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ECOLOGICAL FLOW REQUIREMENTS FOR SOUTH AFRICAN RIVERS

A A Ferrar (Editor)

SOUTH AFRICAN NATIONAL SCIENTIFIC PROGRAMMES REPORT NO

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ABSTRACT

This document contains the proceedings of a workshop which was convened to debate the ecological flow requirements of South African rivers. Topics which are discussed include the influence of weirs and impoundments, the quantity requirements of flora and fauna associated with the riverine habitat, in addition to many physical, chemical and biological concepts concerning the assessment of minimum flow in South African rivers.

ACKNOWLEDGEMENTS

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CHAPTER 1. INTRODUCTION

The need for cooperative research on the ecology of southern African rivers has been a priority in the minds of aquatic biologists and environmental planners for many years. As a focused national activity it was initiated in 1984 when the first conceptual documents and project proposals emerged from meetings within the Nature Conservation Research section of CSIR's Ecosystem Programmes. At that time the Department of Water Affairs had recently revised it's 1970 estimate of water demand for nature conservation. This estimate had been increased from less than one per cent of total demand to a figure between 10% and 15% of total demand. What is noteworthy about these figures is not the values themselves, or the relative proportions they represent, but the scarcity of real data on which they had to be based. This fact, more than any other, has given rise directly to the current emphasis in the river research programme, of focusing on the instream flow requirements of regulated rivers.

The text that follows and the workshop that generated it were developed as a result of the Rivers Working Group, under the chairmanship of Dr Mark Chutter, identifying this information gap together with conceptual problems of how to conserve river systems.

The difficulty of managing any ecological system towards some vaguely perceived "optimum sustainable state" is immense and predisposed to failure. This is especially the case with rivers, characterized as they are by extreme dynamics, fluvial functions and other attributes, such as their special biodiversity and socio-economic values. These all make for increased complexity and therefore difficulty, in managing rivers towards conservation goals.

A researcher's normal response to complexity is to reduce it to primary components, analyse and model it and then test the applicability of such models to the real world. This is precisely what many leading river ecologists are currently preoccupied with; activities that are also reflected in the South African river research community and in this document. Most of the research experience and knowledge of the ecological structure and functioning of rivers has been gained in the temperate and cold-water streams of Europe and North America. South African researchers have concentrated on differences between local rivers and those from which these general models have been derived. The obvious differences, ie being warmer and more seasonally variable, are readily acknowledged and have already given rise to new research or management approaches. In preparation for and participation in this workshop, new thinking has been developed on how to model the flow requirements of regulated rivers.

The layout and content of this volume represents both the way South African river scientists and managers think in terms of the general models of riverine function, and it also represents the current state of knowledge and understanding.

The text refers to engineering management, which in South Africa is quite advanced and, due to high water demand, is widely developed and tightly controlled. By contrast the level of catchment management is poor to nonexistent. Informal use of water, both for abstraction (irrigation) and for waste disposal is poorly controlled, inefficient and widely abused. Add to this the almost universal problem of soil erosion and situation with the associated extremes of drought and flood and a national picture of deepening and unavoidable crisis is evident. Against this background, our understanding of how rivers function ecologically, is woefully inadequate. Their role in maintaining biodiversity and is affecting the rates of change in landscapes and ecosystems can only be assessed by means of ecological commonplace ("data-free estimates").

The text is arranged in the logical sequence, looking first at physico-chemical properties of the water and then the physical and biological dynamics of the entire system. The real inadequacies of our knowledge are evident when the biological needs for water in river systems is investigated from a quantitative point of view. In this discussion the total biodiversity of the hypothetical river system is reduced to three primary components, which are seen as being functionally distinct from a management view point. These are: the needs of aquatic microbiota, invertebrates and aquatic plants of the river channel (Chapter 5); the needs of fish communities (Chapter 6); and the needs of the groundwater dependent river bank and flood plain communities (Chapter 7). All of these discussions illustrate levels of understanding that are at best patchy (the functioning of cold water mountain streams of the western Cape) and at worst, nonexistent (the flood dependence of flood plain woodlands and forests).

With these discussions, however preliminary they may be, it is the intention of the River Research Programme to stimulate research activity into providing a more substantial information base and understanding of the role of rivers in South Africa's landscapes of the future.

CHAPTER 2. FLOW-MODIFYING STRUCTURES AND THEIR IMPACTS ON LOTIC ECOSYSTEMS

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INTRODUCTION

The general aridity of climate in South Africa, combined with the paucity and seasonality of natural lakes and reliable water resources, has hindered economic development in the region (Ashton et al 1986). The growing human needs for water have largely been met by the construction of an array of structures designed to provide water in those regions where the requirements are greatest. Inevitably, as human demands for energy, irrigation, domestic and industrial water consumption increase, the flows in more and more streams and rivers are modified or depleted (Stalnaker 1981). This escalating pressure for human development is in clear and frequent conflict with instream uses of water for aesthetics, recreation and the conservation of aquatic ecosystems. These conflicts of interest require that compromises be made so as to permit maximum benefits to be derived from the resources available. Typically, however, the solution of one problem often leads to the realization of another, perhaps one whose impacts are less easily perceived or solved.

In this chapter, we provide an outline of the different types of engineering structures that are employed in the regulation of stream and river flows and describe, in broad terms the major ecological impacts associated with them and provide suggestion as to how future problems be approached.

FLOW-MODIFYING STRUCTURES AND THEIR MODES OF OPERATION

It has often been stressed that the art and science of controlling water flows, is the one branch of engineering that has contributed most to the development of civilization (Baxter and Glaude 1980). The type of structure built at any particular site and its mode of operation depends on consideration such as its intended purpose (eg storage, flood attenuation, hydro-electric power generation) and the nature and location of the site. In almost every case the primary objective has been to regulate the flow of water for the benefit of man; ecological considerations, if included, have been of secondary importance. Nevertheless, it must be appreciated that the physical and chemical relationships of flowing waters, acting in concert with physiological, morphological and behavioural traits of lotic species, have resulted in a mosaic of complex community relationships that are easily disrupted by man's activities in controlling the quantity and seasonal distribution of flows (Cummins 1979). Indeed, if a river ecosystem is disturbed sufficiently, many of its self-purifying properties may be irreversibly impaired. It is therefore necessary that man's ingenuity in devising schemes for the management of scarce water resources should be matched by a commitment to retain, or conserve as far as possible, these fragile ecosystems for the benefit of all.

Impoundments

For the purposes of this document we do not distinguish between large and small impoundments. Typically, however, impoundments are much larger than weirs and farm dams (dealt with in the sections on weirs and farm dams below), and may often possess facilities for the discharge of water from different depths. Due to their larger size and strategic location, they modify long stretches of the river both upstream and downstream of the construction site. These modification include alterations to:

- flow regime;
- temperature regime;
- chemical regime;
- transport of sediments and organic matter;
- movements of biota both up- and downstream; and
- habitat complexity and the composition and functioning of biotic communities.

Impoundments also impose a variety of human sociological impacts but, while we recognize the tremendous importance of such impacts, these are beyond the scope of this report and are therefore not considered further.

Both the daily and seasonal operation of impoundments is dictated by climatic events and human requirements, both within the catchment and downstream. Pongolapoort Dam absorbed approximately 1 500 x 10^6 m^3 during the cyclone Demoina, arguably an extreme event. With its current operation, some 1 000 x 10^6 m^3 storage capacity is available for flood absorption; this is equivalent to a flow of 3 000 m^3 per second for a period of four days. Nowadays, the Orange River downstream from the Hendrik Verwoerd Dam has lower summer flows and higher winter flows brought about by regulation and hydro-electric power generation. The controlled discharge has eliminated the previous large variations in water depth and has created new downstream habitats that are suitable for the overabundant development of simuliid (Black fly) larvae. During 1983, high sediment loads were released through the silt gates of the Phalaborwa Dam to prevent loss of storage capacity and caused fish kills for some 30 km downstream. The Welbedacht and Stormdrift Dams also possess silt gates; like Phalaborwa Dam, the impacts of their silt loads can be considerable, particularly if they are released as sudden pulses.

Numerous other examples of the impacts of reservoir operating conditions can be quoted for South Africa. Some of the best known are:

- phytoplankton blooms discharged from Bloemhof Dam into the Vaal River persist right down to the Vaal Hartz Weir some 80 km downstream;

- cold hypolimnetic water discharged from the Hendrik Verwoerd Dam maintain lower Orange River temperatures all the way to the P K Le Roux Dam some 70 km downstream;

- continual increases in salinity within the Hartz River below Spitskop Dam to its confluence with the Vaal River 50 km downstream;

- altered chemical quality of water discharged from impoundments such as Roodeplaat, Rietvlei, Hartbeespoort, Shongweni, Albert Falls and the Vaal Barrage;

- migration of fish and eels at Vaalkop and Klipvoor Dams is prevented through lack of fish ladders and periodic dry-season cessation of flow;

- creation of armoured, barren shorelines within large impoundments such as Bloemhof and Hendrik Verwoerd Dams by seasonal drawdowns;

- alteration in riverbed morphology below the P K Le Roux Dam brought about by sudden, high-volume water releases; and

- silt loads trapped within impoundments allow the release downstream of less turbid waters that have a greater silt-carrying capacity and thus enhance erosive powers, resulting in riverbed armouring.

Weirs

These are generally small structures, having walls less then five metres high and limited capacities, constructed to maintain an area of shallow water and thereby facilitate the abstraction of water by canals or pumps for irrigation. Large numbers of these structures have been built on virtually every river in South Africa (Noble and Hemens 1978). Because of their small size, weirs are, mistakenly, often thought to have little effect on downstream reaches of a river. While the influence of an individual weir on a river's flow pattern may indeed be negligible during periods of high flow, this is seldom the case during low dry season flows. Where several weirs are built in series along a river the overall effect is compounded and can lead to a complete cessation of dry season flows. This is very clearly shown in the Letaba River, Eastern Transvaal, where a series of five weirs with a combined capacity of 3×10^6 m^3 has been constructed downstream of the Fanie Botha Dam. High rates of abstraction from these weirs have effectively reduced dry season river flow to a trickle by the time the river reaches the western boundary of the Kruger National Park. The Letaba River has, in fact, been transformed from a perennial river to a seasonal river.

Because of their small size, weirs exert far less influence on fast flowing rivers than they do on slower flowing rivers located in areas of low topographic relief. However, even in first order headwater streams, weirs are still able to trap some silt and reduce the movement of bed load material. Because of reduced current velocities and relatively stable upstream waterlines, new habitats are created that favour the development of submerged, emergent and floating aquatic macrophyte communities. The relatively stable environments also promote colonization by alien free-floating aquatic macrophytes such as *Eichhornia* and *Salvinia*, since indigenous species are morphologically unsuited to occupy these habitats (Ashton et al 1986).

Typical examples of this pattern of colonization are to be seen in the Vaal River weirs at Parys, Schoemansdrift and Orkney, and in the weirs at

Mataffin, Karino, Riverside and Ten Bosch on the Crocodile River, Eastern Transvaal.

Farm Dams

Farm dams exhibit a considerable range in size with an upper limit of 250 000 m^3. Individually, their impacts on river ecosystems are very small, but because of the vast numbers of these structures in South Africa, their collective influence is great. Normally, farm dams are filled during periods of rainfall and all or most of the water is abstracted during the dry season when river flows are reduced or cease altogether. Thus, the important first flows of the early summer months, that serve as vital cues and signals to the river biota, are retained within the filling farm dams. This can cause considerable alteration in the timing, and thus success, of life cycle stages in the river biota. Another, perhaps more serious impact occurs in the frequent cases where several farm dams in series may burst their walls after heavy rainfall. This leads to greatly enhanced erosion of stream and river channels.

Flood control facilities

These structures, eg Beervlei Dam, are similar to impoundments but they are operated with the sole purpose of absorbing and storing large floods. Flood waters are then released downstream at much lower flow rates, thus preventing the erosive damage normally caused by flash floods. Inevitably, very large floods are greatly attenuated whilst downstream discharges of moderately large floods that have been stored often occur during unnatural periods of the year compared with the normal flow regime of the river. This can lead to the elimination downstream of those components of the biota that rely on strictly seasonal water flows and prevent the natural scouring and cleansing of riverbeds by natural floods.

Off-channel storage facilities

These are usually small impoundments located away from the mainriver channel and are filled from it by pumping. A typical example is the Klipheuwel Dam near Klein Brak. The stored water is discharged as needed, usually into a different stream, occasionally in another catchment. Individually, these structures cause small flow reductions in the stream of origin and even smaller additions in the receiving stream, after evaporative losses. On occasion, these structures can facilitate the intercatchment transfer of alien plant and animal species.

Hydropower facilities

Impoundments used for the generation of hydro-electricity are often of very large size. Their main impacts are determined by the timing and the quantity and quality of water discharged. This is seen quite clearly at both the Hendirk Verwoerd and P K Le Roux Dams on the Orange River, whose power stations are often operated twice a day during periods of peak demand in the early morning and at night. The discharged water is usually cold hypolimnetic water which increases turbine efficiency. The major impacts are associated with lowered river water temperatures and sudden, short duration surges and falls in river flow rates. These, in turn, cause very large fluctuations in water depth and wetted shorelines.

Pumped storage facilities

Pumped storage facilities are built to economize on electric power demands and consist of an upper and a lower storage reservoir, connected by a set of pumps and pipes. Water is pumped from the lower reservoir to the upper one during periods when excess power is available. At times of peak demand, power deficits are made up by releasing water from the upper reservoir to the lower one through turbines that generate power. The best knownecsmple in South Africa is the Drakensberg Pumped Storage Scheme between the Woodstock and Kilburn Dams in Natal, while another system is located at Steenbras Dam in the western Cape. A third, system, the Palmiet Pumped Storage Scheme, also in the western Cape, is due to commence operation shortly. Their impacts are usually small since only small river sections are involved. Where a pumped storage reservoir is placed directly on a river, it will have a similar effect downstream as a normal dam. In the case of the Palmiet scheme, this will also involve interbasin water transfers and the impacts are likely to be greater here.

