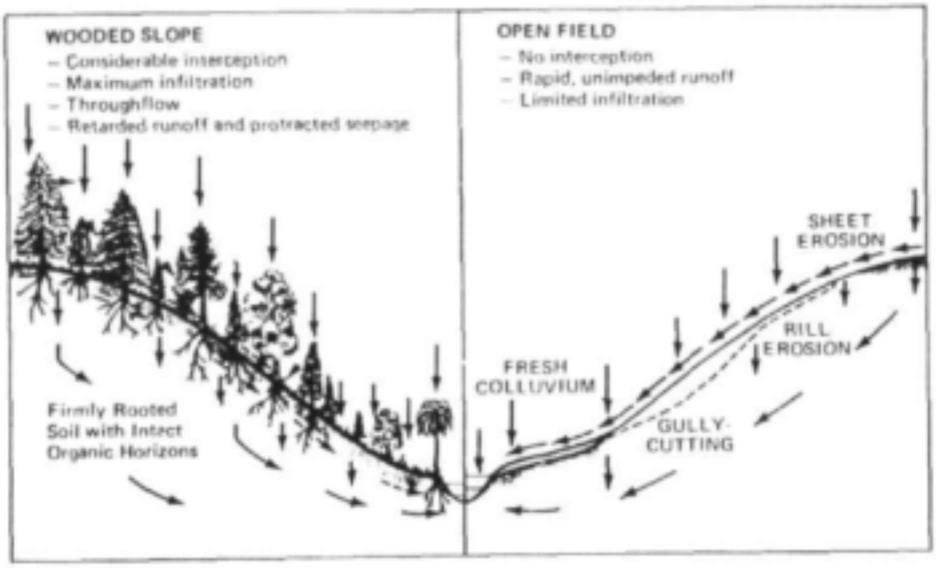


Figure 25a. Contrasting runoff and infiltration on wooded slopes and cultivated slopes.[18]

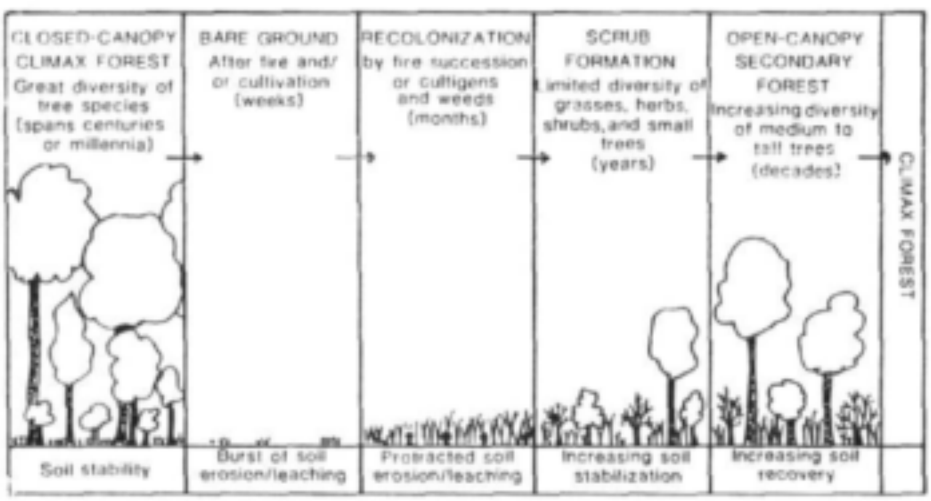


Figure 25b. Vegetation succession in woodland. Protracted grazing by livestock can lead to an indefinite subclimax vegetation of degraded scrub.[19]

been substantial, adding greatly to variation in river flow and erosion. Note also the consequences of the removal of closed-canopy climax forest on the subsequent vegetation succession. This is a frequent sight today where tracts of climax forest are bulldozed and burnt to allow inferior grasslands to develop, which leads eventually to scrub formation and may be secondary forest, although this is unlikely where the intention of the clearing in the first place is to increase the area of land for grazing. The Amazon Basin is of course the classic case of the disaster that awaits!!

* *Burning:* Burning of vegetation during different seasons and on different ecological cycles results in changes in composition and structure of the vegetation, and thus evapotranspiration. The effect may be less significant than expected. No immediate effect on water yield has been shown following burns in grassland, while small increases of ± 60 mm in water export for a period of about 10 months followed the burning of fynbos.[20]

* *Riparian treatment:* Manipulating vegetation type and structure in riparian zones has a direct and significant effect on water yield. The effect of vegetation on stream flow is dependent on factors such as climate and catchment characteristics. Preliminary results of riparian treatments in South Africa have indicated that the effects of, for example, clearing the vegetation will depend on the recovery rate of the vegetation in such zones. Kate Rowntree[21] draws attention to the subsequent invasion of alien vegetation. Woody species are the most important invasives of streambank habitats. And while in general it can be expected that they will enhance bank stability due to a more effective root system than grass banks, this is not always the case. Many of these species form a dense canopy which inhibits undergrowth, leading to a poorly protected soil surface which is prone to particle detachment by flow erosion. This accelerated bank erosion has been associated with *Acacia mearnsii, A. longifolia, A. saligna, Lantana camara* and *Pinus piaster*. These species have shallow rooting systems which are unable to withstand flash floods that rip out trees insubstantially anchored in the soil or cause the bank to collapse. This effect is illustrated in Figure 26.

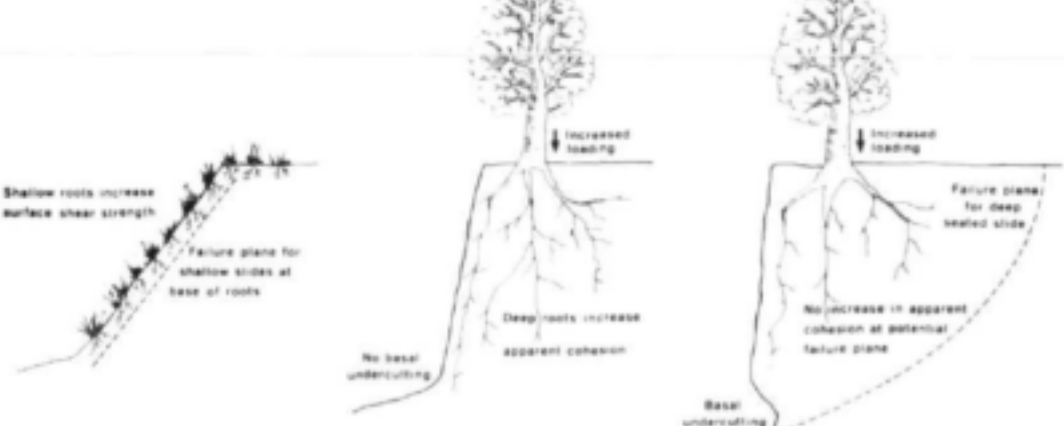


Figure 26. The effect of vegetation on bank stability.[21]

* *Irrigation:* Irrigation attenuates water yield from catchments and thus increases evapotranspiration to the detriment of stream flow. 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 in Australia is used for irrigation and has contributed to a substantial decrease in river flow especially in years of low rainfall. Similar effects are evident in South Africa.

* *Draining wetlands:* We have seen earlier from the investigations in Natal that wetlands are being lost from the hydrological operation of the river and its valley at an alarming rate. This is not peculiar to South Africa: according to the International Union for the Conservation of Nature and Natural Resources (IUCN), wetlands are one of the most globally endangered habitat types. Throughout the world vast areas of wetland have been modified to alternate land use.

Their biological role appears to be well described, but we are less certain about their hydrological role. Certainly they are part of the river or surface manifestations of underground supplies, and if these sources dry up so will the wetland. The dominant hydrological feature is, however, the water storage they provide, so that in times of drought they contribute materially to the maintenance of a base flow.

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

* *Urbanisation:* The runoff coefficient (millimetre runoff/millimetre rainfall) from urban landuse catchments is usually appreciably higher than that for rural catchments. 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. 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. This illustrates the 'flashy' nature of runoff in urban catchments and the erosion potential resulting from high velocities produced in receiving waters.

## 4. Man-induced influences on the water quality of freshwater systems

It is important to realize that as rainwater flows over the surface it collects particles and dissolves soluble material from the rocks and plant cover. As has been noted earlier, in South Africa surface waters are divided into two major types: the dark peat-stained, acid streams of the Western Cape which arise predominantly from the Table Mountain Sandstone series and other areas where this geological formation outcrops; and the alkaline, turbid waters of the Eastern Cape, the Highveld and Natal. This distribution is roughly divided between winter and summer rainfall regions of the subcontinent.

To assist the reader and in particular those ultimately responsible for the sustained supply of potable water to the community, attention is focused in this next section on three particularly important features of the aquatic ecosystem and the influence of human activities upon them.

### 4.1. Export of suspensoids

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 more focused yields and have increased the rate at which sediment is delivered to the river.

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. See Figure 27.

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, and transport them to a point further downstream. This transport 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. Fine material such as the colloidal and silt fractions will tend to move through the system in a single flood event. Coarser particles are not taken into suspension but "leapfrog" 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 the physico-chemical conditions at the sediment/water interface of the riverbed.

Sediment export from a catchment cannot be determined with the same precision as can the export of water. The reasons are twofold. 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.[22]

Routine bathymetric surveys provide the best available information on the volumetric transport of sediments. Such data are available for major reservoirs in South Africa (Figure 28). Statistics relating to sediment concentrations of riverflow are less comprehensive but are available (Division of Hydrology of the Department of Environment Affairs, South Africa).

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 mobilisation. For example, summer and autumn 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 per litre was measured in river stormflow five months after a burn. In this case there was no organic litter left or established natural vegetation to prevent continuous soil creep taking place. Before the burn, mean annual sediment concentrations were 4 mg and 105 mg per litre under baseflow and stormflow conditions, respectively, compared with a mean annual export of 3.9 g per litre under stormflow conditions after the burn.

Clearfelling and burning of riparian zones in the subtropical 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.

In the first instance the "internal" or autochthonous primary production processes may be severely attenuated seasonally. The studies by the Botany Department of the University of the Orange Free State of the Vaal River downstream of Johannesburg have shown how sensitive phytoplankton primary productivity is controlled by changes in suspensoid concentration. Table 3 illustrates some of their results.

Table 3. Changes in suspensoid concentration for four periods in 1985, and the response in phytoplankton concentration as Chl *a* and total water column primary production.

| | 1985: April 20 | August 14 | November 26 | 1986: February 18 |
|---|---|---|---|---|
| Transparency (Secchi disc mm) | 340 | 500 | 200 | 300 |
| Turbidity (NTU) | 8.5 | 4.1 | 33 | 4 |
| Suspensoids (TSS) (mg $\ell^{-1}$) | 30.0 | 26.9 | 69.5 | 33.5 |
| Chlorophyll *a* ($\mu$g $\ell^{-1}$) | 23 | 56 | 8 | 12 |
| Total column primary productivity (mg C m$^{-2}$d$^{-1}$) | 840 | 2047 | 147 | 1474 |

The onset of the rainy season during November reduced Secchi disc transparency to a mere 200 mm. Measured in nephelometric units (NTU) the river turbidity increased by an order of magnitude over the winter or dry season conditions. All these measurements are clearly linked to the primary cause: an increase in suspensoids (TSS).

The biological response is immediate with both chlorophyll concentration in the water column falling to a minimum of 8 $\mu$g $\ell^{-1}$ from a high of 56 $\mu$g $\ell^{-1}$. The impact on the photosynthetic fixation of carbon is striking, from over 2000 mgC m$^{-2}$ d$^{-1}$ to just under 150 mgC m$^{-2}$ d$^{-1}$; recovery is equally impressive once the transparency of the water increases.

The purpose behind this information and its interpretation is to point out how small (seemingly insignificant) environmental changes can give rise to disproportional changes in biological response. Thus an increase in suspensoid concentration by some 33 mg $\ell^{-1}$ brings about a fourteen-fold decrease in the primary fixation of energy, namely photosynthesis. Thus where suspensoid concentrations are maintained at high levels for long periods of time, we may expect material change in the remainder of the biological structure of rivers.

It has been shown that within the Vaal River the density of the invertebrate animal community, largely dominated by the immature stages of insects, is highest in the dry, early summer months when the transparency of the water is highest and the impact of allochthonous organic material is low. The important implication, very much supported by the work of the University of the Orange Free State, is that this fauna depends almost entirely upon the autochthonous production in the river.

Any increase, therefore, in the suspensoid concentration of the river at this critical period would materially influence the successful and continued colonisation of the river's habitats by this diverse array of animals, the primary role of which is to reduce the macroparticles which commonly enter streams and rivers to finer particles. Without this the streams and rivers would become clogged by the detritus from the terrestrial ecosystem. It is this sequential trituration of organic material which makes the original food resources available to the hierarchy of feeding groups within the biota of a river and lake.

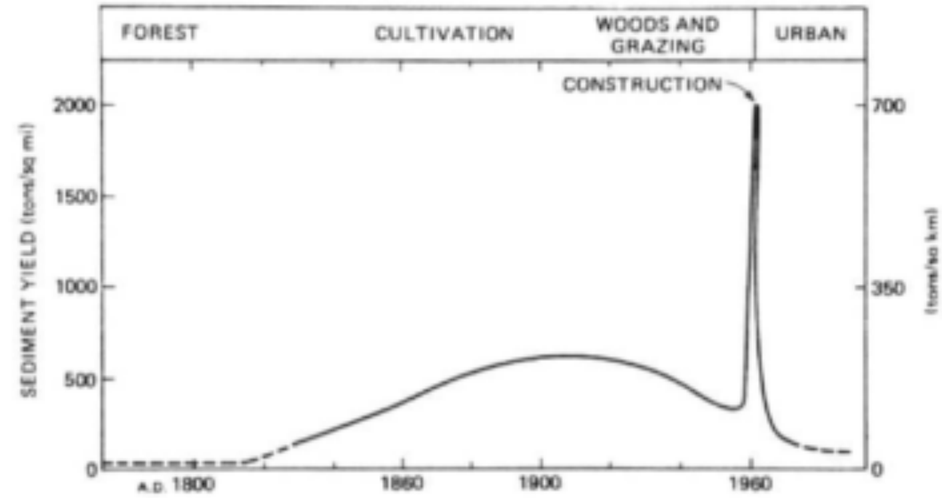


Figure 29. Effects of cultivation and urban construction on sediment removal from a Maryland watershed AD 1800-1965.[27]

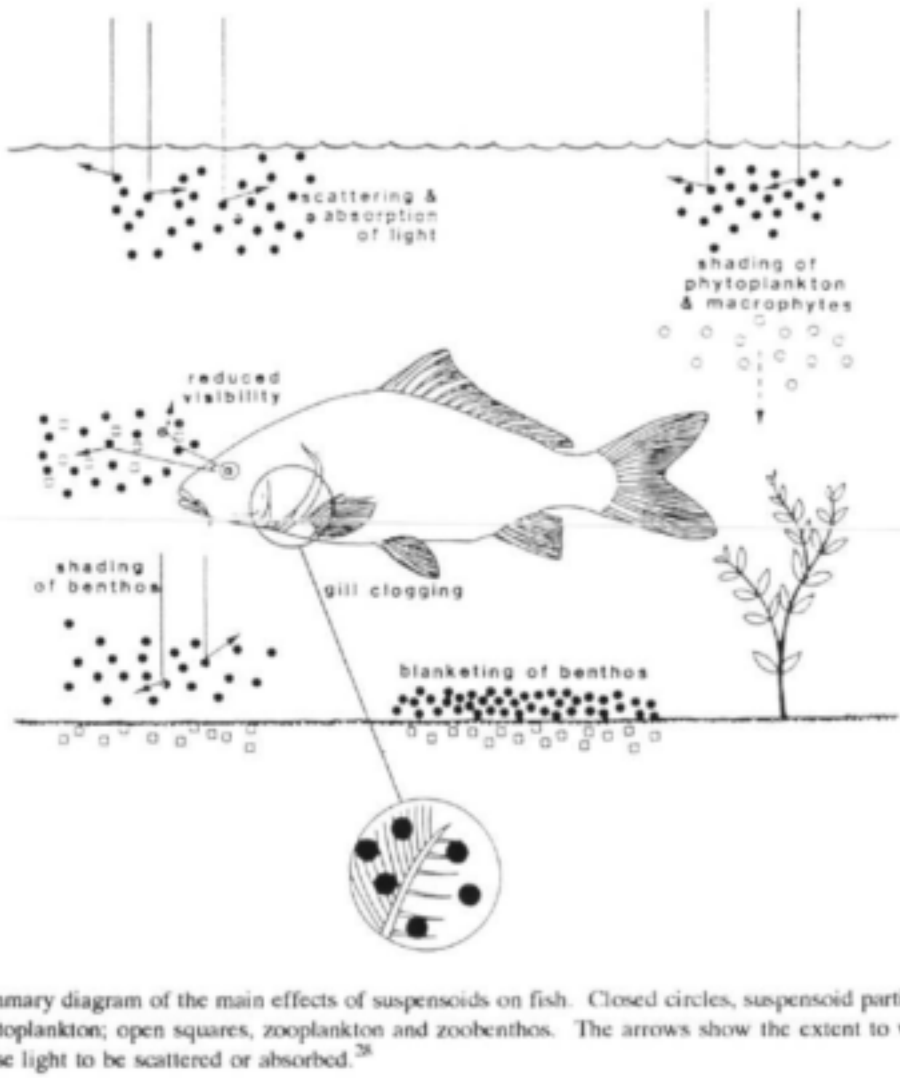


Figure 30. Summary diagram of the main effects of suspensoids on fish. Closed circles, suspensoid particles; open circles, phytoplankton; open squares, zooplankton and zoobenthos. The arrows show the extent to which suspensoids cause light to be scattered or absorbed.[28]

It is appreciated that the invertebrate groups are less obvious to the users (apart possibly from the trout fisherman) and managers of a water system than are the fish. This group of vertebrates has long been used as indicators of riverine health, and while it is generally known that they respond directly to toxic conditions, that of increase in suspensoids above background or natural levels has only recently received the attention due in an excellent review by Professor Mike Bruton.[28] The main effects of suspensoids on fish are illustrated below. The direct physiological effects are upon the gills which may become clogged or suffer hyperplasia in the event of the suspensoids having a very high clay content, as in the chalk streams of south-west England. These impacts are clearly deleterious.