Interbasin transfers

Interbasin transfer systems are built to transport water from a catchment where the available supply exceeds human needs to one where human demands exceed available supplies. Several interbasin transfer schemes are in operation in South Africa, the best known examples being the Tugela/Vaal, Usutu/Vaal, Orange/Fish and Berg/Riviersonderend systems. A further, very large system, the Lesotho Highlands scheme, is entering the design stage. This system will bring water from the upper reaches of the Orange River in Lesotho to the Vaal River. Typically, the operation of interbasin transfer schemes causes great alterations in flow regimes, changed chemical composition of the receiving waters, altered sediment and temperature regimes, habitat alteration and the translocation of biota from one catchment to another.

Canalization and bank stabilization

Canalization and/or bank stabilzation are employed in efforts to open blocked channels and reduce bank erosion, particularly in urban areas, and to prevent river meanders and the flooding of low-lying areas, and to prevent river meanders and the flooding of low-lying areas. They are usually employed in smaller rivers to enable floodwaters to drain away as quickly as possible. Their main impacts are on flow patterns and complete alterations of habitat. Typical examples include the Moreletta and Apies Rivers in Pretoria and the Black and Liesbeek Rivers in Cape Town.

Direct abstraction

In South Africa, direct abstraction from both perennial and seasonal rivers is widely used as a means of meeting the water demands of the agricultural sector. In many cases, dry season flows are also stabilized by controlled releases from upstream impoundments, thus ensuring a year-round supply of water. In extreme cases, where the demand for water equals or exceeds the available supply, rivers may dry up completely by the end of the dry season. Good examples of such extreme cases are the Letaba River in the Eastern Transvaal and the Eerste River in the western Cape, where direct abstraction completely removes dry season flows. As can be expected, the major impacts are those relating to drastic habitat alteration and changed temperature and chemical regimes caused by reduced dry season flows.

Return flows

In a semi-arid country like South Africa with its limited water resources, return flows from agriculture and industry often form an important component of the available water resources. Inevitably, these waters have a greatly altered chemical composition and, because they are often impounded and re-used, have the potential for tremendous chemical effects on downstream river reaches. Rivers such as the Vaal and Hartz, where return flows form a high percentage of the total river flow, provide clear examples of the chemical impacts involved (Bruwer et al 1985).

OBSERVED AND ANTICIPATED IMPACTS ON RIVER ECOSYSTEMS

Structures designed to modify the timing and duration of river flows have a wide variety of influences on the river ecosystem. These are functions of the type and size of structure involved, its mode of operation, the associated environmental inputs and whether or not the structure is in series with other structures. It is thus apparent that the environmental impacts imposed on downstream river reaches are highly complex and are compounded by interacting processes. A diagrammatic representation of these features is shown in Figure 2.1.

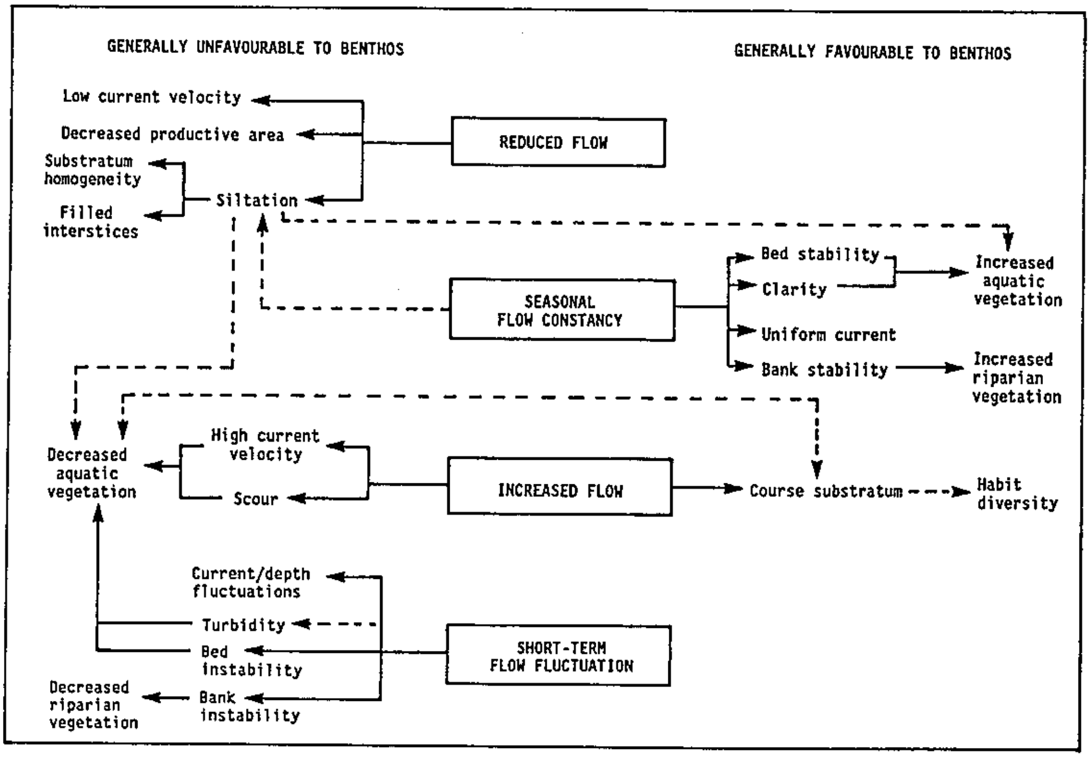

FIGURE 2.1 Potential effects of various flow patterns below dams on ecological factors having an important influence on stream benthos; --- indicates less definite relationships.

In broad terms the impacts can be categorized into five classes, namely: flow; turbidity and sediments; chemical effects; temperature effects; and habitat alteration. The types and degrees of impacts imposed by flow-regulating structures on downstream river reaches are often site--specific. Therefore, they are extremely difficult to predict and should be approached on a multidisciplinary basis. Table 2.1 provides a generalized list of responses shown by simple parameters measured in downstream river reaches.

TABLE 2.1 Expected anticipated responses of parameters in downstream river reaches to discharges of epilimnetic or hypolimnetic water from a hypothetical reservoir (modified from Ward and Davies 1984)

Parameter	Epilimnetic water	Hypolimnetic water
Discharge volume	Highly variable	Highly variable
Erosive capacity	Greatly increased	Greatly increased
Turbidity	Reduced	Usually reduced
Silt and sediment load	Reduced	Usually reduced
Water temperature	Increased	Decreased
Dissolved oxygen	Often increased	Variable, often anoxic
Salinity	Variable	Variable
Reduced compounds (Fe, Mn)	Reduced	Increased
Nutrients	Often reduced	Increased
Phytoplnakton	Greatly increased	Occasionally increased
Zooplankton	Increased	Often reduced
Benthic species diversity	Often decreased	Often decreased
Benthic faunal biomass	Variable	Variable
Fish	Variable	Variable often decreased
Detritus	Reduced	Usually reduced

Flow

River habitats are defined by several physical characteristics: width; depth; current velocity; cross-sectional area; total surface area; shoreline profile; wetted perimeter; hydraulic radius; sinuosity; channel shape; gradient; bed roughness; pool:riffle ratio and discharge. All or most of these are altered directly by modifications to streamflow regimes imposed by flow-regulating structures. These habitat alterations, in turn, determine the composition of the faunal and floral communities that remain. Several observed and anticipated impacts can be listed:

- elimination of variability in flows, through constant rates of discharge, give rise to steady (constant) current speeds; communities reliant on variable flow regimes are eliminated; lack of scour leads to increased periphyton growth and greater phytobenthos biomass;

- constant flow rates and/or reduced current speeds lead to greater riverbed stability. The growth of vascular aquatic plants is promoted and conditions become suitable for encroachment by, for example, *Phragmites* reed beds;

- the banks of regulated rivers develop a greater density/biomass of riverine vegetation;

- reduced amplitude of fluctuations in flow can promote consolidation of alien and indigenous aquatic macrophytes and their spread upstream;

- loss of high-flow events due to flow attenuation by impoundments can eliminate seasonal signals to migratory and annually-breeding biota and reduce channel scouring;

- reductions in flow can reduce the spawning frequency and success of migratory fish;

- unseasonal flow patterns dictated by downstream human demands can lead to complete elimination of certain species and change the species composition of river biota; and

- when several flow-regulating structures in a river are operated in series to satisfy extensive irrigation demands, flow rates can drop to zero and encroaching vegetation can block the river channel. This will lead to elimination of all those species that require flowing water to survive.

A schematic diagram of perceived and potential effects of different flow patterns on stream benthos communities below impoundments is shown in Figure 2.2. The high degree of interrelationship between the different factors is clear, showing the situation to be highly complex.

Sediment loads and turbidity

The term turbidity is used here in a general sense, indicating the extent to which water lacks clarity. Typically, turbidity is regarded as a function of the suspended organic and, especially, inorganic material in the waters of rivers and reservoirs. The sediment loads of rivers and the turbidity of their waters are dependent on complex interactions between soil characteristics and agricultural practices ;within the catchment and the flow rates of rivers draining the catchment. Progressive decrease in water flow rate causes deposition, or settling out, firstly of coarser material and finally, in stationary waters, of finer clay particles. Thus, the influence of flow-regulating structures in rivers on sediment loads and turbidity is closely related to the type and size of the structure and its mode of operation. Several effects have been observed:

- storage facilities trap sediment particles, resulting in the discharge of water with reduced sediment load and increased erosive capacity. This, in turn, leads to armouring of the riverbed immediately downstream and changes in river channel morphology;

- decreased sediment loads cause the interruption or complete cessation of sediment deposition processes on levees and lead to reduced nutrient inputs to downstream habitats (eg the Pongola floodplain) and alterations in the light regime of downstream rivers; and

- impoundments trap (and thus remove from suspension) inorganic particles whilst the discharged waters contain higher quantities of organic particles such as phytoplankton, zooplankton and detritus. These lead to large alterations in the optical properties of the discharged water as well as changes in the nature and abundance of food sources for downstream biota; these changes can, in turn, influence the biotic communities in downstream habitats and thus the functioning of the river.

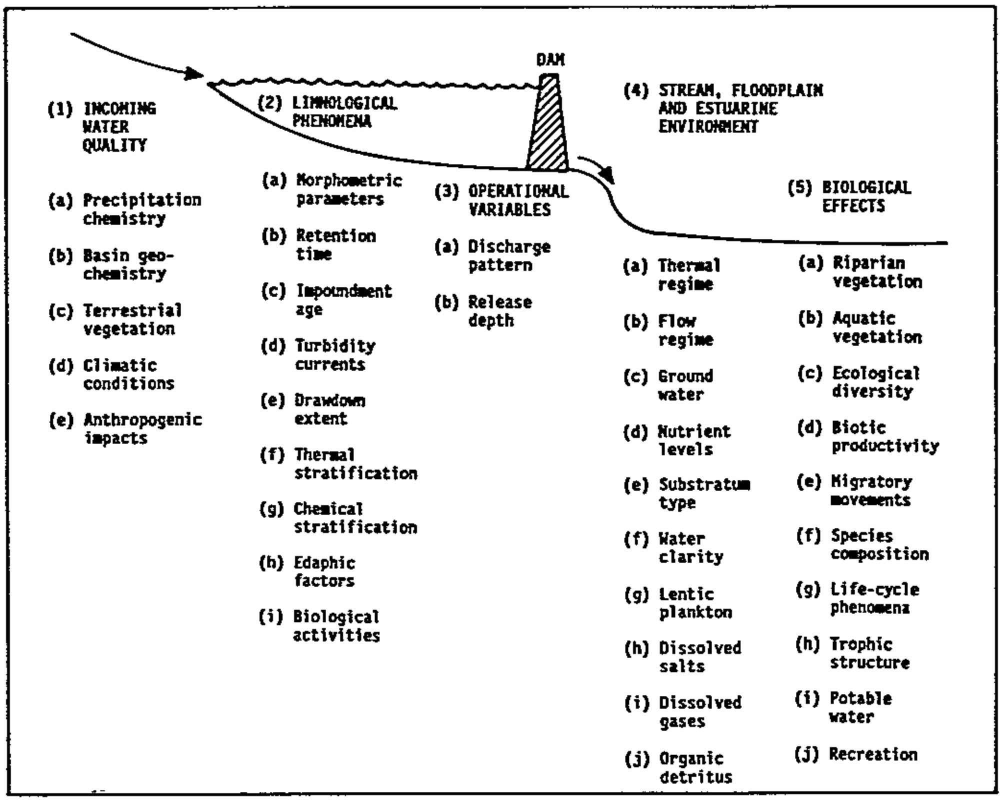

FIGURE 2.2 Major factors that have an effect on the river ecosystem below impoundments.

Chemicals

The influences exerted by flow regulating structures on the chemical composition of downstream waters are functions of the type and size of the structure as well as physical, chemical and biological processes within the stored water and the depth and rate of water release. Typically, these influences include:

- increased concentrations of nutrients, dissolved organic material and reduced compounds such as H_2S, NH_4, Fe and Mn in hypolimnetic discharges;

- decreased dissolved oxygen values and increased biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values in releases of hypolimnetic water lead to severe oxygen stresses on downstream biota;

- decreased nutrient concentrations in discharges of epilimnetic water;
- gas super-saturation (eg oxygen) where spillways discharge into deep plunge pools such as those at the Kariba and Cahora Bassa Dams on the Zambezi River. Super-saturation levels of oxygen can cause extensive damage to the gills of fish;
- the variable chemical quality of discharges from impoundments with multilevel drawoffs can cause abrupt fluctuations in downstream water quality leading to elimination of sensitive biota;
- alteration of chemical composition of waters may mask or eliminate the chemical cues or signals used by downstream biota to initiate different life cycle phases;
- new impoundments cause very marked changes in water chemistry; the extent of the changes depend on the type and quantity of soil and vegetation flooded and the retention time of the reservoir;
- seasonal changes in the quantity and quality of discharged water often lead to a drastic alteration of the downstream reset distance;
- evaporative concentration in off-channel storage facilities leads to more saline return flows to the receiving river; and
- the effects of individual impoundments are compounded when such impoundments are operated in series.

Temperature

As outlined in previous sections, temperature influences are related to the size and mode of operation of the particular flow-regulating structure. However, geographical position and associated climatic influences also exert a marked effect on the thermal regime imposed by, for example, an impoundment on a river. Typical impacts related to alterations in the thermal characteristics of discharged water include:

- alteration of seasonal patterns of temperature fluctuation as determined by the volume and release pattern of water discharges;
- postponement of, or complete elimination of, thermal signals, to downstream biota associated with particular levels of flow;
- delays or changes in the timing of discharges can lead to altered seasonal water temperature patterns; delayed thermal maxima and minima cause marked changes in life cycles of both alien and indigenous river biota, often leading to complete changes in community structure;
- changes in thermal regimes may allow the existence of parasites and their vectors, such as bilharzia snails, which would not normally have survived in such areas;
- altered thermal regimes can cause drastic alterations to both macro- and microbiological processes downstream with concomitant ramifications throughout the food web; and

- deep-release reservoirs can eliminate diurnal and seasonal temperature changes downstream.

Ward and Stanford (1979) have detailed the possible mechanisms whereby thermal modifications below deep release impoundments impact the interrelationships between organisms and their habitat, leading to the elimination of certain species.

Habitat alteration

Influences related to habitat alteration can be purely physical, as caused by a particular structure and its mode of operation, or as interrelated functions of flow, turbidity, temperature and water chemistry changes. Here we consider the influences related primarily to physical alteration of the habitat, which include:

- altered flow patterns leading to changes in riverine processes;
- the blockage of upstream and downstream migratory pathways;
- mortalities due to passage of organisms through hydro-electric turbines;
- changed patterns of movement leading to increased predation levels of certain species in altered habitats. For example, fish trapped downstream of dam wall are vulnerable to predators;
- absence or reduction of flow leading to the elimination of flow-dependent organisms or those that require a minimum depth of water;
- elimination of specific habitat types and/or creation of completely new habitats, eg increased armouring of the riverbed below a dam wall results in a completely new habitat; and
- disturbance/alteration of original hydrological events promotes invasions by unwanted or alien species.

It is important to note here that several of the adverse impacts of flow-regulating structures can be ameliorated or avoided by appropriate engineering modifications to the design of the particular structure and by the optimization of operational criteria. However, for this process to be effective, engineers urgently require appropriate information from ecologist.

GUIDELINES FOR ASSESSING THE IMPACTS OF FLOW-MODIFYING STRUCTURES ON RIVER ECOSYSTEMS

The influences and impacts of flow-modifying structures on the composition and functioning of river ecosystems are extremely complex and have attracted much attention throughout the world. Various methods have been employed to assess the ecological consequences of flow modification. These range in complexity (and effectiveness) from cause-effect matrices, socio-economic surveys and modelling exercises to full environmental impact assessments (EIA's). However, in many cases, so-called EIA's have been conducted after the decision to erect a particular structure has already been taken, when no alternatives remain to be considered. In the past this has often been due to a lack of understanding and communication between ecologists and engineers, against the background of rapidly increasing human pressures for the country's dwindling water resources. In effect, the present lack of ecological information on South African rivers is a serious drawback when attempts are made to assess the ecological consequences of a particular action in a river. Nevertheless it is vitally important for all to recognize that the involvement of ecologists from the beginning of the planning process will greatly enhance the chances of minimizing adverse ecological impacts. It is equally important for the ecologist to contribute to the planning process, albeit often with very limited available data.

In all engineering and ecological projects, quantification is essential. In many instances numerical modelling approaches are entirely appropriate for solving engineering problems. However, the degree of uncertainty surrounding estimates of most ecological processes results in a far lower level of reliability that can be placed on such estimates. Thus, the use of numerical approaches, particularly when employing simplified or average estimates, is very seldom appropriate in the determination of ecosystem responses. How, then, can this extremely complex problem be resolved?

The answer may be found, partly, in the statement on the use of matrices and environmental impacts made by the Committee on Damming and the Environment of the International Commission on Large Dams (ICOLD). In expanded form, this statement says: "However these methodologies are used, it must not be forgotten that they are, above all, individual aids to thinking. None can replace a thorough ecological survey be specialists in the field. On the contrary, these methodologies must convince users, of the need to seek expert advice on each specific point of the impact". There must be different levels of choice to each option or the assessment becomes nothing more than a prediction of unalterable effects. The remainder of the answer lies in the realization of, and adherence to, the following:

a) the determinization of the impact of a water resource development on the river ecosystem is not strictly a part of the strategic planning phase though it is part of the project planning phase which originates during the strategic planning phase. Ecologists must become involved earlier in the planning of projects so that adequate provision can be made for minimizing impacts. Involvement at later stages of the project relegates the ecologist to attempts to mitigate impacts;

b) determination and assessment of ecological impacts is not an engineering discipline but consists of a multidisciplinary approach that has, in all successful examples worldwide, been the responsibility of an experienced project team under the guidance of a carefully selected project leader;

c) ecological considerations should be included at the same time and to the same depth as economic, social and political factors when deciding if a particular water resource development is necessary of desirable. During the period of progress from the strategic to the project phase, the intensity and depth of the environmental impact should be continuously evaluated and updated;

d) the responsibility of ensuring the establishment of a suitably experienced environmental impact project team rests with the planner;

e) ongoing monitoring after completion of the development project in order to compare its performance against its clearly stated and ordered goals. This monitoring to be designed and implemented by the project team to serve as feedback input into the adaptive management process.

Where then with more definite direction does one go from here along the complex path of determining the ecological impacts of water resource developments on river ecosystems in southern Africa? A simplified description of the basic interrelationships between the more common types of engineering structures, the way in which water is manipulated and recycled from these structures and the broad categories of their impacts on the river ecosystem could provide guidelines which would simplify matters considerably. Supported by examples from the literature and specific examples from southern Africa, these guidelines would not be a review of the impacts caused by engineering structures on river ecosystems. Instead, they would provide a rationale for use by planners, indicating very clearly which aspects of any water resource development have to do with impacts, that should become the responsibility of the environmental impact project team.

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CHAPTER 3. PHYSICAL AND CHEMICAL ATTRIBUTES IMPORTANT IN THE BIOLOGICAL FUNCTIONING OF RIVER ECOSYSTEMS

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INTRODUCTION

All ecosystems have been, and continue to be moulded by a changing environment. River systems naturally fluctuate on daily, seasonal, annual and even longer cycles in response to cyclical environmental and biotic processes such as:

- daily and seasonal cycles of evapotranspiration;
- daily and seasonal annual changes in solar radiation and temperature;
- seasonal cycles in rainfall and runoff;
- seasonal variation in silt loading and deposition; and
- long-term climatic changes.

In broad terms these fluctuations in rivers have two components. First there are the seasonal and other cyclic changes which pocess elements of regularity and predictability. Secondly there are the irregular and sometimes chaotic changes which are much less predictable. Both these components of change, which in rivers have greater extents and amplitudes than in most other ecosystems, contribute to the diversity and resilience of riverine communities ie their ability to bounce back from the apparently massive impacts of perturbations such as major droughts, floods and pollution events.

Natural climatic variability makes it highly unlikely that the precise seasonal lows and peaks in temperature, silt loads, flow volume or discharge rates of any one year will be repeated in the next year. Yet that is exactly what we achieve for many rivers when they are regulated. In unregulated rivers, regularity of gross pattern is repeated, but shorter-term patterns are extremely variable. We recognize, however, that local variations in micro-climate (highveld thunderstorms, evapotranspiration of riparian vegetation, etc) will automatically take care of such day-to-day variation. Hence, such fine tuning can effectively be ignored in the design of strategies for controlling river flows.

We are aware that the workshop overall, is addressing minimum flow requirements for maintenance of lotic ecosystem functioning. Human beings, essentially interfere with river ecosystems in four basic ways, covered by the broad headings:

- Abstraction/consumptive uses of water.

- Creation of discontinuities by erection of barrages, dams and weirs and the resulting desynchronization of processes and events through managed discharges into receiving streams.

- Pollution of various forms and strengths.

- Transfer of water between catchments.

We are aware that geology, climate and geomorphology (and hence gradient) are determinants of the structure and functioning of lotic ecosystems. They do not form subheadings of this chapter simply because we refer to them repeatedly throughout the general discussion of other attributes.

We have tried to concentrate on the physical and chemical characteristics of rivers that are affected by the erection of discontinuities along river systems (eg dams) and the transfer of water from catchment to catchment as well as the effects of effluent discharge; frequently the effects and requirements of these types of manipulation are totally different.

The effects of interbasin transfers on the biological functioning of lotic ecosystems are a "black hole" in knowledge and research on a global, let alone a local, scale eg Golubev and Biswas 1985). Current interbasin transfer schemes in South Africa offer an ideal opportunity for research, and yet planning and implementation has gone ahead without any independent ecological assessment (eg in the Tugela-Vaal, Orange-Fish-Sundays, Eastern National Water Carrier and Theewaterskloof schemes). The implications for the maintenance of biogeographic integrity, the swamping of indigenous biota, the alteration of water quality in receiving systems, the spread of invasive species, and many other ecological aspects, are very far-ranging indeed.

In addition, South African limnology has lagged behind the rest of the world in examining the effects of regulation on streams. Instead, research has concentrated upon the functioning of reservoirs with little concern for the effects of dams on the rivers below the walls (Davies 1979). This is not to denigrate the high quality of this research, but to point out that the South African database for this workshop is almost nonexistent. Only Chutter (1963, 1968, 1969) and Coke (1970) have provided insights into the changes effected by impoundments upon receiving rivers (see Chutter 1973; Davies 1979). Thus, this document contains a set of ideas and rather little in the way of "hard science".

There is yet one more type of water storage and resulting flow modification which has been utterly neglected: storage in farm dams and weirs. While they may provide useful refugia and additional habitat for a variety of animals and plants, their impact on flow, suspensoids, temperature and water chemistry of our rivers requires urgent assessment.

All the characteristics of rivers discussed in this chapter are subject to change depending upon catchment landuse and upon effluent discharges into rivers. Any change in landuse will be reflected in the physical and chemical properties of the rivers draining a catchment. Managers must, therefore, take cognizance of the potential effects of long-term land-use changes during the design and planning stages of water projects. For example, urbanization, deforestation and overgrazing all increase runoff, while afforestation and urban and industrial consumption all decrease runoff. As well as altering runoff rates, changes in land use may also lead to alterations in the chemistry, temperature and suspensoid loads in rivers.

In this chapter we describe the effects of various physical and chemical attributes within the normal limits experienced by natural riverine ecosystems, although we do attempt to predict the effects of changes outside those limits. Clearly some streams, eg in the more urbanized and industrial parts of the country, and those receiving effluents from mines, may have levels of certain chemical species that are orders of magnitude greater than those in any undisturbed rivers.

HYPOTHESES AND CONCEPTS RELATING TO THE BIOLOGICAL FUNCTIONING OF LOTIC ECOSYSTEMS

Headwaters are, in the main, heterotrophic detrital-based systems, relying upon allochthonous imports of organic material for their respiration derived energy. This is because gradient, current speed, narrowness of channel and shading by riparian vegetation result in low biomass of plants in these sections. Progressing downstream, the system slowly becomes more autotrophic: as the stream widens, the gradient falls and shading decreases, so that plants can live in the stream and produce autochthonous organic material. In the lowest reaches, the system again reverts to heterotrophy as the flow slows further, and deposition of particulates (organic and inorganic) occurs, and thus respiration again becomes the overriding process.

Essentially, the foregoing is a brief outline of the so-called River Continuum Concept (RCC) of Vannote et al (1980). (See Ward et al 1984; Davies and Day 1986; Day et al 1986, for more detailed explanations of this concept, and in particular, the idea of a continuum of changing animals and plants and production:respiration (P:R) ratios downstream.) Changes in the flow rates and volumes will alter these components significantly. For instance, dams create a discontinuity (Ward and Stanford 1983: the Serial Discontinuity Concept), disrupting a wide variety of abiotic and biotic processes. The intensity of the disruption, and the distance downstream for which the effects will still be detectable, are dependent, according to Ward and Stanford (1983), upon where the discontinuity (the barrage) is sited along the length of the continuum (see also Ward et al 1984). In addition, different processes will take different distances below the barrage (be it a large dam, a farm dam or a weir) to return to the normal conditions in that stretch of the river: the reset distance will differ. The hypothesized interactions are exceedingly complex and the Serial Discontinuity Concept is as yet untested.

P:R ratios are said to alter from <1 in headwaters, through >1 in mid-reaches and back to <1 in the low-lying sectors of rivers. This generalization is still to be tested, although we feel that some of our systems might not conform to the general pattern (eg the Palmiet River in the western Cape with an open fynbos canopy). Whatever the case, alterations in the dynamics of groundwater and bank stability will have an effect on this ratio, and hence on the instream biota.

Linked to P:R ratios is the most important process of remineralization of organic material. In a closed system (such as a lake), nutrients are cycled, taken up in their mineral form by the biota and then remineralized in the process of decomposition. Streams are "open-ended" systems, exporting material from headwaters to the sea.

Nutrients are thought of as continually being displaced downstream - they traverse an imaginary spiral or more correctly, a helix. As material is moved downstream by the moving water mass, it is "fixed" by the benthos, only to be released later on the death of the organisms concerned. This Nutrient Spiralling Concept of Webster (1975; see also Newbold et al 1982), however, has a number of uncertainties and needs thorough testing before acceptance as a real process important in stream functioning.

PHYSICAL ATTRIBUTES OF LOTIC ECOSYSTEMS

Flow

Undoubtedly, hydrological, geological and topographical attributes form the primary driving forces for lotic ecosystems. Dependent upon flow volume, rate and timing are many of the other major features of flowing systems: channel morphology, depth, hardness and stability of the substratum and its structure and composition, habitat structure and diversity (and hence species and community diversity and structure), extent of riparian zone, and floodplain morphology, groundwater turnover and quality etc.

In terms of volume and flow-rate of water, lotic systems are reliant upon periodic flushing of accumulated detritus and sediment. Related to this is the depth and width of river covered by water at intervals throughout the year and between years. By removing or depositing particulate material, and by altering the oxygen content of the water column and the interstitial/hyporheic water, the rate of flow determines habitat diversity and hence the nature and diversity of the organisms of the system. High flow velocities, erosive in nature, will create heterogeneous boulder-strewn substrata, while low flow velocities will produce more uniform sedimentary substrata. Obviously flow rate varies from season to season, leading to a change in the sedimenting and eroding characteristics of any particular reach of river throughout the year, although of course gradient is the ultimate determinant of flow-rate and thus of channel morphology. Rivers are, in a way, predictably fluctuating systems and, as such, the biota is adapted so that different stages in the life cycles of individual species respond to the variations by, eg spawning migrations of fish, emergence in the case of insects. Most impoundments reduce daily, seasonal and inter-annual variations in the volume and rate of flow: a general damping effect that can result in reduction of habitat diversity, desynchronization of life cycles, the appearance of pest species and ultimately in elimination of elements of the natural biota of the system.