The reduced transparency of the water column has resulted in a reduction in visual acuity, and the development of tactile barbels surrounding the mouth. These coupled with an acute olfactory sense are adaptations adopted in those fish species which normally inhabit naturally turbid waters. Where suspensoids are increased through anthropogenic agencies it has been established that the eggs of minnows laid in stony reaches of rivers are frequently smothered and die from oxygen lack.

As shown in Figure 30, suspensoids heavy enough to sink during periods of low water velocity can shade or blanket the benthos of the river bottom, so making this food resource less available to foraging fish. There is some evidence that in the yellowfish (*Labeo capensis*) which naturally inhabit turbid waters, intestinal bacteria generate fatty acids from the ingested detritus which are absorbed by the fish.

***Guidelines for planners and managers***

So far we have demonstrated that the features which distinguish rivers from other aquatic environments are the (i) unidirectional flow, (ii) linear form, (iii) fluctuating discharge and (iv) unstable channel and bed morphology. An important consequence of these properties of a river, and in particular its narrow, linear form, is its intimate link with events in the surrounding terrestrial ecosystem. Thus as regards the required reduction in suspensoids in South African river systems, good land use 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.[29] 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 (e.g. 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 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. In many of the tributaries of the mainstem rivers of the highveld and also of the coastal streams, wetlands begin to appear as the stream gradient decreases.

Throughout Africa the riverine wetland is a striking feature of the river ecosystem, and one upon which the survival of so many communities including those of Man depend. It is, therefore, ironic that developers see them as hindrances to development. For this reason the next two sections look in some detail at the role of these hydrological features of our limnological landscape.

Riverine wetlands are of two principal types:

*(i)* ***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. 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.

*(ii)* ***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. Endorheic wetlands play little part 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.

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.

Riparian strips including fringing wetlands 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 it has in bank stabilization and as a prime source of potential energy and nutrients for aquatic ecosystems.

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. *The intercalation of wetlands* into runoff channels which are frequently highly modified natural drainage lines will add materially to the retention and amelioration of pollution loads into the mainstem river, reservoir or estuary. These wetlands may take the form of small impoundments, slow flowing reaches of rivers, and fringing wetland communities in urban areas, which may play an important role in retaining particulates of all types and so reduce export from the catchment.

## 4.2. Export of dissolved material from a catchment

Dissolved material consists of inorganic nutrients and minerals (nitrogen, both of inorganic origin as in coal-fired power plants and organic nitrogen from plant and animal wastes; phosphorus; potassium; and sulphur, usually as its oxide $SO_2$), 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).

Human activity, through the discharge of effluents rich in nitrogen and phosphorus, 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 in output could be due to inherent factors affecting runoff or the nature of human enterprise in the catchment).

The spectre of acid rain and the increase in acidic discharge from mine dumps and disused coal mines is before us and if allowed to continue will materially alter the capacity of rivers to handle these organic inputs.

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.

Table 4. Mean ionic concentrations (mg $\ell^{-1}$), 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 |

A summary of ionic concentrations occurring in headwater streams of various regions in South Africa is presented in Table 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 headwaters in the Natal regions while the lowest nutrient content is to be found in headwaters in the Northern Transvaal.

***The effects of Man***

*(i) 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.

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 per hectare per month. This effect lasted for only 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 baseflow 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 growth 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 (e.g. fertilizer and pesticide applications and irrigation) have markedly increased the concentrations of dissolved solids and toxins entering receiving waters via runoff[30], particularly with the first heavy rains following application. This is a well documented phenomenon and will not be discussed here.

*(ii) Urban* - The quality of runoff from urban catchments is extremely variable during runoff events. High concentration 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, are shown in Table 5. The concentrations of suspended solids, nitrogen and phosphorus are significantly higher than those normally found in undisturbed catchments. Apart from the erosion and wear products produced in urban areas, 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 for rural catchments. Table 6 shows the export coefficients determined for urban catchments in South Africa.

Table 5. Weighted mean runoff water quality characteristics and range of event concentrations for an urban catchment.[25]

| PARAMETER | December 1978 to November 1979 | RANGE |
|---|---|---|
| Suspended solids mg $\ell^{-1}$ | 117 | 12 - 422 |
| Phosphate-P $\mu g\ \ell^{-1}$ | 50 | 2 - 412 |
| Soluble - P $\mu g\ \ell^{-1}$ | 79 | 19 - 560 |
| Total - P $\mu g\ \ell^{-1}$ | 438 | 65 - 5887 |
| Nitrate - N $\mu g\ \ell^{-1}$ | 404 | 8 - 2687 |
| Ammonia - N $\mu g\ \ell^{-1}$ | 109 | 11 - 2105 |
| Soluble Kjeldahl - N $\mu g\ \ell^{-1}$ | 565 | 142 - 4925 |
| Total Kjeldahl - N $\mu g\ \ell^{-1}$ | 1956 | 449 - 28365 |
| Soluble COD mg $\ell^{-1}$ | 35 | 13 - 228 |
| Total COD mg $\ell^{-1}$ | 108 | 26 - 643 |
| Total BOD mg $\ell^{-1}$ | 18 | 1 - 170 |
| Copper $\mu g\ \ell^{-1}$ | 38 | 2 - 255 |
| Lead $\mu g\ \ell^{-1}$ | 260 | 14 - 1084 |
| Zinc $\mu g\ \ell^{-1}$ | 665 | 259 - 19800 |
| Iron $\mu g\ \ell^{-1}$ | 3860 | 342 - 32480 |
| Chromium $\mu g\ \ell^{-1}$ | 23 | 5 - 71 |
| Manganese $\mu g\ \ell^{-1}$ | 86 | 12 - 408 |
| Conductivity, mSm$^{-1}$, 20°C | 8.3 | 3 - 60 |

Table 6. Annual export of solids, nutrient and metals from urban catchments (all values in kg ha$^{-1}$ yr$^{-1}$).[25]

| | |
|---|---|
| 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 |

Acid rain and the primary origins of this most insidious of man-made atmospheric pollutants, together with the deterioration in the seepage water quality from disused coal mines in the Eastern Transvaal and from the mine dumps south of Johannesburg, have been receiving the attention of decision makers only quite recently, although the problem of acid drainage from mine dumps and disused coal mines has been acknowledged for over 30 years !

The pollutants responsible for acid rain are sulphur dioxide ($SO_2$) and the oxides of nitrogen ($NO_X$). In north-west Europe sulphuric acid contributes some 70% of the mean total annual acidity.[31] Nitric acid makes up the remainder ! The origin of these atmospheric pollutants in South Africa is largely the coal-fired power stations and the increasing urbanization of the highveld resulting in open coal fires in the populous townships on the Reef.

The acid drainage from the mine dumps and the disused coal mines is caused by bacterial oxidation of iron pyrites to sulphuric acid. In the Klipspruit, a tributary of the Olifants River north of Witbank, stream pH's of 2.9 are common !

***Limnological consequences or how does the discharge of dissolved substances influence the aquatic ecosystem?***

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. While 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 but it should be stressed that the two examples represent extremes between which a continuum of possibilities exists.

*Conservative dissolved substances:*

Conservative components (e.g. 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 ground waters 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 reservoirs or the sea can be reliably estimated directly from hydrological and chemical data.

*Acidification*

While the immediate limnological effects in South Africa are not as acute as they are in Europe and North America because of our paucity of lakes, the Department of Water Affairs and Forestry has recognised that acid rain will materially influence the major forest plantations in the Transvaal, with its consequent impact upon the areal hydrological cycle; and the acid drainage from the mines will affect the supply of irrigation water from major dams such as Loskop Dam, which is under continual threat from the Witbank drainage.

While the sources of this severe pollutant are well known both here and in all industrialised nations, its amelioration is a difficult task. But notwithstanding, solutions have to be found and management implemented as the limnological consequences are extreme.

The acidification process in freshwater[31] is summarized in Figure 31.