Rapid fluctuations in discharges cause reductions in standing crops of benthic invertebrates (Ward and Stanford 1979), probably due to increased instability of the bed combined with increased fluctuations in stream width. On the other hand, the standing crop may be enhanced where high flow peaks are curtailed (eg Pearson et al 1968) and the bed becomes more stable. Populations of benthic algae and rooted hydrophytes are enhanced by flow constancy, which is commonly associated with releases from impoundments (eg in the Crocodile River (Eastern Transvaal), and in the Orange River below the Verwoerd and P L le Roux Dams), owing to decreases in turbidity and increases in bank stability (Ward and Stanford 1979).

The steep climatic gradients across the subcontinent of southern Africa produce extremely wide variations in rainfall. There is an increasing aridity and variability in rainfall, with increasing reliance upon convective rainfall-producing mechanisms, from the east and south-east to the west and north-west (Alexander 1985). In addition, climatic changes run through the spectrum of summer rainfall throughout most of the region, to winter rainfall in the extreme south-west.

For the subcontinent, the average proportion of the annual precipitation that is converted to river flow is less than 10%, with a range from zero to 25% (Alexander 1985): variability is the key word. Accordingly, most of our central, northern and eastern rivers exhibit highly variable discharge patterns, with extremes of low and high flow, while most southern and south-western systems are perennial and more stable, although still seasonally variable. It is inevitable that the biotas of such widely disparate systems will differ from each other. It may also be true that instream processes such as decomposition and energy utilization, and life cycle adaptations of the biota, will also vary enormously. Generalizations for southern Africa are therefore dangerous and each lotic system should be viewed as a separate entity with different natural hydrological regimes and therefore different requirements when regulated and managed.

The extreme variability of many of our systems is exemplified by Noble and Hemens (1978), who quote values for the mean annual runoff of the Hartbees River, a tributary of the Orange: the MAR ".....in one year was 1 700% of the annual average, the minimum in one year was only 19% of the average and in 1961 alone, the runoff was more than the total of the previous 27 years of record." Cambray et al (1986) have noted that the Orange ceased to flow in 1862/63, 1903, 1912, 1933 and 1949. It also ceased flowing between Aliwal North and the Fluitjieskraal Weir in 1985 (B Benadé personal communication). Even here, there is no regularity of pattern, with intervals of 40, 9, 21, 16 and 36 years between periods of flow cessation. Obviously, the biotic components must be resilient enough to cope with such extremes, or the system must be recolonized from elsewhere.

In south-western Cape systems, however, the other extreme is found: many of the systems have not dried out in recorded history, although some are beginning to do so as a result of flow manipulations. For example Petitjean (1987) has reported that grossly insufficient release of water from the Kleinplaas Balancing Reservoir in the Jonkershoek Valley has led to cessation of flow in summer in the Eerste River. Presently, 1,5 x 106 m^3 is provided in summer, ceasing in each year on 1 April regardless of whether or not rains have commenced in the catchment. All of this compensation water is utilized by the farming community and others in the town of Stellenbosch who have riparian rights. The river ceases to flow for several months.

There are relatively few floodplains in South Africa: the Levuvhu, Pongolo, Mkuze and Mfolozi Floodplains are examples. Features of the Pongolo system and its requirements for continued biological functioning are detailed in Heeg and Breen (1982). Water requirements for floodplains are somewhat different from the requirements for streams because the floodplain, as its name implies, is a system that relies on one of the extreme ends of the hydrological cycle - the flood. The river must overtop its banks and spill regularly, usually once a year, for normal biotic functioning. Suspended materials and their associated nutrients are then deposited over the floodplain, stimulating post-flood regeneration of vegetation. Invasive vegetation (woody shrubs, as opposed to annual grasses) is suppressed by inundation, thereby improving grazing quality, and at the same time pools are flushed and fish reproductive and spawning cycles are stimulated. The floodplain is essentially a detritus-based component of the river ecosystem (in so far as it creates the bulk of its own detritus, whereas the river itself is reliant upon external detritus production), and is reliant upon flushing and deposition processes. Any interference with the timing, duration, rate of recession and intensity of the flood will lead to alteration of the system in the medium to long term. The timing of releases of water to produce artificial floods is thus extremely important for this sector of the river (Heeg and Breen 1982; Ward et al 1984).

In the case of fish and the problem of artificial floods from impoundments, Welcomme (1986) has detailed four components of flow important to floodplains:

- <u>low water</u> when communities are stable and sheltered in permanent waters, and there are longitudinal migrations of a few species;
- <u>rising water</u> where most fish begin longitudinal migrations, and after "bankful" conditions, lateral migrations onto the floodplain;
- <u>high water</u> when fish are distributed over the floodplain (some remain in the channel); and
- <u>falling water</u> when return movement to the channel occurs, followed by longitudinal movements to regain low-water habitats.

Artificial flows must carefully simulate all of these features.

<u>Depth</u>

In perennial lotic ecosystems, the critical feature for maintaining the diversity of benthic organisms is probably the depth to which the riffle is covered. (A riffle is a stretch of water rapidly moving over a heterogeneous bed which comprises particles of cobble-size and larger - not a waterfall). What this minimum depth should be is open to debate, but at a recent workshop on the minimum flow requirements of the rivers of the Kruger National Park (KNP), F M Chutter suggested an average depth of 10 cm over the lowest riffle. For the Sabie River (a perennial system), this means a minimum flow of 0,7 cumecs (0,6 for the lowest riffle cover plus 0,1 cumecs to compensate for consumptive needs of the KNP: Davies et al 1987). We, as workers more familiar with mountain streams, have some difficulties with this, however; in most mountain streams much of the bed is exposed. Obviously different zones of a lotic system must be catered for differently; 10 cm over the lowest riffle may be far more than the normal summer depth in some streams, while it may not even come near normal low flows in others. Each system must be treated separately, depending upon its characteristics.

Temperature

As Ward and Stanford (1979) point out, stream temperature is related to stream order. Generally, smaller streams are subject to considerable local influences (eg the canopy of riparian vegetation, steep-sided banks) as well as to short-term changes in air temperature. Temperatures in small streams fluctuate more rapidly than large stream temperatures (exceptions are where thermal constancy is dictated by groundwater input), over both daily and seasonal cycles (see Ward 1985). The intermediately sized (3rd to 5th order) streams tend to have the greatest variation in diel temperature pulse (Vannote et al 1980), while, owing to the greater heat capacity, and hence increased thermal stability, of larger systems temperature fluctuations are reduced. This variation is obviously directly related to the volume of water involved and therefore to stream order.

By far the majority of organisms in lotic systems are poikilotherms (animals other than birds and mammal, whose body temperature adapts to the temperature of their surroundings). Thus any alteration in daily, seasonal and/or annual water temperatures will have profound effects upon communities of animals and plants and also upon the biological and chemical processes occurring within the system (decomposition, remineralization of nutrients etc). For every rise in temperature of 10°C, biochemical reactions will increase approximately two-fold (the Q_{10}). Life cycles, insect emergence, growth rates and rates of food assimilation will all alter as temperatures alter and may result in elimination of species from the system, with repercussions right through the food web.

The responses of invertebrates to modified thermal regimes are complex. Ward and Stanford (1979) detail five major types of alteration in the thermal characteristics of lotic systems, and their effects on the invertebrate fauna:

- delayed maximum temperatures (delayed insect emergence, sexual asynchrony, incomplete life cycles);

- winter warming (extended insect emergence, increased food availability; sexual asynchrony);

- seasonal constancy (slowed warming/cooling, broken seasonal cues for hatching/breeding/emergence);

- summer cooling (decreased fecundity, and hence competitive disadvantages for indigenous species; lowered growth efficiencies);

- diurnal constancy (low growth efficiency and so on).

All of the effects in parentheses above are interrelated (there are many more), and all can ultimately result in the elimination of locally adapted indigenous species. Ironically, although the thermal regime is recognized as a key factor in the functioning of lotic ecosystems, there are virtually no experimental data available (eg Ward 1985) and the list above has been extrapolated from knowledge gained in related fields (Ward and Stanford 1979).

The depth from which water is released from impoundments is of paramount importance to the functioning of the receiving stream. In summer deep lakes and reservoirs stratify themally into a warm surface layer and a cold deep layer maintain radically different temperatures and frequently very different nutrient concentrations throughout the summer. Water discharged from the warm surface waters will thus have different thermal and chemical properties from water discharged from the colder deep layers. Discharges can, however, be balanced so as to reflect more accurately the pre-impoundment thermal and chemical characteristrics of the receiving reach. In this context, it is important to note that there are very few data concerning pre-impoundment temperatures of most South African lotic systems. It is a relatively simple operation, however, to mix waters of different temperatures through multilevel draw-off outlets in order to simulate the temperatures that prevailed in the river before regulation. Such multilevel outlets are relatively inexpensive and should be considered for all future projects.

Interbasin transfer schemes confer thermal constancy on lotic ecosystems or at least the smoothing out of natural daily/seasonal thermal fluctuations. If coupled with constancy of other factors such as flow, turbidity and so on, this will have a compounding effect upon biological functioning and diversity of river ecosystems (Ward and Stanford 1979). Increased constancy can for example, encourage the growth of algae and rooted hydrophytes, with concomitant repercussions for the food web.

We would like to point out that the potential for transfer of waterborne diseases and disease vectors is high in the case of interbasin water transfers. It is well known (eg Appleton 1977a,b,c) that schistosomiasis vector snails are distributed according to water quality and temperature regimes throughout South Africa. Although at first sight it may seem unlikely that such vectors could survive a highveld winter, for instance, continuous transfer of water from infested systems could act as a continuous inoculum of the snails (and hence the disease) to recipient systems.

It is likely that cooling will be more important than warming for the lotic systems of our subcontinent. Many of our systems are warm by comparison with European and American systems. With this in mind, the concept of "Entwicklungsnullpunt" (the minimum critical temperature for insect growth, below which all growth will cease) of Illies (1952) may well become important, although temperature requirements of South African lotic organisms are virtually unknown. To the best of our knowledge, there have been only two indepth studies in South Africa on this topic, one on molluscs (Appleton 1976,1977a,b,c) and the other on a mountain stream amphipod (Buchanan et al in press). This is a serious gap in basic knowledge.

Inorganic suspended components

The third important physical attribute of lotic systems, the suspended particulate component, is strongly associated with the flow characteristics of the system and the surface characteristics of the catchment.

The inorganic fraction carried by South African rivers varies widely throughout the country and is dependent upon local geology and land-use patterns. As Noble and Hemens (1978) point out, suspensoids ("fluvial sediments") mainly comprise particles less than 0,2 mm diameter. Silt loads are very low in the black, acid waters of the south-western and southern Cape, but are considerable in many other parts of the country: South African rivers transport between 300 and 400 x 10^6t a^{-1}; before it was dammed, the Orange River alone transported more than 70 million tons to the sea each year. Systems overlying Molteno and Beaufort series mudstones and shales are particularly susceptible.

Lotic systems are affected by suspensoids which destroy habitat by smothering (see Chutter 1969; Bruton 1985), thus decreasing habitat diversity and hence species diversity, and by altering hyporheic processes (see above, Hypotheses and concepts), including remineralization of decomposing detritus. In addition, suspensoids carry a large load of adsorbed nutrients and affect the biota in very complex ways. Although this has not been quantified in any of our rivers, Melack (1985) has recently reviewed some of the processes which may occur: flocculation of phytoplankton provides a large surface for nutrient and bacterial adsorption, influences diffusion of nutrients between bacteria and the surrounding medium, and enhances bacterial growth by acting as a "stable" substratum. Suspended solids also play an important role in the transport and distribution of toxic pollutants as well as decreasing light penetration through light attenuation and scattering (Kirk 1985), thus reducing the effective euphotic depth in larger rivers and seriously impeding visual predators. In this last case, invertebrate communities may completely alter as predation pressures are eased. Suspensoids may also alter the temperature characteristics of lotic systems. In the case of fish communities, as well as the impact on visual predators, effects include reduction in suitable habitat for substratum spawners, restriction of migratory movements, reduction of growth rates, clogging of respiratory surfaces and a decrease in size at first maturity (Bruton 1985).

Impoundment of turbid rivers leads to trapping of silt and, depending upon release depths and patterns, to a variety of impacts on receiving reaches (Simons 1979). The clearing of water in an impoundment increases its erosive capacity upon release (it becomes "sediment-hungry") (see also Leopold et al 1964). The equilibrium load of the released water then is regained by entrainment of bed sediments and bank erosion (Simons 1979). Thus, the channel degrades, substrata and habitat diversity are completely altered as the bed armours (it develops a layer of particles too large for transport), and the community diversity inevitably alters accordingly. Bank dynamics alter, and riparian vegetation growth is affected, seepage rates change as well as bank moisture-holding capacities. Further, such degradation may seriously alter (reduce) the water table in floodplain systems and, therefore, drastically effect the dynamics of the riparian vegetation. Clearwater releases may also, if combined with altered nutrient and temperature regimes, greatly favour benthic algal production, with repercussions for the food chain.

Of interest in this context are the effects of the Kainji Reservoir on the River Niger. Here, the reduction of silt loads in released waters was such that the increased transparency of the water column prevented fishermen from pursuing traditional fishing methods, which relied upon the fact that fish were unable to see the nets in the naturally turbid waters of the undisturbed river (Wellcomme 1986).

Channel morphology

We have dealt with a number of features of channel morphology in the section above; they will not be repeated. Channel morphology is essentially simple in the lower reaches of lotic systems: the lowered flow rate and generally steady seasonal rise and fall of water means that the system is predominantly depositing in nature, so that the bottoms of most low-lying river reaches are covered by soft sands or muds. Large numbers of organisms are often found associated with marginal plants and soft substrata, but generally, species diversity of animals other than fish is low. Further upstream, depending upon gradient and local geology, the substrata are more heterogeneous and dominated by boulders, bedrock and gravels, with numerous microhabitats in interstitial spaces and pools. The gradient and climate determine the degree of scouring and hence the community structure of the biota.