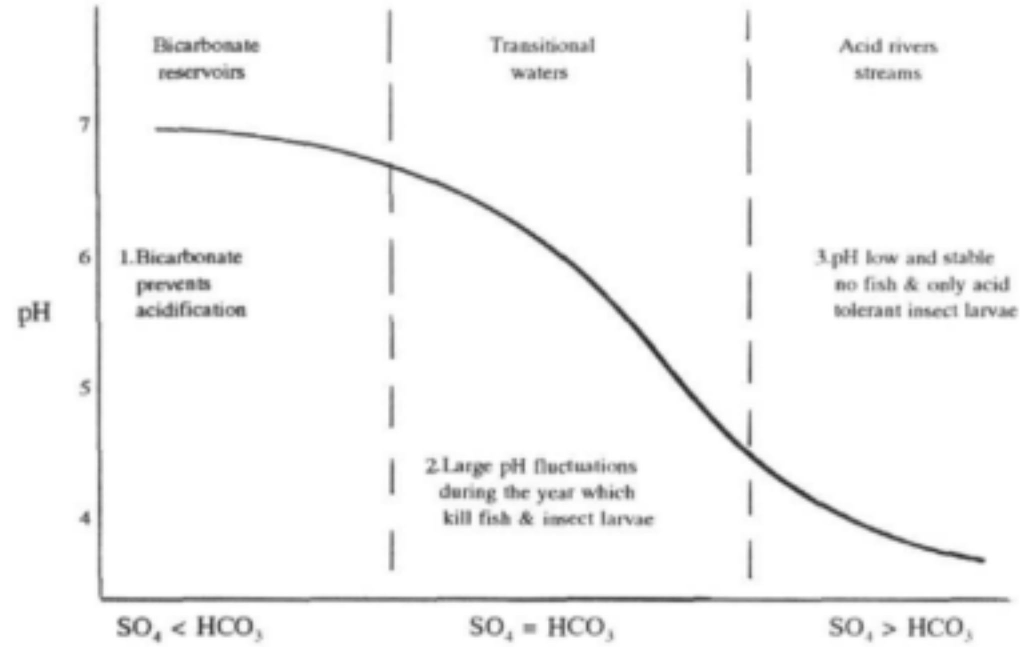


Figure 31. The acidification process in reservoirs and rivers.[31]

While as yet there is no sustained acidification of reservoirs, periods of sustained drought may lead to a transitional phase being established as was reported in Loskop Dam during the 1960's. It is now well established in some highveld streams in which the abundance and diversity of macrophytes has declined and the *Sphagnum* mosses become increasingly dominant. The reduction in pH inhibits bacterial activity and nitrogen fixation. This in turn delays decomposition of organic material which accumulates with the concomitant decrease in nutrient availability.

The river invertebrate fauna is impoverished, although some highly specialized acidophilic species of Chironomidae (Diptera) and an extremely tolerant mayfly, *Baetis harrisoni*, are the only insect representatives in the Klipspruit. Fish are absent. Records of declining fish stocks are often the first indication that environmental conditions are deteriorating. The effect of sustained high hydrogen ion concentration is to disrupt the ability of the fish to maintain and regulate body fluid cation composition.

*Non-conservative dissolved substances:*

Under natural conditions non-conservative components (e.g. soluble phosphate) are relatively scarce in the biosphere. They are extremely important in plant nutrition and are involved in abiotic exchange processes in catchments usually involving soil particles. For these reasons they are relatively immobile in catchments and are transported in low quantities in comparison with conservative components in surface and ground waters.

*Eutrophication*

The hydride and salts of nitrogen, principally $NH_3$ and $NO_X$, are likewise considered non-conservative as nitrogen is an essential element, along with phosphorus, in the building of proteins and therefore the generation of biomass. It is the delivery into river catchments, either via agricultural fertilizers, feed lot and sewage works effluent or stormwater runoff from urban catchments which seriously alters the natural loadings and results in the eutrophication of waterways, lakes and reservoirs.

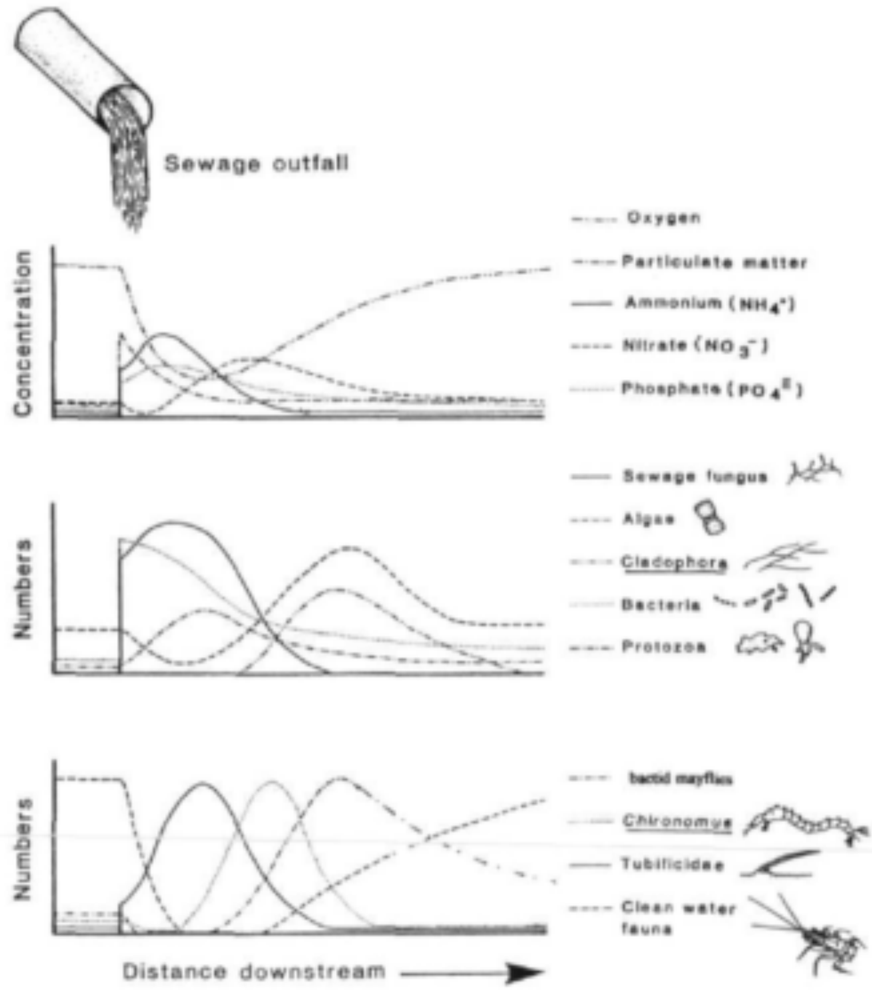


Figure 32a. A simplified graphical description of the response of a river to the effluent from a sewage outfall.

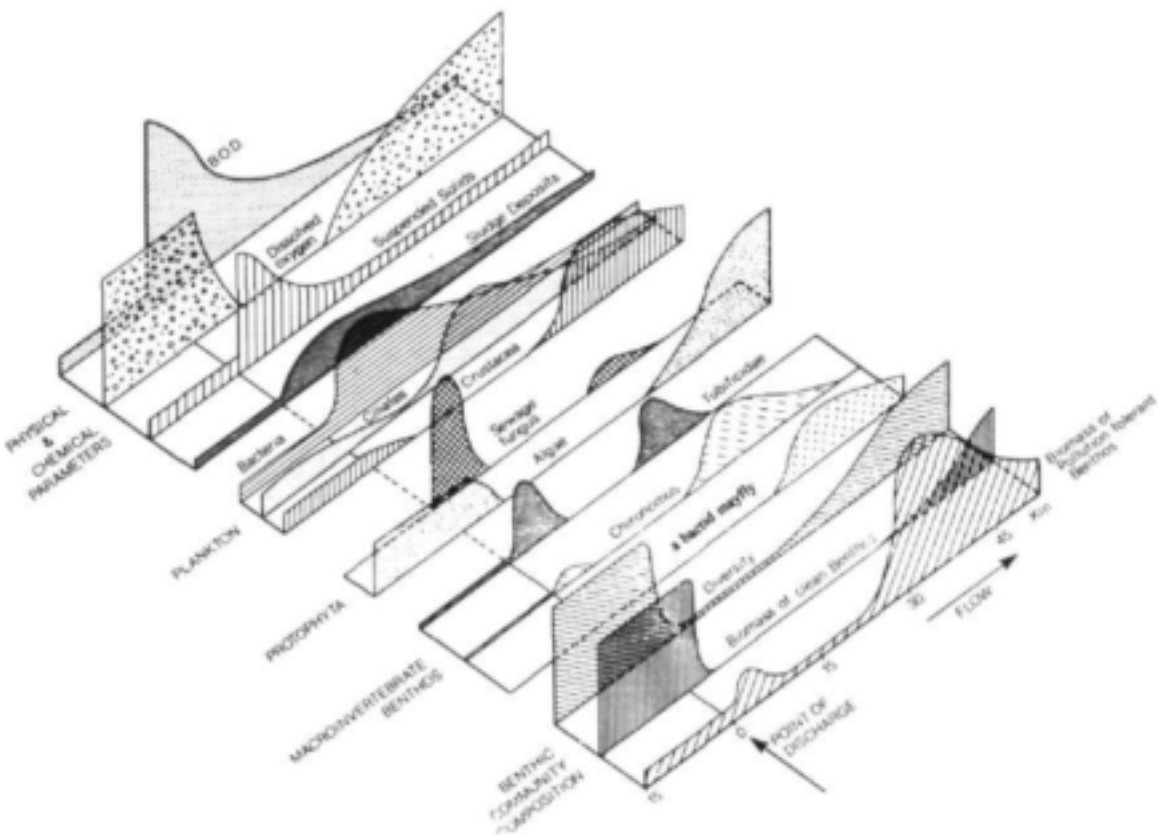


Figure 32b. An exploded view of Figure 32a to show the spatial variation of physical, chemical and biological consequences of the continuous discharge of a severe organic load into flowing water.[32]