Channel morphology can change markedly with season, aggrading in high flows and depositing in low flows, thereby adding to the heterogeneous nature of the channel and its bed. This can in turn promote seasonally diverse communities.

CHEMICAL ATTRIBUTES

Conductivity/total dissolved solids/salinity

Conductivity is a measure of the total number of ions in water (ie of dissociated salts). Total dissolved solids (TDS) is a measure of both the ions and the uncharged dissolved material in water. In simplest terms, salinity is a measure of the combined concentrations of the major inorganic ions dissolved in fresh water (although this is not quite true for seawater) and includes no organic fraction. Conductivity, on the other hand, also measures the charged fraction of the dissolved organic material (DOM). Conductivity and salinity under most circumstances refer to essentially the same components, since the concentration of charged organics contributes almost insignificantly to the conductivity of most fresh waters.

Generally the conductivity of a stream is lowest in its upper reaches and, as the stream increases in volume, it leaches ions from the rocks over which it is flowing and also picks up charged organic molecules from the biota and its detritus. By the time the stream reaches the estuary its conductivity may have increased several fold. Naturally it increases enormously in the estuary, where the highly saline seawater mixes with the dilute river water. Salinities may also increase at any point in a river as a result of effluent discharges and geological point sources of saline water.

The lithology of a catchment will determine to a large extent the salt concentration in a river's waters. For example, those tributaries of the Berg River in the western Cape that flow over Table Mountain Sandstones have very low salinities (mean TDS 100 mg l^{-1}), while TDS in the lower reaches may exceed 9 500 mg l^{-1} (Fourie and Görgens 1977). The same holds for the Breede (Hall and Görgens 1977) and the Fish and Sundays Rivers (Tordliffe 1980).

The major man-induced causes of high salt concentrations in rivers are irrigation and effluent discharges. Two of the most commonly used methods of irrigation are sprinkler and furrow systems. In areas of high evaporation, much of the irrigation water is lost by evaporation before it reaches the crop, thus concentrating its salt content. Depending upon soil texture, irrigation water percolating through the soil profile can increase in salinity ten-fold or more. The soil solution available to the plant is therefore many times more saline than the irrigation water. In areas of high rainfall, the leaching action of infiltrating rainwater will "flush out" the salts from the soil before the crop becomes salt-stressed. Depending upon the permeability of the underlying soil and rock formations, the leachate will enter the groundwater system and ultimately the river (which may not necessarily be the river from which the irrigation water was originally abstracted).

In areas of low rainfall, regular leaching and flushing of the soil is minimal. The salt content of the soil solution may thus build up to the point at which crops become stressed. Upward capillary action of salts may also result in salt crusts on the soil surface. For a review, see Williams et al (1984).

Salinity in rivers can also be increased by effluent discharges. Their character differs widely but, for example, effluents from mines generally have extremely high concentrations of salts such as $NaCl$, $CaSO_4$, $FeSO_4$ and $MnSO_4$. The aquifers of many deep South African mines tend to have naturally high levels of $NaCl$. Further, oxidation of the pyrite in the ore, combined with the sulphuric acid used in the processing plants, or sulphur occurring naturally in coal shales, also leads to the generation of $FeSO_4$ and $MnSO_4$. Acidity increases the solubility of iron and manganese ions, which are mobilized only under extremely acid conditions. As the acidity is neutralized $CaSO_4$ and $MgSO_4$ tend to appear. Many of the newer mines recycle their water, while excess water pumped from underground is either evaporated or pumped to "dry" mines. Seepage from mine dumps, hillside adits, catch dams etc, as well as direct rainfall, ends up in the rivers either by direct overland flow or by groundwater seepage. Thus considerable quantities of polluting salts enter the rivers of the mining regions in the Eastern Transvaal, northern Natal, the Witwatersrand and the Orange Free State: few of these rivers can be considered to be "natural" from a chemical point of view.

Although the degree of salinization is less extreme, treated sewage effluents contain concentrations of salts much higher than those in domestic water supplies. In situations such as those in the PWVS and Greater Cape Town complexes, where sewage effluents may make up 30% or more of the flow in some rivers, the receiving systems become severely stressed.

From a biological point of view, increased salinity in lakes up to about five to seven per cent (conductivity up to about 700 $mS\ m^{-1}$) may result in some changes in community structure. At this level there is generally a marked decrease in faunal species richness, after which a more saline-adapted biota replaces the true freshwater fauna (Wetzel 1983). With very few exceptions (eg in parts of western Australia) rivers are not naturally saline, so that similar predictions are not available for the biota of such rivers. Nonetheless it can be predicted that riverine fauna will be more sensitive to increases in salinity or conductivity, not least because of the effect that increased ionic concentrations have on oxygen tensions (see below). Further, the biota of all but the lowest reaches of rivers, in this country at least, is probably entirely unadapted to high salt loads.

The environmental cues that determine initiation of breeding in most freshwater organisms are poorly known. In those (particularly fish) that breed on floodplains, for example, it is possible that changes in conductivity associated with increased rainfall (and therefore with the beginning of the flooding of the floodplain) provide a (or the) necessary environmental cue. The changes in conductivity associated with rainfall events have been well documented. Immediately after the onset of a storm event, the conductivity levels in rivers will increase sharply owing to salts being flushed down the system; as dilution occurs, they return rapidly to pre-flood, or even lower, levels.

Dissolved gases

Dissolved oxygen. The fauna of fast flowing streams is seldom subjected to low oxygen tensions because oxygen is readily picked up by turbulent waters. Oxygen levels are, however, directly influenced by temperature and salinity, increases in both of which result in lower oxygen saturation values (see Williams 1985). For example, 11,3 mg of oxygen will dissolve in a litre of fresh water at 10°C, whereas only 8,2 mg will dissolve in a litre of fresh water at 25°C; at 25°C, no more than 4,7 mg will dissolve in a litre of seawater. Thus since in rivers a decrease in flow-rate can concomitantly increase the temperature, the result may be a sufficient decrease in oxygen levels to alter both the numbers and species of organisms living in the system. Generally organisms adapted to living further down the river, where oxygen tensions may be naturally lower, will replace the original community. The effect of a simultaneous increase in salinity will, of course, be synergistic.

Decomposition is the major biotic process that affects oxygen levels in water. This is true for the decomposition of both naturally occurring organic matter and for sewage, although the development of entirely anoxic conditions in rivers is commonly a result of sewage discharges and seldom occurs in undisturbed rivers.

Hypolimnetic water released from impoundments may be cool, but is often deficient in oxygen as a result of biotic activity in the hypolimnion. A component of the stream biota may therefore be eliminated from the reaches of a river immediately below a dam with hypolimnetic discharge. In addition, reduction of dissolved oxygen increases the toxicity of certain poisons to fish because of the increased velocity of respiratory flow (Jaag and Ambuhl 1962), a synergistic effect that is often overlooked.

Carbon dioxide. Carbon dioxide is approximately 200 times more soluble in water than is oxygen but its solubility is also strongly temperature-dependent. Whereas 1,1 mg of carbon dioxide can dissolve in a litre of fresh water at 0°C, only 0,6 mg can dissolve at 15°C and 0,4 mg at 30°C. Carbon dioxide (as H_2CO_3) is in equilibrium with HCO_3^- and CO_3^{--} ions, the concentrations of each depending on, and partly contributing to, the pH. Although carbon dioxide is the major nutrient required for photosynthesis, CO_2 levels in rivers are unlikely to be limiting to plant growth. (See Hutchinson 1957 for a review of CO_2 equilibria in freshwaters.)

Hydrogen sulphide. Under the normal oxidizing conditions found in most rivers, the levels of H_2S will be extremely low, although it may be produced in the sediments of stagnant pools or elsewhere if massive decomposition of organic matter is taking place. Hydrogen sulphide may, however, be generated by bacterial decomposition in the hypolimnion of lakes and may accumulate under the anoxic conditions that often prevail there, particularly during the "unstable phase" immediately after impoundment. Hydrogen sulphide is extremely toxic to most organisms, especially animals, so that the discharge of H_2S-rich hypolimnetic water from dams can have the same lethal effect as the discharge of anoxic water. In practice, of course, such water is likely to be both rich in H_2S and poor in oxygen, and yet the effect is normally very short-lived because the water is well aerated as it is discharged from a dam.

pH, acidity and alkalinity, redox potential

pH is a measure of the concentration of hydrogen ions, while acidity is a measure of the amount of strong base, and alkalinity the amount of strong acid, required to neutralize the water. For a given pH, waters that are better buffered (that is, that contain relatively high levels of certain salts) may therefore have higher alkalinities (or acidities) than those that are poorly buffered. Since pH gives a measure of the overall result of the equilibrium between CO_2, HCO_3^- and CO_3^{--}, as well as strong acids and bases (ie usually the major ions) and organic acids, it is a useful and convenient attribute to measure in rivers.

The pH levels in most rivers vary around 7, although values as low as 3,9 have been recorded in undisturbed upper reaches of the Berg River in the western Cape (Harrison and Elsworth 1958). Where photosynthetic activity is high, especially in eutrophic waters, pH may vary diurnally as the $CO_2/HCO_3^-/CO_3^{--}$ equilibrium changes in response to uptake of CO_2 by plants during the day and its release at night. pH values up to 10 or more may be recorded in lakes (and possibly in the downstream reaches of highly eutrophic rivers) under these circumstances. We have found no reference to naturally high pH values in rivers as a result of their abiotic chemical nature, although alkaline effluents may result in very high pH values (>10) and, of course, natural "soda lakes" are known in which the pH may also exceed 10. Naturally low pH values are usually found only in extremely poorly buffered waters dominated by organic acids (the "humic" complex, which often results in very "black" waters).

When high pH values in rivers are the result of biological activity they are unlikely to limit biological functioning. Low natural pH values, on the other hand, may have a profound effect on the structure of biological communities in rivers. In these waters the buffering capacity is low, the organic acids retard microbial activity, and nutrient levels may either be enhanced or may be diminished by complexation with the organic acids. These waters tend to have rather restricted and specific biological communities. In the south-western Cape, for example, it appears that certain species of invertebrates are incapable of living in these waters, although others that do live there have a wider distribution (Harrison and Agnew 1962): Harrison and Agnew could find no evidence of a fauna restricted to acid streams. On the other hand, it was commonly said that B J Cholnoky could give a good estimate of the pH of water from the diatom assemblages he found there (see Cholnoky 1959).

Acid rain appears thus far not to be of great significance in South Africa and in the published literature has only been confirmed for the south-western Cape during stormy conditions (Bohm 1983). There is no doubt that it also occurs in the Eastern Transvaal (Lamb 1984), where there is a concentration of coal-burning power stations, and where very low pH values have been recorded for rain (R W Skoroszewski personal communication). It should be pointed out, however, that pH per se is a poor indicator of "acid rain" in the sense of rain polluted by oxides of nitrogen and sulphur.

Although virtually no published data are available for South Africa, increasing acidity of rainfall is a very real potential threat. ESCOM is presently monitoring acid precipitation at various stations throughout the country and the National Institute for Water Research, CSIR is examining the impact of atmospheric pollution on the streams of the Drakensberg Escarpment.

The reduction in pH of acid rain is due to inorganic ions, largely SO_4^{--} and NO_3^-, and the major effect on biological systems seems to be in the mobilizing of toxic metal ions, particularly various species of aluminium, rather than any effect of increased concentrations of hydrogen ions per se. Nonetheless, the interbasin transfer of water from areas affected by acid rain may have deleterious effects in the receiving stream, especially if it is naturally poorly buffered.

The redox potential (a measure essentially of the capacity for oxidation or reduction) is usually high and positive in river waters: they are strongly oxidizing. As is the case with oxygen and hydrogen sulphide levels, it is only if strongly reducing waters are released from a dam that the redox potential is likely to fall to a level low enough to have a detrimental effect on the biota by shifting the chemical equilibria towards reduced rather than oxidized chemical species.

Major ions

The eight ions usually considered to be "major" in fresh waters are Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, SO_4^{--}, HCO_3^- and CO_3^{--}. Most fresh waters in the Northern Hemisphere are dominated by Ca^{++}/Mg^{++} and HCO_3^- and this has therefore been long considered to be the norm, on which "world average river water" has been based. (See updated values in Wetzel 1983). In fact, many waters in Africa and South America, and all in Australia, are dominated by Na^+ and Cl^-. The overall significance of these ions in the biological functioning of riverine ecosystems is dealt with in the section on conductivity above. Individually, Na^+, Cl^- and SO_4^{--} are not of great significance in undisturbed rivers and will be discussed no further except in relation to ionic ratios (see below). Salinization, and the carbonate/bicarbonate system, have already been discussed in the section on Conductivity above.

Ca^{++} and Mg^{++} are required "nutrients" (but see Nutrients below). Their concentrations in river water depend largely on the lithology of the river's catchment and many, but by no means all, African waters are dominated by calcium (Talling and Talling 1965). Very low levels of Ca^{++} (and Mg^{++}) in some soft and often acid waters may result in exclusion of molluscs and most fish (Ca^{++} is required in the formation of both shell and bone). In some high-pH, carbonate-dominated waters,

Ca^{++} may precipitate out as $CaCO_3$ and essentially be lost to the system; Mg^{++} salts are far more soluble and tend not to be lost in this way except in very concentrated brines. Although this process of precipitation is well known for lentic systems, it is probably highly unusual in streams.

Potassium is usually present in very low concentrations and may be limiting in mountain streams (J M King personal communication; Minshall and Minshall 1978). Proportional to Na^+, K^+ levels are sometimes considerably higher in the biota than in the water. One of the consequences is that the levels of K^+ in particular are greatly elevated in streams in recently burnt catchments.

The ratio of monovalent to divalent cations (M:D) appears not to have been examined in any detail in rivers but in lentic systems it is certainly important in the distribution and dynamics of certain plants, especially algae. It has been shown eg (Vollenweider 1950), that algal populations can increase to apparently unfavourably high concentrations of Ca^{++} and Mg^{++} if the concentration of K^+ is also increased. Further, diatoms tend to dominate waters with a low M:D ratio (<1) and desmids waters with a high (>1,5) M:D ratio.

NaCl versus $CaCO_3$ waters. Waters influenced strongly by sea salts tend to be dominated by Na^+ and Cl^- ions, whereas many inland (and most African) waters are dominated by Ca^{++} and HCO_3^-/CO_3^{--} ions. As far as we know, the significance of this phenomenon for riverine fauna and flora has not been examined, although it may be of some importance, eg in interbasin transfers between the Ca^{++}-dominated Orange-Vaal River and the NaCl-dominated Great Fish and Sunday Rivers (but see Forbes and Allanson 1970).

Minor ions

The relative concentrations of minor ions (eg Fe, Cu, F, B, Mn, Al, Co, Hg, Pb) in river waters depends, under natural conditions, on the lithology of the river's catchment. Of course, today many of these elements, particularly the heavy metals such as Cd, Mn, As, Hg, Fe, Au and Pb, are encountered more frequently as a result of anthropogenic pollution from many sources. Levels are generally low (Hutchinson 1957), and are probably biologically insignificant in unpolluted waters, although they may rarely be high enough to be toxic where streams pass over mineral lodes. Heavy metals, whether of natural or anthropogenic origin, can be directly toxic to aquatic organisms. Further, under certain chemical conditions they can complex with nutrients, either alone or in conjunction with high-molecular-weight organic compounds, and effectively remove the nutrients (particularly phosphorus) from the system.

Nutrients

Any element required for the functioning of organisms is by definition a nutrient. Thus the list is a long one and includes several elements that have been implicated, rightly or wrongly, in growth or reproduction of one or more species. The major nutrient, of course, is carbon. Normally, though, when using the word "nutrients" one is referring to those elements that are likely, when present in short supply, to limit biological functioning. The major elements usually considered by biologists to fall into this category are compounds of N and P, although Si (more frequently limiting in the marine sphere), K and S should perhaps be included. This discussion is limited to N, P and Si.

Volumes have been written on the occurrence, distribution and dynamics of N and P; even the South African literature is vast (see NIWR 1985 and references therein). Nonetheless, most literature refers to nutrients and nutrient cycling in lentic systems. The essential facts are as follows.

Phosphorus occurs in many organic forms (species) within living organisms. In water it is present either in particulate form, where it is complexed with, or part of, organic molecules, or in the form of dissolved phosphates (PO_4^{3-}: orthophosphate, or soluble reactive phosphate - SRP). The particulate fraction frequently settles out at low current speeds but, depending on the pH and redox potential of the substratum, there is a dynamic equilibrium between adsorption of P onto the particles of the substratum and its release to the water in soluble form. Not all of the particulate P in water is available to all organisms but the microbiota is certainly of great significance in recycling most of the P that is available from this source. The essence of the P-cycle is that much of the P that enters a river is lost either by downstream transport or by becoming adsorbed onto particles that are in turn either lost downstream or settle to the bed of the stream (see Inorganic suspended components above). The proportion of soluble P in the water-column is small. The dynamics of P are presumably rather similar in lower rivers and lakes, so that the work done on lakes would largely apply to lower rivers. The dynamics of P in upper reaches are very poorly understood although, if other freshwater systems are anything to go by, P is the limiting nutrient in these streams too. The work on nutrient spiralling (see Hypotheses and Concepts above) in North American systems (Webster 1975; Newbold et al 1982) is largely theoretical.

The dynamics of the N-cycle are more complicated than those of the P-cycle in one major respect: nitrogen in the atmosphere can be converted to inorganic nitrogen species that can be used by living organisms. Apart from organic nitrogen compounds, N is found in freshwaters in the form of NO_2^-, NO_3^- and NH_4^+. All of these can be used to some extent by various micro-organisms, although NH_4^+ is the nutrient of choice for most green plants. Nitrogen compounds, then, are far more "plastic" than are P compounds. Nitrifying bacteria and (of particular importance in fresh waters) blue-green algae (Cyanobacteria) can convert atmospheric N_2 to nitrate, while denitrifying bacteria convert inorganic N compounds (NO_2^-, NO_3^-, NH_4^+) back to atmospheric N_2. Thus N is seldom a limiting nutrient in freshwaters that support populations of blue-green algae.

Silica is of vital significance to diatoms since it is a major component of their frustules. It seems not to be limiting in rivers, however, (Wetzel 1983), and to vary very little with season or rate of flow.

Synergistic effects of nutrient availability. There is clearly a synergistic effect between the three nutrients discussed above. Where P is not limiting, blue-green algae can fix sufficient N to allow the growth of various plants; where Si is not limiting, these will include diatoms.

Eutrophication. Where nutrients, especially P, are available in excess in rivers, explosive plant growth can result. This is least evident in the upper reaches, where the dynamics are dictated mainly by flow characteristics. Where flow is slower, and particularly where it is more predictable, such as in impoundments or in the lower reaches of rivers, eutrophication can be significant. Not only do plants (particularly phytoplankton) grow explosively, but so does the fauna and the microbiota. Eutrophication can result in choked waterways with greatly reduced species diversity but an increase in the numbers of pest plants and animals.

The main sources of excess N and P include agricultural runoff and sewage effluents, while high levels of N are also often found in industrial and mining effluents, as the result of the use of ammonia in many industrial processes and the production of nitrate from the use of explosives.

Dissolved organic matter (DOM)

Dissolved organic compounds in rivers result naturally from excretion from all elements of the biota and from decomposition of detritus, largely by the microbiota, although, today anthropogenic sources of DOM, both point and nonpoint, may greatly exceed natural loads (see Organic pollution below). The range of compounds is vast and includes small-molecular-weight compounds such as sugars and amino acids, intermediate ones such as proteins, and very high-molecular-weight compounds like humic substances. The low-molecular-weight compounds are suitable substrates for microbes, while the larger ones tend to be refractory and can accumulate, particularly in slow-flowing systems. They also frequently precipitate and form a layer of very fine particulate organic material, even in mountain streams. For a review see Robarts (1986).

PARTICULATE ORGANIC MATTER (POM)

Natural riverine ecosystems

POM consists of both particulate inorganic matter (see Inorganic suspended components above) and POM, often referred to as particulate organic carbon, or POC. POM in streams originates both from outside the system in the form of detritus of terrestrial origin (allochthonous POM) and within the system as whole drifting organisms, faeces and detritus. The fate of this material is less well understood for lotic than for lentic ecosystems but essentially the situation is as follows. Large POM (CPOM, usually greater than one millimetre: see Melack 1985; King et al 1987, for definitions) is either decomposed directly by the microbiota or, after some "conditioning" by the microbiota, is shredded and consumed by macroinvertebrates and fish, which in the process produce small uneaten particles and faeces which drift downstream. Thus in the lower reaches, where allochthonous POM is less important, the dominant fraction of POM is finely divided and known as FPOM: fine particulate organic matter, usually less than one millimetre but greater than 100 µm. This in turn is also decomposed by micro-organisms or collected by filter-feeding invertebrates or fish. Overall, then, there is a trend in POM from a coarse fraction in the upper reaches of a river, to a finer fraction in the lower reaches, where collectors predominate. Phytoplanktonic and zooplanktonic communities in these lower reaches also form part of the POM.

The ratio of CPOM:FPOM is significantly altered by discontinuities (Ward and Stanford 1983), an important point if the idea of "functional feeding groups" (part of the RCC) is valid. The idea is that groups, or guilds, of invertebrates are adapted to utilize particular fractions of POM in rivers as food sources, and that the proportional representation of these guilds changes down the length of the river. CPOM in headwaters is supposed to cause the invertebrate community to be dominated by "shredder" organisms, with "collectors" next in importance. Further downstream this structure changes in favour of "grazers" and collectors, while in the lowest reaches, with soft substrata, collectors dominate the community. Dams in headwater reaches alter the ratio of CPOM:FPOM by significantly increasing the FPOM fraction and thus altering the guilds of invertebrates dominating the system. In fact, dams markedly increase the FPOM fractions of the receiving streams, regardless of stream order, resulting in increases in standing stocks of collectors (such as the pest Simuliidae studied by De Moor 1982, 1986), particularly where pulses of POM, in the form of planktonic organisms, are released in epilimnetic waters from a dam. Water rich in POM as a result of hypolimnetic release will also alter the numbers and/or proportions of the guilds of invertebrates and fish in downstream reaches.

Organic pollution

Direct pollution by organic waste, and effluent from waste water treatment plants, contains high levels of POM, much of which may be in the form of bacteria consuming the waste itself or growing as a result of the high levels of nutrients in the effluent. Where the pollution is extreme (eg at the point of origin), oxygen tensions and redox potentials may be very low so that reducing conditions pertain. Under these circumstances, the diversity of higher organisms may be extremely low. The mineralization of the organic material to CO_2 and inorganic salts results in a slow recovery of the system so that further downstream there is some recovery of the macrobiota, largely in the form of filter-feeding or deposit-feeding invertebrates. The combined action of these and the microbes reduces the load of pollutants even further until eventually a macrobiotic community similar to that above the source of pollution will again become established. (See Hynes 1966 for a detailed treatment of this topic.)

Aggradation of substratum

In very slow-flowing eutrophic or otherwise polluted waters, phytoplankton, and bacteria covering POM, may die or otherwise come out of suspension, falling to the bottom. Thus the substratum may gradually become covered by an accumulation of POM that can eventually clog up the river channel. This ooze harbours a different community from that of sandier, less organically rich, riverbeds and may in fact support an extremely high biomass of rather restricted numbers of species of animals.

OVERALL AND SYNERGISTIC EFFECTS

All other things being equal, alteration of one aspect of the chemical or physical environment may have a small overall effect on the biological functioning of a riverine ecosystem. Unfortunately, however, it is seldom that only a single feature is altered. Usually the construction of a dam, interbasin transfer of water, or organic pollution, for example, will have numerous effects. The result is nearly always a considerable change in the structure of the biotic communities of a river. If the alterations result in a different degree of periodicity, predictability or stability, and/or alteration in some of the more significant chemical attributes, then the resulting communities are likely to be less diverse and less likely to be able to respond to stresses in the form of organic pollution, reduced flow-volumes etc.

INFORMATION AND RESEARCH NEEDS

- Temperature regimes and their modification by dams and transfer schemes.
- Temperature tolerances of lotic organisms.
- Effects of salinization on faunal communities (invertebrates and fish).
- Effects of metals on faunal communities.
- Effects of low and high pH on riverine biota.
- Effects of changed chemical conditions on the fauna of streams affected by interbasin transfer schemes.
- Nutrient cycling in lotic ecosystems, especially the significance of the microbiota relative to the macrobiota; relative importance of N and P and other elements as limiting nutrients.
- Reset distances for recovery from organic pollution and from modifications caused by impoundments in various zones of rivers in different parts of the country.
- Retention mechanisms of the hyporheos and hyporheic functioning, or: Is nutrient spiralling a real phenomenon?
- Nutrient/suspensoid relationships in lotic ecosystems.
- Effects of suspensoids upon lotic communities.
- Quantitative effects of alterations in flow, and timing of releases, resulting from regulation of rivers, on lotic communities.
- The effects of farm dams (particularly cascades of them) upon all aspects of river system functioning.
- The effects of weirs upon all aspects of river system functioning.
- Identification of and monitoring of river systems that are under threat from acid rain.

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CHAPTER 4. GENERAL CONCEPTS AND APPROACHES TO INSTREAM FLOW ASSESSMENT

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INTRODUCTION

River flow can be modified in a number of ways: it can be regulated and decreased by impoundment; regulated and increased or decreased by interbasin transfer; decreased but not regulated by run-of-the-river abstraction; or the relative duration of floods and droughts can be altered by changes in catchment vegetation, with little change in the mean annual runoff of the river. The consequences of different kinds of flow modification may be very different, and it is not possible in this chapter to deal exhaustively with all of them, but we shall be referring, at least in general terms, to all types of modification which tend to decrease river flow, since the central theme of the document is ecological flow requirements.

Ecosystem responses to flow modification are inevitably the sum total of the responses of the vertebrates, the invertebrates, the microbiota, the macrophytes and the riparian vegetation to the physical and chemical characteristics of the river and its channel. Most of these are being dealt with in detail in separate chapters. In this chapter we therefore propose a) to examine some of the general ecological concepts that might be useful in assessing ecological flow requirements, and b) to describe different approaches to the assessment of ecological flow needs as a general framework on which to base requirements of specific rivers.

4.1.1 The concept of flow needs for the ecosystem

From an ecosystem perspective, we define the ecological flow need of a river as "that flow which is critical for the maintenance of the essential ecological functioning of the river". Essential ecological functioning includes such processes as nutrient cycling, sediment transport, decomposition of organic material and transport of water. The maintenance of these processes is vital for any river that is to be used for transport or abstraction of water for human use, for the cleansing of effluents, for recreation and so on.

Ecological flow needs are often defined with respect to specific objectives, such as the maintenance of the natural community structure or of fish population, or of the riparian vegetation, or of the river's capacity to absorb and recycle effluents. Nonetheless, all of these biotic components require functional ecosystems in which to thrive, so that the needs of the entire river have to be examined even when a particular component is specifically identified as requiring attention.

THE FUNCTIONS, BIOTA AND ECOSYSTEM COMPONENTS OF RIVERS

The maintenance of essential ecological functioning in rivers requires an understanding of the processes that govern the riverine biota, and of the interrelationships within the various components of the biota. Perhaps the most important attribute of a biota is its resilience in response to flow reduction. The greater that resilience is, the lower will be the ecological flow requirement of the river. Some of the central theories of river ecology provide a framework for testing the resilience of the South African riverine biotas.

Inclusive theories of river functioning

There are at present two main schools of thought as to how rivers function ecologically. The River Continuum Concept (RCC) (Vannote et al 1980) suggests that plant and animal communities adjust to spatial resource gradients imposed by changes in environmental conditions down the length of the river (Ward et al 1984). This concept assumes that biotic communities in rivers have been able to adapt to relatively predictable environmental changes down the stream. Workers such as Minshall et al (1983) have provided evidence in support of the RCC, from small temperate streams in North America. The assumption of adapted communities has been criticised by Winterbourn et al (1981) for New Zealand and Barmuta and Lake (1982) for Australia, who argue that rivers are stochastic systems prone to violent events such as floods and droughts, and that the biota is unstructured, consisting largely of hardy opportunists that colonize the river between periodic catastrophes: the Unstructured Community Concept. These two concepts are the extremes of an axis along which different rivers will be found to lie. Although not yet resolved, it seems likely that the lower reaches of most South African rivers might tend towards the unstructured community state, since our rivers are less stable and predictable than those in north temperate climates (O'Keeffe 1986).