The immediate response to the discharge of effluents rich in unstable organic matter is a decrease in the dissolved oxygen levels (or an increase in the biological oxygen demand, BOD) of the water column (Figure 32), which, depending upon its magnitude, will either be associated with a complete replacement of the normal biota of the river bed with a grey-white fungus in which low oxygen tolerant insect larvae and aquatic oligochaetes live, or if the effluent discharge is advanced in its stability with somewhat elevated BOD, the fungus will not appear, but the more oxygen intolerant water organisms will be replaced by dipterous larvae and worms. Representatives of these taxa are always present, existing in refuges in the river bottom or within its trailing vegetation where organically rich niches are permanently available. With the discharge of organically rich effluents, these niches in effect expand within the downstream river space, and with them their characteristic fauna. Such fauna successfully compete for the changed river space and a characteristic assemblage of plants and animals develops which has become associated with organic effluents.

Provided that there are no further effluent discharges downstream and that the influent tributaries are themselves unpolluted, the river slowly recovers from the primary insult. This gradual improvement in the chemical and biological features of the river is descriptively known as "self-purification". The processes involved are complex, but may be simply expressed as the oxidative recovery of the river. This recovery is (in addition to dilution effected by tributary inflow) very largely the responsibility of those biochemical processes within the water column and upon the bottom which generate oxygen in excess of the demands of those organisms which utilize this element. Thus river plants which grow upon surfaces of rocks and trail in the water from the river's edge generate oxygen which dissolves in the water and adds to that which diffuses across the air/water interface. Once the sum of these agencies is in excess of the heterotrophic demand, recovery from the pollutant load begins.

Of course where the organic pollution load is persistently in excess of the river's capability to provide for its oxidation, the entire river course will exhibit signs of gross organic pollution. Fortunately few South African rivers/streams are in this condition, although some are trembling on the brink of collapse, e.g. the Black River in Cape Town; stretches of the Jukskei River north of Johannesburg; and Msunduze in Pietermaritzburg. In contrast, European rivers are frequently in this condition, or have been until quite recently.

Cultural eutrophication of water bodies is primarily determined by the level of phosphorus in freshwater systems which is delivered to the reservoir. The effect of such loading is to increase the concentration of plant pigments as a result of the growth of phytoplankton. This is particularly true in reservoirs; while in estuaries (e.g. the Knysna estuary) macroalgal growth (principally of *Ulva lactuca* or sea lettuce) is determined largely by the increase in nitrogen, usually as nitrate.

Table 7 gives a useful summary of the trophic categories which are currently in international use, and the boundary values for phosphorus, chlorophyll and transparency.

Table 7. Boundary values for trophic categories of inland lakes and reservoirs. [33]

| **Trophic category** | Mean annual Total P ($mg\ m^{-3}$) | Mean annual chlorophyll ($mg\ m^{-3}$) | Maximum chlorophyll ($mg\ m^{-3}$) | Mean annual Secchi disc transparency (m) | Minimum annual transparency (m) |
|---|---|---|---|---|---|
| Ultra oligotrophic | <4.0 | <1.0 | <2.5 | >12 | >6 |
| Oligotrophic | <10 | <2.5 | <8 | >6 | >3 |
| Mesotrophic | 10-35 | 2.5-8 | 8.25 | 3-6 | 1.5-3 |
| Eutrophic | 35-100 | 8-25 | 25-75 | 1.5-3 | 0.7-1.5 |
| Hypertrophic | >100 | >25 | >75 | <1.5 | <0.7 |

In South Africa the whole range occurs, although the number of mesotrophic to eutrophic reservoirs is increasing. So far only Hartbeespoort Dam near Pretoria has provided unequivocal evidence of hypertrophy.

The consequences of eutrophication in the management of freshwater resources are explicit now that so much work has been done to establish the biophysical and biochemical changes which occur. In Table 8 these changes are summarised.

Table 8. Changes brought about by eutrophication in South African reservoirs.[33]

| | |
|---|---|
| **Biological** | • Increased primary production leading to algal blooms.<br>• Diversity of primary producers increases: in some instances water hyacinth *Eichhornia crassipes* increases rapidly over the surface of the reservoir so shading the water column.<br>• Where hyacinth fails to establish, the bloom is principally of *Microcystis aeruginosa* with some early conditioning of the water column by green algae and diatoms.<br>• The diversity of heterotrophic organisms (macro- and micro-invertebrates) and fish declines. Bottom sediments become inhabited by a few species able to withstand the deteriorating water quality. |
| **Chemical** | • Wide variation in oxygen levels in the water column with large volumes becoming anoxic.<br>• pH changes to 9 or 10, certainly inimical to many planktonic species.<br>• $NO_X$ and $PO_4$ levels in excess of algal requirements. |
| **Physical** | • In reservoirs which stratify in summer, anoxic conditions develop below the thermocline.<br>• Transparency may decrease due to biogenically induced turbidity.<br>• Where turbidity due to silts and clays remains high, the eutrophic appearance may be reduced or delayed due to light scattering in the upper levels of the water column, although the water column is enriched with respect to $NO_X$ and $PO_4$. |

Until quite recently, cultural eutrophication was considered to be a problem connected with reservoirs and lakes. Unfortunately the increase in the number of people living permanently near the coast on the banks of estuaries has brought the inevitable signs of this population increase.

The Knysna estuary is currently exhibiting those selfsame signs of eutrophication as have been recorded in other urbanized coastal watersheds of the world. The growth of *Ulva* and *Cladophora* depends on the supply of nitrates and ammonium and where these nutrients are in rich supply, the estuarine or lagoon floor is covered by a thick layer of these macroalgae.

Figure 33a records the change in nitrate (N) concentration in the Knysna estuary since the initial measurements made by Korringa.[34] The exponential rise is obvious and alarming, and particularly so, as the growth of *Ulva* in the Ashmead channel (Figure 33b) possesses all the features of a macro-algal response to this increase in nitrate. It is hard not to attempt a correlation between the two !

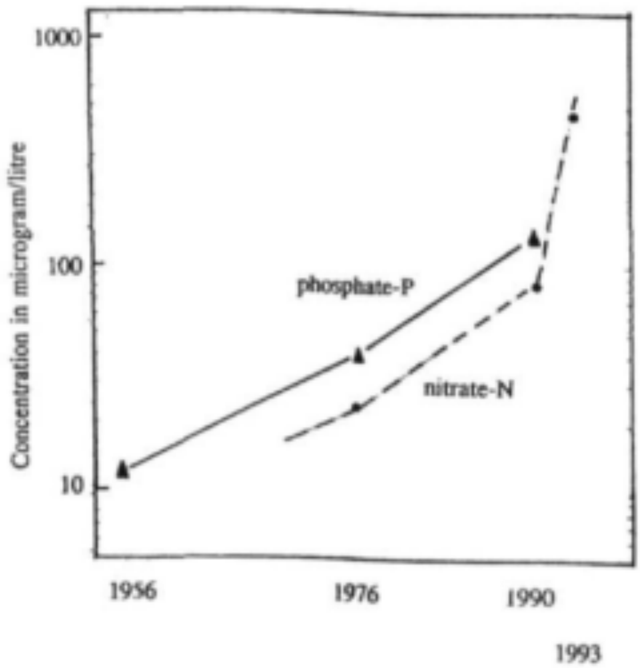


Figure 33a. Increase in phosphate P and nitrate N, respectively, in the water column of the Knysna estuary from 1956 - 1993. Note the log scale of the Y axis.

Figure 33b. Growth of *Ulva* sp. in the Ashmead Canal, Knysna estuary, October 1994.

***Guidelines for planners and managers***

Point sources of undesirable dissolved substances must be identified and their concentration levels and loadings determined as far as possible. 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 the 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 management procedures different from 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 assessed and modelled where this is considered relevant. In this regard the powerful computer-based GIS has provided the opportunity for these relationships to be more widely established and used. 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.

It should now become abundantly clear that agents responsible for eutrophication and agents of acidification of our waterways must be subject to the most rigorous control. And, in addition, use must be made of the remarkable recovery mechanisms which the aquatic ecosystem continues to provide. Once again the role of wetlands requires evaluation.

*The role of wetlands*

Both fringing and endorheic wetlands generate dissolved 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 recognise 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 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 (e.g. 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; of DOM is generally variable; of phosphorus is seasonally irregular; of pesticides is potentially good; of hydrocarbons is unknown; and of acidity is good.

Wetlands are generally intermediate stages in natural progression from aquatic to terrestrial systems. Management techniques are required to maintain wetlands as entities to ensure their continuing contribution to the mitigation of the influence of Man on the aquatic ecosystem.

# Part III

## The catchment as a management unit

### 1. Matrix analytical method

The difficulty for the decision maker and manager, when faced with a complex web of natural interactions so very much inherent in any natural ecosystem and made even more so when coupled with the impact of man's activities, as described in Part II, is to focus in on what should be considered as immediately relevant.

In developing this Introduction, the author was faced with an exactly similar problem, and a solution seems to have come through the application of a tabular or matrix approach called a ***Leopold Matrix,*** which provides us with a direct way of getting quickly to management priorities needed in the river valley or catchment. Begg[14] has used a similar approach to assess the forms of wetland disruption and the expected environmental effect.

These matrices are in reality very simple **but** exceptionally comprehensive and precise, incorporating as they do fundamental information on first-order cause and effect relationships. This format is very useful in highlighting areas of particular concern, of high risk or where further investigations are required. You will also appreciate the adaptability of the method, allowing us to move with equal ease from mountain source to river floodplains.

In the application of this method to the development of management protocols for freshwater ecosystems, whether it be rivers, wetlands, pans or manmade lakes and natural lakes, the impacts have been listed in accordance with major human activities in river catchments. The observed environmental responses are grouped under five headings and known to be of greatest significance. This approach allows the manager (reader) to locate quickly the *impacts of major concern* and the *array of environmental responses.* Other groupings are possible, but they add another level of complexity in which the non-specialist is minimally interested.

For each matrix cell the severity of the impacts can be ranked in terms of importance, probability, time of occurrence, duration, benefit, remedial measures and risk. The manager should provide for himself a set of symbols which individually make the reading of the matrix easily understood.

Environmentalists accept that a completed matrix is, as Richard Fuggle[35] concludes, "no more than a detailed record of an evaluation team's judgements on a wide range of issues relevant to the environmental implications of a project." Obviously a fully complete matrix contains so much information that its impact upon the management group may well be quickly dissipated. It is for this reason that a summary matrix is required which focuses attention through suitable colour coding upon those impacts and responses giving rise to real concern. Likewise problem areas about which there is doubt, but which really require further work on the component water area, can be identified by means of another colour. An example of a complete matrix is given in Table 9.

The application of this technique to **specific** river reaches and their catchments and the impacts which have become obvious and their essential management are given in the following synopses.

Table 9. A Leopold Matrix presenting the impacts commonly occurring in catchments in South Africa and the environmental responses to these impacts.

| **ENVIRONMENTAL RESPONSES** / **IMPACTS** | **Hydrology:** flash flooding | reduction in base flow | increase in bank erosion | increase in sheet erosion | habitat destruction | increase in suspensoids | **Water Quality River:** salinisation | lowered dissolved oxygen | increase in biochemical oxygen demand | increase in N & P | impaired self-purification capacity | increase in bacterial & viral densities | fish deaths | **Water Quality Reservoirs:** enrichment of reservoirs | deoxygenation of hypolimnion | change in downstream temperature | reduction in N & P in outflow | increase in food particles in outflow | fish deaths | **Biological community:** changes in plant communities | increase in alien plants | algal blooms - *Microcystis* | changes in animal communities | increase in disease vectors | obliteration of animal communities | **Human environment:** decrease in aesthetic value | loss of enjoyment of river & wetland | increase in public health risk | loss of house and homes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Farming:** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| toxic sprays | | | | | | | | | | | • | | • | | | | | | | | | | | | • | • | • | • | |
| dips | | | | | | | | | | | • | | | | | | | | | | | | | | • | • | • | • | |
| irrigation | | • | | | | | • | | | • | | | | • | | | | | | | • | • | | • | | | | | |
| overgrazing | • | • | • | • | • | • | | | | | • | | | | | | | | | | | | | | | | | | |
| destruction of riparian | | • | • | | • | • | | | | | • | | | | | | | | | | | | | | | | | | |
| farm dams | | • | | | • | | | | | • | | | | | | | | | | • | • | • | | • | | | | | |
| feedlots | • | | | • | | • | | • | • | • | • | • | | • | • | | | | | | | | | | | | | | |
| draining of riverine wetlands | • | • | • | | • | • | • | | | | • | | | • | • | | | | | • | • | | • | | • | • | • | | |
| **Afforestation:** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| clearing of indigenous vegetation | • | • | • | • | • | • | • | | | | • | | | | | | | | | • | • | | | | • | • | • | | |
| pine and eucalypt plantations | | • | • | | • | | | | | | | | | | | | | | | • | | | | | | • | • | | |
| invasive aliens (black wattle) | | • | • | | • | | | | | | | | | | | | | | | • | • | | | | | • | • | | |
| logging tracks | | | • | | • | • | | | | | | | | | | | | | | | | | | | | | | | |
| **Urban:** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| point discharge of sewage works | | | | | • | • | • | • | • | • | • | • | | • | • | | | | | • | • | • | • | | | • | • | • | |
| diffuse discharge (storm water) | • | | • | | • | • | • | • | • | • | • | • | | • | • | | | | | • | • | • | • | • | | • | • | • | • |
| failure of sewer systems | | | | | | | | • | • | • | • | • | | • | • | | | | | | • | • | • | • | | • | • | • | |
| suspensoids | | | | | | • | | | | | | | | | | | | | | • | • | | • | | • | • | • | | |
| littering | | | | | | | | | | | | | | | | | | | | | | | | • | | • | • | • | |
| **Industrial:** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| toxic effluents | | | | | | | | • | | | • | | • | | | | | | • | | | | | | • | • | • | • | |
| stormwater runoff | • | • | • | | • | • | • | • | • | • | • | • | | • | • | | | | | • | • | | • | • | | • | • | • | |
| air pollution (acid rain) | | | | | • | | • | • | | | • | | | | | | | | | • | | | • | | • | • | • | • | |
| abandoned mine workings (acid discharge) | | | | | | • | | • | | | | • | | | | | | | | | • | | | • | | • | • | • | • |
| slimes dump seepage and slumping | | | | | • | • | • | | | | | | | | | | | | | | | | | | | | | | • |
| **River regulation:** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| dam construction | | • | | | • | • | • | • | • | • | | | | • | • | • | • | • | | • | • | • | • | • | | | | | • |
| irrigation schemes | | • | | | | | • | • | • | • | • | | | • | • | | | | | • | • | • | • | • | | • | • | • | |
| inundation of wetlands | | | | | | | | | | | | | | | | | | | | • | • | | • | • | • | • | • | | |
| river channel alteration | • | • | • | • | • | | | | | | • | | | | | | | | | • | • | | • | • | • | • | • | • | • |
| canalisation | | • | | | • | | | • | • | • | • | • | | • | • | | | | | | | | | • | • | • | • | • | |
| sandwinning | | | | | | • | • | | | | • | | | | | | | | | • | • | | • | | • | • | • | • | |

### *1.1. The Headwater Zone*

While many rivers arise in the eroding great scarp of the Drakensberg, and the coastal fold mountains, a number of important rivers, for example the Mgeni in Natal, arise in the Midlands where the source sponges are particularly sensitive or vulnerable to human interference. As three of South Africa's most important rivers arise in the Mountain Massive of Lesotho, the protection of their river resources in this alpine region of southern Africa is paramount. Each is threatened in one way or another. The application of a Leopold Matrix to assess the impact of human activities upon these alpine regions is recorded in Table 10.