The importance of the RCC is that it provides us with testable hypotheses, such as the prediction that there will be ordered change in the dominance of different invertebrate guilds down the river. It has also led to the development of an important spin-off theory, the Serial Discontinuity concept of Ward and Stanford (1983), which predicts the effects of dams on downstream river reaches. In contrast, stochastic ecosystems inhabited by an unstructured biota are not fertile ground for research aimed at predictive understanding. For determining ecological flow needs, an important question is, how robust and resilient will the community be to disturbance. A highly structured and interrelated community, adapted to a particular set of environmental conditions, is likely to be more vulnerable to artificial disturbance than is a loose collection of more generalist, opportunistic species. If this is true, and we accept the assumption that South African river biota tends to the unstructured state, we assume that it will be more resilient in the face of disturbance, then perhaps ecological flow requirements will be at a lower level than for American rivers. On the other hand, it may be that the biotas of many South African rivers are already near the lower limit of adaptability and that further reduction in naturally low dry-season flows will reduce their ability to maintain essential ecological functions. In other words, they may be resilient but already stretched nearly to the limit of endurance. We are aware that ecological theories linking diversity, stability and resilience are highly controversial, and that these ideas need to be verified by research.

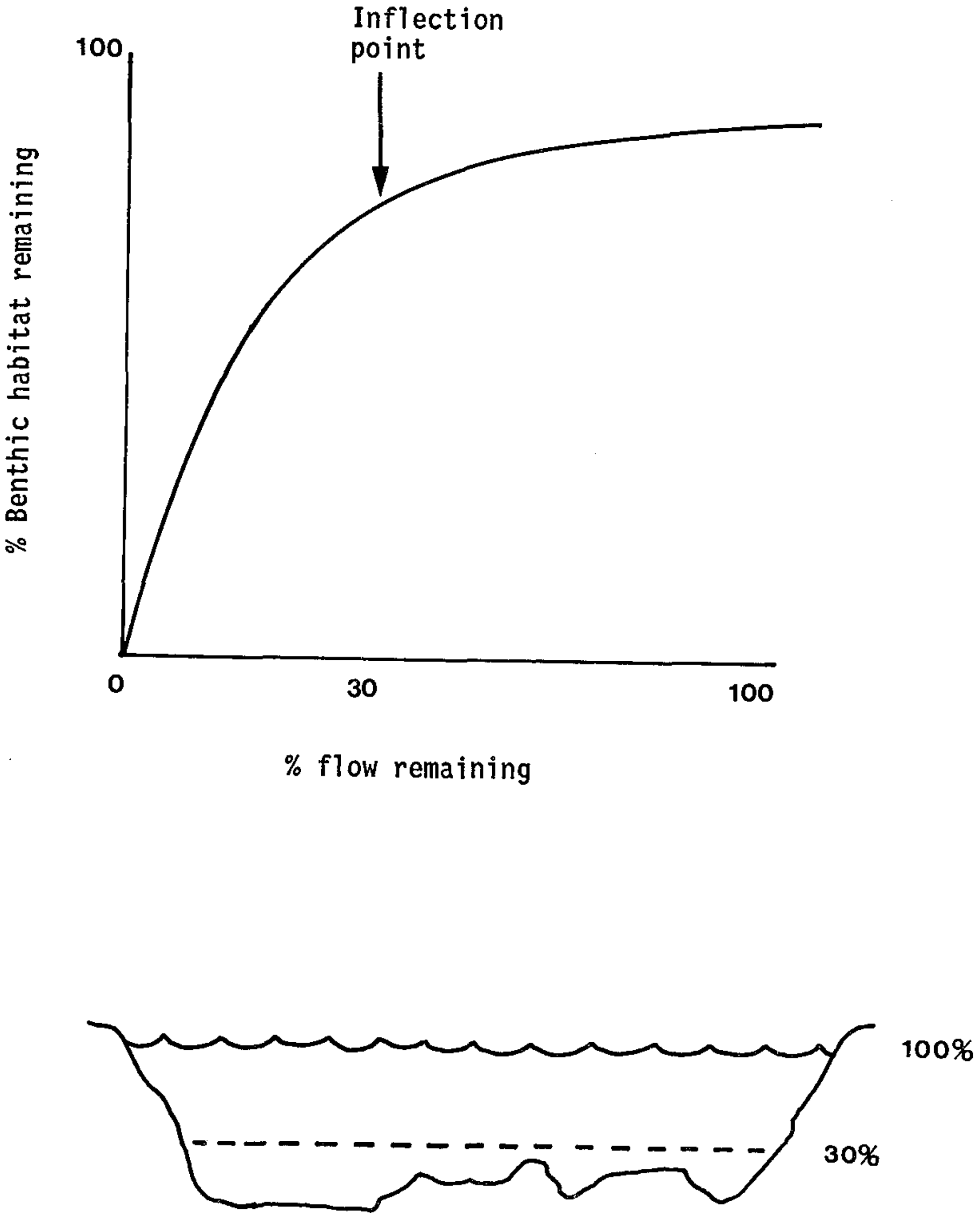
One of the first considerations when calculating an ecological flow-need for a river is the objectives to be achieved. Perhaps the aim is to conserve the biota in its preregulated or present (in a predam situation) form while extracting a proportion of the discharge in the rainy season. There may be a plan to upgrade a presently degraded system - a stated wish of the Department of Water Affairs for some of its degraded "Special Standard" rivers. However, the objective may be merely to retain some form of life in the river, in the hope that it will perform some kind of cleansing function for the water flowing downstream. There might be a need to conserve a special feature associated with the catchment eg a nature reserve, animal migratory routes, rare species of plants or animals with specific life-cycle needs, wetlands, a flood-plain or an open estuary. Commercial attributes of the system, present or potential, that have specific water needs would have to be considered, eg estuarine fisheries, freshwater animals or plants that are food sources, recreational areas and areas of flood attentuation and enhancement of water quality such as wetlands. Changes in the flow regime might result in shifts in the structure of the riverine community, perhaps the proliferation of pest species. Different kinds of rivers might need allocations of different proportions of their flow, in order to continue normal functioning.

Many of these objectives and considerations could require different water allocations and could conflict with the demands of other water users; some features might require a regular annual allocation of water while for others a more natural allocation (incorporating excessively wet and dry years) might be more appropriate; all will influence calculations of the instream needs of a system. Always to be borne in mind is that the river is only one user of the water; with increasing distance form the point of release there will be an increasing number of incidents of water extraction, increasing amounts of point and nonpoint source pollutants and thus decreasing control of downstream conditions in the river. Fine-tuning of releases from a dam will probably only be possible for downstream reaches in reasonably close proximity to the dam. Clearly, all river systems are different and each will merit individual consideration when allocations for instream flows are calculated.

Since a number of standard methods for instream flow evaluation (eg Gore 1978; Prewitt and Carlson 1980) have been developed in the United States, the ideas outlined above need to be tested in the field in order to judge whether the standard methods are applicable to South African conditions.

Ecological response curves

Rates of ecological response to environmental change are central to the identification of ecological flow requirements using wetted perimeter methods such as those assessed by Prewitt and Carlson (1980). The primary assumption is that rates of change are seldom linear, but are usually exponential or asymptotic. This implies that a slight or moderate perturbation will be largely absorbed in a river, but that an extreme perturbation will have rapidly increasing effects. This is best illustrated by considering the reduction in benthic habitat at successive decreases in river flow (Figure 4.1). The wetted perimeter of a typical flat-bottomed riverbed will obviously not be significantly decreased until flows are drastically reduced, although depth will decrease. The rate of species loss as a result of successive flow reductions and associated



The stream channel

FIGURE 4.1 Reduction in benthic habitat at successively reduced flows. Initially very little habitat is lost, until the "inflection point" is reached (30%). At flows less than 30%, exposure of the stream bed increases rapidly.

changes in physico/chemical variables may thus be expected to be exponential. The art of identifying ecological flow requirements then becomes the identification of the inflection point at which the consequences of further flow reduction begin to increase rapidly. In Figure 4.1 (a completely hypothetical example), this inflection point is at roughly 30%.

The wetted perimeter model is at the basis of many of the instream flow quantifying methods tested by Prewitt and Carlson (1980), Annear and Conder (1984) and Estes and Orsborn (1986).

GENERAL EFFECTS OF FLOW MODIFICATION

In the introduction we listed a number of different types of flow modification which have rather different downstream effects. Table 4.1 is an attempt to summarize these differences. Many of the consequences are self-evident and do not need further explanation, but some general conclusions emerge.

Flow modifications act in a number of ways, apart from the reduction or increase of water down the stream. Of particular importance is the effect of flow modification on the amplitude of variation in flow and other parameters (characterized under the headings Floods, Seasonality, and Predictability in Table 4.1). If the biota of South African rivers has developed in extremely unpredictable conditions then the maintenance of flow variability may be more important than the maintenance of a base flow to conserve the riverine flora and fauna. The appearance of the livestock pest *Simulium chutteri* in large densities in the Vaal, Orange and Great Fish Rivers in the last 20 years is a direct consequence of river regulation. *Similium chutteri* is adapted to a perennial flow in which the over-wintering larval population gives rise to high spring densities. It has become the dominant invertebrate in the above rivers, which were previously inhabited by a balanced simuliid fauna of many species. The most successful control measures have been achieved by attempting to simulate natural seasonal flow regimes.

The ecological management of river flow by copying natural seasonal fluctuations at reduced rates will lead to the dampening of the amplitude of variations in the river. A more sensible policy might be to sacrifice a portion of the base flow in order to provide periodic larger floods. Except in the case of impoundments, flow modification has no effect in decreasing floods (see Table 4.1). Impoundments will reduce moderate floods, but will usually have insufficient capacity to intercept large floods. It is therefore the intermediate-sized floods which are most important in managing releases from impoundments.

The primary effects of flow modification on the total flow, flow variation, sediment loads and temperature regime are understood qualitatively, if not quantitatively. The secondary, often synergistic, effects on the biota, on water quality, and on channel morphology, are less well known and may operate on relatively long time scales which are not apparent to managers.

TABLE 4.1 Some ecological effects on rivers downstream of different types of flow modification structures

Type of flow modification	Total flow	Floods	Seasonality	Water quality	Predictability	Suspended sediment concentration	Water temperature range	Biotic diversity
Impoundment	Decrease	Decrease (moderate floods)	Decrease	Improvement or deterioration	Increase	Decrease	Decrease	Decrease (usually)
Flood Control impoundment	No change	Decrease	Decrease	No change	No change	Decrease	No change (usually)	No change (usually)
Interbasin transfer:								
Donor river	Decrease	No change	Increase	Deterioration	Decrease	No change	Increase	Decrease (usually)
Recipient river	Increase	No change	Decrease	Improvement	Increase	Decrease	Decrease or increase	Variable
Run-of-the-River abstraction	Decrease	No change	Increase	Deterioration	Decrease	No change	Increase	Decrease (usually)
Catchment modifications	No change or decrease or increase	Increase	Increase	Deterioration	Decrease	Increase	No change	Decrease (usually)

Case histories

Petts (1980) reviewed long-term consequences of upstream impoundment and identified three types of impact:

- Process alterations, such as reduction in flow, trapping of sediment (large reservoirs trap more than 95% of suspended sediment), and erosion immediately below dams (although this may be minimized if floods are sufficiently regulated by the impoundment).

- Second-order impacts (form alterations), such as increased sedimentation downstream of impoundment-induced erosion.

- Third-order impacts (feedback effects), such as the alteration of fish habitats leading to changes in fish communities, and in turn to changes in invertebrate populations.

Petts concluded that "the diffusion of the effects of an applied stress (such as dams), will be a slow process and will be characterized by time-lags between the different components". As a result, "the use of short-term observations immediately after dam construction for planning purposes may lead to serious management problems in the long term".

Baxter and Glaude (1980) reviewed the effects of dams in Canada and concluded that stream communities are maintained by periodic floods. They also found that biotic diversity generally decreases downstream of an impoundment, but biomass may increase or decrease. Reset distances (see chapter on the impact of dams, weirs etc) for the reestablishment of the invertebrate fauna were as long as 110 km. Walker et al (1978) investigated the effects of Lake Hume, an impoundment on the Murray River in Australia, and concluded that the temperature range was reduced by six degrees Centigrade, with a one-month time lag. The reset distance before the natural temperature regime reemerged was 120 km. Anoxic bottom-released water reached 50% oxygen saturation at one kilometre below the dam and 70% at 10 km, but only reset completely after more than 100 km.

Buma and Day (1977) monitored changes in channel morphology at eight locations below a dam over five years in Deer Creek, Ontario. Half the locations experienced a net increase in bed-depth, at two sites there was an increase in channel width but no depth increase, and at four sites there was no measurable change. This serves to illustrate the very variable nature of impoundment-induced downstream changes, even in a single river. Similarly, the effect of impoundments on the chemical composition of the downstream flow according to Hannan (1979) is a function of many variables, including evaporation, biological activity, age of impoundment, stratification, water release depth, catchment soils, geometry and size of reservoir, and heat and mass transfer processes as major determinants.

A number of researchers have found large increases in faunal biomass downstream of dams. Doubling of average density has been found by Briggs (1948), Okland (1963) and Armitage (1977), while Ward (1976) reported an 11-fold increase. This increase is normally ascribed either to nutrient enrichment from deep releases, or to the development of dense phyto- and zooplankton communities in the reservoir. A few studies have tried to define reset distances for the biota: Pearson et al (1968) concluded that the biota reset by 150 km below Flamingo Gorge Dam in the USA; in contrast Chutter (1969) found that the benthic fauna had recovered by eight kilometres below the Vaal Barrage, but that dense simuliid populations persisted for 50 km below the Vaal Hartz Diversion Weir, a condition he ascribed to the seasonal modified flow regime. Lehmkuhl (1972) found that the benthos of the South Saskatchewan River in Canada was still impoverished 110 km below Lake Diefenbaker.