Table 10. The application of a Leopold Matrix to assess the impact of community occurring anthropogenic activities of the headwater zone of rivers.

| **Observed environmental response** / **Form of impact** | habitat loss | erosion | increased sediments downstream | algal & plant community change | deleterious temperature changes | water retention loss | litter & garbage -- aesthetic | water quality lowered | reduced continuous discharge | Environmental impact index |
|---|---|---|---|---|---|---|---|---|---|---|
| Trampling of sponges | * | * | * | | * | * | | * | * | 7 |
| Enrichment (N & P) | | | * | * | | | | * | | 3 |
| Mining (diamondiferous pipes) | * | * | * | * | * | * | * | * | * | 9 |
| Hiking trails (tourism) | | * | | | | | * | | | 2 |
| Subsistence farming | * | * | * | | | * | | * | * | 6 |
| Draining | * | * | | * | | * | | * | * | 6 |

Here attention is focused on the effect of six forms of impact. The observed environmental impacts number at least nine. By adding across the rows we conclude that of the impacts observed, three have the most intense effect upon the montane source zones, namely

* Mining of diamondiferous pipes
* Trampling of sponges by livestock
* Subsistence farming

with mining having the most severe impact. The use of a simply determined environmental impact index or coefficient has been introduced to express the result of the analysis in a quasi-quantitative way. Thus mining would have an index of 0.27, determined simply by dividing the frequency of response (in this case 9) by the total number of responses assessed or observed, i.e. 33. But it is not always as simple as this. An impact with a small frequency of responses may result in a sustained and very serious response. For example mining in Table 11b has a low frequency index but the effect on the salinisation of raw water resources is substantial and sustained. Thus it is essential to assess not only the frequency but also the intensity of the responses.

By such a simple analysis it becomes possible to begin the assessment of how best to reduce the impact(s), in which of course a variety of interested and affected parties become involved. Readers will appreciate that as soon as this simple analysis is made, the development of an Environmental Impact Assessment (EIA) profile becomes possible, and within it the concerns of the community can then be judged against the environmental issues which either have developed or are likely to do so.

Clearly the short-term economic value of diamond mining has to be judged against the long-term destruction of primary water resources. We recognise that such decisions, because they are very often largely of a political nature, move outside the expertise and practice of engineers and environmentalists **but** we must recognise that we have a tool with which to express the reasons for our concern in a more direct way than perhaps before.

### *1.2. The Middle Zone*

Implicit in the management of the feeder streams both to the Vaal to the south and to the Crocodile and Olifants to the north of the Witwatersrand, is the need to ensure that the water quality of the streams is restored by strict control of industrial and urban pollution sources, factories, sewage works and stormwater drainage. It is illogical in the extreme to create an Inter-Basin Transfer system of the magnitude of the Highlands Water Scheme only to retain a lax attitude towards the polluting foci in the Vaal catchment ! Put another way, the Highlands Water Scheme with its ancillary support systems (Tugela) is our last "immediate" resource. If the ecosystem management of the Vaal, Olifants and Crocodile is ignored, the next millennium will require major inter-basin transfer from the north-east, namely the Zambezi !

The maintenance of the upland freshwater ecosystems of the highveld and Bokkeveld rivers requires management policies which are sensitive to the primary requirements of these ecosystems, namely retention and/or restoration of the riparian vegetation. These plant communities may be of the fynbos group with no riparian trees; grasslands; and, at somewhat lower altitude, where trees appear in the riparian canopy, they must be protected (Figures 34a & 34b).

The conservation or restoration of the riparian vegetation (Figures 35a and 35b) will allow many of the essential biological and biochemical river processes to continue, provided of course that organic and/or toxic pollutants are not influencing water quality.

Note that there are many instances where the riparian is in an acceptable condition, but where the quality of the river water is far from acceptable. We would not expect, however, the upland river sections to experience impaired water quality, as they occur in protected mountain forest or fynbos areas, but this is not invariably so and their environmental health requires careful review, irrespective of the limnological region in which they occur.

Many large metropolitan complexes are situated on these middle zone rivers of the highveld, though fortunately developments of similar magnitude are not yet threatening the Bokkeveld rivers such as the Olifants in the Cedarberg. Some of the tributaries of these highveld rivers are severely impacted by the largest urban sprawl in the Southern Hemisphere, the Witwatersrand complex, and streams such as the Jukskei and the Klip which flow north and south respectively from the Witwatersrand are grossly impacted. Some degree of restoration is presently occurring due to the environmental sensitivities of a number of people and groups who have been stimulated by the DWAF to rescue these remnants of what must have been in reality "The Ridge of White Waters" before the discovery of gold.

The application of a Leopold Matrix analysis to the environmental issues of particular concern to the middle zone of highveld and Bokkeveld rivers is given in Table 11.

Figure 34a. Fynbos source zone of many middle zone rivers.

Figure 34b. Middle zone of the Olifants River, Western Cape. Note very well developed riparian.

Figure 35a. Orange River, near Colesberg: dry season flow.

Figure 35b. Orange River, near Colesberg: showing the extent of the riparian.

Table 11a. Middle zone - upland reaches

| **Observed environmental response** / **Form of impact** | increase in/reduction of runoff/seepage | deterioration in water quality | bank erosion | smothering of river bottom | elevation of temperature | dampening of temperature signal summer/winter | decrease in dissolved oxygen | elevation in faecal coliforms | loss of *all* or nearly all water-living animals and some plants | aesthetics: sense of place | reduction in light, therefore in autochthonous primary production | Environmental impact index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Afforestation | * | * | * | | | | | | | | | 3 |
| Farming in which the riparian is affected | * | * | * | * | * | | | | | * | | 6 |
| Stream regulation | | | | | * | * | * | | | | | 3 |
| Thermal pollution | | | | | * | * | * | | * | | | 4 |
| Organic effluents (BOD) | | * | | | | | * | * | | * | * | 5 |
| Toxic effluents | | * | | | | | * | | * | * | | 4 |
| Garbage/litter | | | | * | | | * | * | | * | | 4 |
| Suspensoids | | * | | * | * | | | | | | * | 4 |
| Atmospheric ppt - acid rain | | * | | | | | | | * | | | 2 |

Table 11b. Middle zone - lower reaches.

| **Observed environmental response** / **Form of impact** | decrease in runoff (sustained) | decrease in infiltration | decrease in base flow | increased runoff: storm flows | bank and sheet erosion | sustained temperature change | reduction in seasonal temperature signal | increase in subtropical disease carrier potential | aesthetics - sense of place | decrease in light climate - influence on primary production | retention of *E.coli* | animal community change | loss of animal and greater part of plant community; self-purification capacity impaired | decrease in dissolved oxygen | increase in salinization (mineralisation) | Environmental impact index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Afforestation | * | * | * | * | * | * | | | * | * | | * | | | | 9 |
| Farming, riparian | | | | | * | | | | | * | | * | | | | 3 |
| Urbanization: | | | | | | | | | | | | | | | | |
| Stream regulation | | | | | * | * | * | * | | * | | * | * | * | * | 8 |
| Wetland drainage | * | | * | * | | | | | * | | * | * | * | | * | 8 |
| Thermal pollution | | | | | | * | * | | | | * | * | * | * | | 6 |
| Organic (sewage) effluents | | | | | | | | * | * | | * | * | | * | * | 6 |
| Toxic effluents | | | | | | | | | * | * | | * | * | * | * | 6 |
| Garbage/litter | | | | | | | | *[1] | * | | * | | | | | 3 |
| Suspensoids | | | | | | | | | | * | | | * | | | 2 |
| Inter-basin transfer | | | | | * | * | * | * | | | | * | | | | 5 |
| Atmospheric ppt: acid rain | | | | * | | | | | * | | | * | * | | * | 5 |
| Irrigation canals | | | * | | | | | * | | | | | | | * | 3 |
| Mining activities | | | | | | | | | | | | * | | * | * | 3 |

*[1] *Aedes* sp. - yellow fever vector

In this tabular analysis the expected environmental impacts are less specific than in Table 10; nevertheless the array of responses is substantial even at this more "generic" level of description.

It becomes a simple but very informative exercise to home in on a particular impact or group of impacts and build a more detailed matrix. This as we have said before becomes a very valuable environmental analysis tool; even more so when the engineer, developer and planners are faced with a new industrial or urban development. By adopting this approach the really cogent environmental issues are brought into focus.

Thus, stream regulation, wetland drainage, sewage and toxic effluents, thermal pollution, litter and suspensoids account for 58% (EI = 0.58) of the expected environmental response in the middle zone of the river and its valley. This is to be expected as each of these components is a significant feature of the process of urbanisation; Figure 36.

It follows that being aware of this environmental index, the responsibility of the manager is to ensure that each constituent impact or potential impact be carefully assessed and either removed from the management demands or its effective amelioration seriously considered. Thus the developments in sewage purification engineering should not allow the building of a substandard works; or if costs are material to the development, all the best advice on simpler but effective means of disposal should be sought. Similarly, and having regard to the stress which has been laid upon the ecological advantages of wetlands, no attempt should be made to destroy existing wetlands: urban and industrial development must accept that their integration is essential.

Figure 36. Glimpses of the urban sprawl of southern Johannesburg.

Table 12. Lower zone - the mature river.

| **Observed environmental response** | runoff increase or decrease | flood control | decrease in baseflow infiltration | increased runoff | increase in bank and shear erosion | sustained temperature change | increase in subtropical disease vectors | aesthetics - sense of place | decrease in light penetration: effect on primary production | elevation of P., *E.coli* etc | animal community change; alien vegetation | loss of biological community, ∴ impaired river self-purification | decrease in dissolved oxygen | increase in suspensoids | salinisation (increase in TDS) | eutrophication - algal cells - water treatment | decreasing public health | loss of homes | loss of life (Man and animals) | Environmental impact index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Form of impact** | | | | | | | | | | | | | | | | | | | | |
| **Alien/invasive plants** | * | * | * | | * | | | * | | | | | | | | | | | | 5 |
| **Canalisation** | | * | * | | | | * | * | | * | * | * | * | | | | | | * | 9 |
| **Destruction of riparian vegetation** | * | * | * | * | * | | | * | * | | * | | | * | | | | * | | 10 |
| Development-supporting activities (roads, quarries) | * | * | * | * | | | | * | | | | | | * | | | | | | 6 |
| Farming (overgrazing, encroachment onto floodplain) | * | * | * | * | * | | | | * | | * | | | * | * | | | | | 9 |
| Garbage scatter | | | | | | | * | * | | * | | * | * | | | | | | | 5 |
| Irrigation supply discharge seepage | * | | * | | | | * | | | | * | | | | * | | | | | 5 |
| Organic discharges | | | | | | | * | * | * | * | * | * | * | * | * | * | * | | | 11 |
| River regulation: | | | | | | | | | | | | | | | | | | | | |
| farm dams | * | | * | * | | | * | | | | * | | | | | | | | | 5 |
| major dams | * | | * | | * | * | * | | * | | * | | | * | * | * | * | * | | 12 |
| Sand winning | | | | | | | | * | * | | | | | * | | | | | | 3 |
| Stormwater | * | * | * | * | * | | | | * | * | * | | * | * | | * | * | * | | 13 |
| Thermal pollution | | | | | | * | * | * | | | * | * | * | | | | | | | 6 |
| Toxic discharges | | | | | | | | * | * | | * | * | * | * | * | | | | * | 8 |
| Urbanisation: | | | | | | | | | | | | | | | | | | | | |
| formal | * | * | * | * | | | | | * | * | * | * | * | * | | * | * | | | 12 |
| informal | * | * | * | * | * | | * | * | * | * | * | * | * | * | | * | * | * | | 16 |
| Water abstraction | * | | * | | * | | | | | | | | | * | | | | | | 4 |
| Wetland modification and destruction | * | * | * | * | | | * | | * | * | | * | * | * | | * | * | | | 12 |

### *1.3. The Lower Zone - the mature river*

Floodplains so typical of European and North America rivers are rare in South African rivers. A few, such as the Great Berg River on the West Coast and the Pongola River in Maputaland have quite sizeable floodplains through which the rivers continue to widen and flow rates decrease. Other consequences of this maturity are the increases in sedimentation so that the river bottom becomes muddy and the oxygen levels tend to fall away from saturation. This will of course depend upon the diversity and abundance of rooted macrophytes, filamentous algae and diatom assemblages which develop where flow rates decrease and nutrient inputs are high enough to support their nutrient requirements, particularly of filamentous algae and diatoms.

The decrease in flow rate encourages growth in phytoplankton and zooplankton communities, although many of the taxa found are not truly planktonic except in very large rivers like the Amazon, rather they are responding to the turbulence in the water column which may sweep them into suspension for varying lengths of time.

It is in these slow reaches of the great European and North American rivers where the impact of man's effluents become most obvious and severe. Fortunately the relative youthfulness of our rivers particularly along the Cape South Coast, the Transkei seaboard and Natal has resulted in very limited floodplains, but with the ever increasing intensity of soil erosion in many of their catchments, the reaches of the lower river including their estuaries have become filled with sediments from the catchments and in some cases a small flood plain through which the stream meanders is built up between major flood periods. The commonly occurring impacts and their environmental responses are given in Table 12.

Once again those impacts associated directly with urbanisation dominate the environmental response; viz 50% or an EI = 0.5. In addition new impacts have been presented, e.g. sand mining and canalization. They are more likely to occur in the low reaches of the rivers and hence their impact must be assessed. Canalization is often favoured by engineers when faced with seemingly intractable flood control problems. Once canalized, the river or stream segment loses all its natural attributes, and as Table 12 illustrates, canalization, while effecting flood control to some degree, generates other environmental responses which have to be assessed in the planning stages. In some instances there are immediate benefits, as for example the Camps Drift canalization of the Msunduse River. In the impact assessment of this development a somewhat parallel analysis showed that the canalization would increase the recreational potential of this part of the river. This it has done, but the authorities were informed of the other negative issues, e.g. silt accumulation and pollution from hospital stormwater discharges.

It is our view that matrices of this type, albeit not strictly matrices in the mathematical sense, are valuable tools with which to examine environmental issues.

Finally the river meets the seas (Figure 37) and through their interaction, the estuary is formed: a remarkably interesting and environmentally sensitive aquatic area in which some of the most productive wetland communities develop. Their role in South Africa has been primarily recreational, but more and more the impact of urbanisation is taking its toll both of the structural components which make up this complex habitat and of the physical and biochemical processes which regulate their interactions.

A. Kromme River.

B. Seekoei River.

Figure 37. Some floodplains of lower reaches of rivers.

## 2. Management considerations

Arising from such analyses, the really important impacts and responses are highlighted, and the nature and style of management of the resource to be effective becomes clearer. Thus management is required to 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 demands result in conflicts which have to be resolved during the formulation and 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 extent 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 and interpretation 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.

The centralised control of this national resource, water, rests with the Department of Water Affairs and Forestry, but we perceive a need to establish catchment or contiguous catchment control on a management strategy model not too dissimilar from that currently being practised in the United Kingdom by the National River Authority, which reduced the diversity of interests (some 1600 independent organisations responsible for sewage disposal, water supply and river regulation) to ten regional water authorities based on one or more river catchments.


Figure 38. Limnological regions of Southern Africa proposed by Allanson *et al.*[30]

Region 1. A subtropical coastal peneplain with coastal lagoons of varying salinity.

Region 2A. The elevated plateau of the highveld with summer rainfall with temporary and permanent water. Total dissolved solids < 500 mg $\ell^{-1}$ with alkaline pH.

Region 2B. Extensive plateau at somewhat lower level than 2A with summer rains but with clear waters with TDS << 500 mg $\ell^{-1}$ and pH near neutral.

Region 3. The elevated mountain massif of Lesotho: the Australo-montane region. Low TDS < 270 mg $\ell^{-1}$; pH ≤ 7.

Region 4. Temperate peat-stained acid waters of western Cape arising from Cape Fold mountains, variously influenced by transport of salt from the sea via winds.

Region 5. The arid west stretching from inland of Port Elizabeth to Namibia and southern Botswana. Higher TDS > 500 mg $\ell^{-1}$ and often strongly alkaline.

The advantages of this management strategy have been (1) resolution of political conflicts, (2) better utilization of resources, (3) integrated and realistic control of the resource, and (4) economies of scale; granted a possible disadvantage of large basin management is the need for greater personnel resources.

In this we should be guided by the recently developed regional limnology of the subcontinent. Five limnological regions are determined not only by real differences in geomorphology, geochemistry and climate, but also by structurally different hydrological, chemical and biological features.

Accepting that each region is too vast an area over which to establish a central control as has been done for the water management regions of the United Kingdom, nonetheless this regional limnology should provide a foundation upon which to construct a water management structure sensitive to the hydrological and limnological properties which define each region.

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 quantity or 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.

The division of South Africa into new political entities should provide the impetus for the development of this or similar strategy. We are surprised and pleased to note how reasonably consistent is this political dispensation with the broad features of the regional limnology described earlier. Region 2 requires the greatest extent of subdivision and this principally with a south-eastern coastal region which geographically is distinct from the elevated highveld of the Orange Free State and the PWV (now Gauteng), north-eastern and eastern Transvaal. Indeed in the original regionalisation proposed by myself and my colleagues[36], Region 2 is so subdivided (Figure 38).

Thus in simpler terms such a strategy will retain the responsibility for ultimate control in the hands of the Department of Water Affairs and Forestry while giving the management of the resource to regional authorities, autonomous from provincial government, and which will generate income from the sale of water and services. The present dichotomy into a myriad of municipal and local authority units levying fees is anachronistic.

The question has to be asked as to whether this devolution to municipal level is the most cost-effective and efficient. As regards the protection of the aquatic ecosystems, this is unlikely to be the case, as it is very much at this level that the economy of scale comes into play. Thus a small municipality requiring a new sewage works or a substantial extension to an existing one is faced with enormous financial issues of borrowing and financial charges often well beyond the means of the local authority. The result is that no expansion takes place, the sewer reticulation system breaks down and the downstream or estuarine habitat is severely impacted. Only by the regionalisation of our management of this vital resource will we move successfully into the next millennium !

# Part IV

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