Despite an increased biomass, species diversity is usually reduced below dams. Pearson et al (1968), Radford and Hartland-Rowe (1971), Spence and Hynes (1971), Hilsenhoff (1971), Lemkuhl (1972) and Ward (1976) all describe reduced invertebrate diversity, while Edwards (1978) found a reduction of seven species of fish below Canyon Reservoir in the USA, and that introduced exotics made up 28% of the fish community below the dam compared to 14% above.

Johnson and Carothers (1987) have documented the impacts of the Glen Canyon Dam on the river ecosystem of the Colorado River, which flows through the Grand Canyon National Park in the United States. The ecosystem has been greatly modified by the dam and United States management over the past 25 years. The article highlights the dilemma of conflicting interests in developing management alternatives.

EXISTING METHODS FOR ESTIMATING MINIMUM FLOW REQUIREMENTS

A number of different methods for the estimation of ecological flow needs for rivers have been developed and tested, most of them in the United States. These methods range from regional estimates of flow needs based on national supply and demand; largely subjective estimates of habitat availability; and more detailed calculations of wetted perimeters and requirements for different life-cycle stages of specific riverine species.

The following section describes these methods, while the section: A critical evaluation, below, points out their advantages and shortcomings, and suggests guidelines for the appropriate choice of method.

An examination of available flow methodologies, taking into consideration the resources available, should be the first step to take when assessing instream flow requirements (eg Figure 3, Weche and Rechard 1980). Most methods fall into one of two categories: those that deal mainly with the hydrological data and those that incorporate biological data.

Methods based primarily on hydrological data

a) A regional approach to the determination of water requirements for environmental management.

The proposal of "11% for conservation" originated with Roberts (1983) in a paper designed to introduce South African civil engineers to the idea of allocating water for environmental management. Such an allocation, though mentioned before, had been assumed to be a very minor proportion (less than one per cent of the total estimated water consumption of the country. There has been much subsequent discussion on the validity of Roberts' suggested allocation, perhaps without the general realization that the figure was based not on the particular instream flow needs of rivers, but on much wider issues, namely:

- the countrywide evaporative water demand of estuaries and lakes;
- the flooding requirements of the country's estuaries;
- the water demand for recreation, wildlife and the riverine habitat in nature reserves;
- an unknown requirement for wetlands and rivers in general; though it was recognized that the water requirement of wetlands needs to be quantified, that of the riverine biota was presumed to be met normally by the water already being conveyed along the river to consumers - ie by the compensation flow. No mention was made of the fact that this compensation flow usually gradually fails downstream due to extraction and becomes a more concentrated solution of pollutants, though this must be greatly to the detriment of downstream aquatic communities.

As at 1983 the estimated allocation for environmental management was nine per cent of the total exploitable water resources of the country (ie the mean annual runoff less that lost by evaporation and through floods), or 11% of the estimated total water requirements of all sectors in the year 2000. The nine per cent estimate is the more pertinent here, therefore, as it indicates the figure that could be used in calculations of instream flow needs if no others are available.

Roberts' (1983) estimates for estuarine requirements have subsequently been updated in Jezewski and Roberts (1986). In the latter paper the total estuary and lake freshwater requirement (defined as a single annual flood with the characteristics of a two-year flood, to open a closed estuary) amounts to approximately eight per cent of the total exploitable water resources of South Africa. Allanson and Read (1987) suggest that regular floods of this volume would be disastrously high for the Kariega and Great Fish estuaries.

The approach of Roberts (1983) and Jezewski and Roberts (1986) has been a useful stimulus for South African ecologists to start thinking about ways of estimating ecological flow needs, but is not a method that should be used to calculate volumes for individual rivers.

b) The fixed percentage, Tennant or Montana method.

Tennant (1976) recorded field observations of changes in such parameters as wetter perimeter, cross-sectional area and velocity for a range of flows. From these, the quality of the stream as an aquatic habitat (optimal to severely degraded) was related to a specific percentage of mean annual flow (MAF). A flow of 10% of MAF, for instance, was regarded as an absolute minimum below which only short-term survival of aquatic life could be expected. It was considered that 30% of MAF would "sustain good survival conditions for most aquatic life forms", while 60% of MAF would "provide excellent to outstanding habitat for most forms".

There are several factors that need consideration both before and after using the method, but two relevant points are that it must be supported by good knowledge of the hydrology and biota of the river in question, and that because it is basically an office method relying on past fieldwork it is very simplistic in approach and has the potential for frequent use and misuse.

c) Single-cross section computer methods.

The following description of the method is taken from Prewitt and Carlson (1980):

Single cross-section computer methodologies utilize cross-sectional dimensions and hydraulic parameters gathered at one stream cross-section at one flow to predict hydraulic conditions at selected but unobserved flows. Computer programs have been developed in the United States of America and a US Forest Service program known as R-2 Cross has been a commonly used such program. Cross-sectional dimensions are measured from a steel tape stretched across the stream channel. Program calculations allow conversion of the sag tape data to straight reference line data. Hydraulic properties including discharge, velocity, wetter perimeter and cross-sectional area were computed for alternate water levels. All users agreed that the single cross-section placement should describe a "critical" area of the study section, usually a riffle. Some agencies have used predetermined depth and velocity criteria to predict minimum flows, while others graphed these quantities against flow and noted inflection points.

These methods have all the disadvantages associated with having only one data collection point, and often result in recommendations which bear little relation to the specific requirements of the biota (Prewitt and Carlson 1980).

d) Multiple cross-section computer methods.

These methods are essentially similar to the previous single cross-section method, but use data collected from more than one section of a stream reach.

According to Prewitt and Carlson (1980) the most commonly used multiple cross-section computer program has been Water Surface Profile (WSP), a program developed by the Bureau of Reclamation (Burec) under the name "Pseudo". The WSP ("Pseudo") program was created by Burec for use in calculating water surface elevations below dams and sediment transport and hydraulic properties near bridges, wiers or orifices. A second multiple cross-section program, known as AVDEPTH utilized observed or predicted discharge-depth relationships to predict hydraulic properties empirically.

Instream flow methodologies associated with WSP vary with the agency or individual using the program, but usually incorporate maintenance of certain velocity, area and wetter perimeter criteria. Graphs of velocity versus discharge or wetter perimeter versus discharge usually display an inflection point below which incremental discharge reductions result in increasing losses of the hydraulic property. Some users have recommended those inflection points as critical flow levels below which further reductions should be made with great care.

Multiple cross-section methodologies allow for comparisons among cross-sections by either an averaging of hydraulic property changes with flow or by the selection of the most critical cross-section by its rate of degradation relative to other cross-sections at the same station.

These are an improvement of the single cross-section methods but more time consuming, since they use field data collected at more than one point on the river and thus provide information on a complete stream reach. The computer output of predicted hydrological properties at unobserved flows allows selection of the flow best suited to the stated objectives of stream management. Probably its most common use has been to ensure that a stream provides water of sufficient width, depth and velocity for the upstream migration of a specific fish species (Prewitt and Carlson 1980).

Methods incorporating biological data

Although regulated or altered flow regimes are usually associated with stream reaches downstream of impoundments, the concern which manifested itself in the development of methods to assess instream flow needs was originally for rivers depleted by water extraction for irrigation and other purposes. Whatever the reason for depletion, however, it became obvious that there was an urgent need to ensure adequate flow in rivers if their biota were to be conserved. The following methods record the refinement of techniques incorporating biological data over the last decade. Efforts appear to have been aimed at discovering which environmental variables are primary determinants of the distribution of the fauna, and how the fauna reacts to changes in these variables (habitat modelling).

a) An early technique for predicting in stream flow needs of benthic invertebrates.

Gore (1978) determined the optimum conditions of depth, velocity, substrate and turbulence (as indicated by the highest community diversity) for several common invertebrate species; from these data he identified site-specific indicator species. Indicator species were those species which had a narrower tolerance than others for flow changes and yet had a preferred habitat closely matching that of the most diverse community. Plotting areas of optimum conditions for species or communities on composite maps of depth and velocity in riffles at different discharges allowed predicting of the flow at which such conditions would be eliminated. This method was further refined by Gore and Judy (1981) who adapted the instream flow incremental methodology (IFIM) for use with macro-invertebrates (see b) below).

b) Instream flow incremental methodology (IFIM) using Physical Habitat Simulation (PHABSIM).

This method is typical of the more sophisticated attempts to marry hydraulic wetter perimeter models to models defining species specific habitat requirements. The following description is taken from Estes and Orsborn (1986):

The IFIM allows for the quantification of habitat that is capable of supporting a targeted species/life phase or combination of species/life phases as a function of selected flows. The ability to evaluate a series of specified flows with this method makes it the most versatile method of those examined for making water allocation decisions.

The PHABSIM system is a collection of computer programs that combine open channel hydraulics and behavioural responses of fish to hydraulic characteristics. The combination of these programs translates flow variations into an index of the availability of fish habitat (weighted usable area, WUA) at a site. The PHABSIM models require extensive hydraulic data (eg water velocity and depth) collection and analyses to simulate available physical (hydraulic) conditions (a physical model). Fish habitat criteria (eg water velocity and depth, and substrate characteristics associated with the water column utilized by fish) are required to develop fish habitat criteria files. The fish habitat criteria files are used to determine, through weighting, the percentage of total wetted surface area at a given flow which provides fish habitat based on physical characteristics simulated by the physical model. The resulting product is designated as WUA and is an index of the capacity of a site to support the species and life stage being considered. WUA is expressed as square fee (ft^2) or percentage (%) of wetter surface habitat area estimated to be available per 1000 linear feet of stream reach at a given flow.

A CRITICAL EVALUATION OF EXISTING METHODS

Except for the regional approach of Roberts (1983) the methods for assessing ecological flow requirements described in Existing methods for estimating minimum flow requirements, above, share some common advantages and disadvantages:

- they are existing methods which have been developed, refined and tested; and
- they provide a range of options which require different levels of information and effort. A method can therefore be found to suit the resources available for any project.

But:

- they were all developed in America, and have yet to be tested in the context of conditions in southern Africa; and
- they are all variations on the theme of habitat reduction resulting from reduced flows, and are aimed at the preservation of target species. They do not address problems of water quality, temperature and sediment changes which will inevitably accompany reduced flows.

Tests of these existing methods have been carried out in American rivers, notably by Prewitt and Carlson (1980), Annear and Conder (1984) and Estes and Orsborn (1986). Of these, Annear and Conder (1984) attempted an objective assessment of the relative bias of 18 methods on 13 streams, by comparing results for each method with a mean recommendation for each stream produced by all 18 methods. They found Tennant's method to be the least biased, but inflexible, and suffering from a lack of biological input. Estes and Orsborn (1986) considered that Tennant's method is best suited to streams in which competition for water is minimal, but that its assumption of universal applicability is suspect. Prewitt and Carlson (1980) stress the need for a thorough understanding of the flow regime of a river before Tennant's method can be used with confidence. They also concluded that the method gives the best results in undisturbed streams, where runoff data for virgin MAR can be used with confidence.

"If cost and time limit or prohibit field studies, flow recommendations by Tennant method procedures are acceptable only if proper consideration is given to the available hydrologic and biotic knowledge of the river" (Prewitt and Carlson 1980).

Of the single cross-section methods, Prewitt and Carlson concluded that the (usually subjective) decision of transect placement is critical, and that the results are often of little use because they fail to take into account species' individual needs. They felt that the multiple cross-section methods are more flexible for use with species response criteria, but that they require some increased field sampling effort, and there are some technical difficulties associated with their use. Annear and Conder (1984) found that all wetter perimeter models showed bias (mostly predicting flow requirements in excess of the mean) and they felt that the subjective identification of inflection points (see Figure 4.1) is a possible source of error.

Estes and Orsborn (1986) recommend IFIM for the assessment of flow requirements in streams where competition for water is high, and where detailed information can be collected on the different life-phase requirements of critical species. They also felt that IFIM is flexible since it allows for incremental flow evaluations, but that it assumes that the physical model represents the range of physical conditions needed for seasonal use of a reach by a species. Annear and Conder (1984) found that PHABSIM results for small streams recommended higher than average flows, but lower than average recommendations for larger streams.

The problem in reaching a definitive decision as to which method may be most appropriate is that there is no truly objective method of testing methods. A "true value" instream flow recommendation may or may not exist for each stream or stream segment (Annear and Conder 1984), and may in any case be different for different species.

Our own conclusion is that each of the methodologies may have a role to play in suitable circumstances, but that all should be used with caution, and should be checked by alternative methods where possible. The use of the Tennant method, which is the lease resource-intensive of those reviewed, appears to give results little different to those achieved by the more sophisticated methods, and should therefore be preferred, with the reservations described above.

Two alternative methods were developed at the Espada workshop, known as the "Skukuza Approach", which relies on an evaluation of individual consumptive and nonconsumptive water uses in the river, and the "Flow Record Simulation Approach" which relies on a historical or simulated hydrological record. These two methods, adopting very different methods are described in detail in Chapter 9, and are felt to be the most useful approaches for South African rivers. They address conditions in the river as a system, rather than simply one aspect or species in the river, and they both attempt to deal with seasonal flow variation and the amplitude of that variation. Although they are approaches developed independently from the American methods reviewed above, they could usefully incorporate one or more of these methods wither to augment the database of as an independent check on the resulting flow recommendations.

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CHAPTER 5. WATER QUANTITY REQUIREMENTS OF INVERTEBRATES, MACROPHYTES AND OTHER MESOBIOTA

J M KING, F C De MOOR, A J BOTHA and A H COETZER

INTRODUCTION

There is presently no legislation in South Africa dealing with the allocation of water to ensure the continued ecological functioning of rivers (instream flow needs). River ecosystems need to become recognized as users of water (in both the consumptive and nonconsumptive senses), and river ecologists need to initiate quantification of flow requirements of the riverine biota. Although initial efforts in this direction in the Northen Hemisphere were designed to improve the habitat of selected fish species, more recent research has indicated that some riverine invertebrates (important transformers of biological energy and sources of food for fish) may have narrower tolerances to flow changes than do many fish species (Gore and Judy 1981). A small loss in fish habitat could therefore be indicative of a much larger loss of habitat for benthic macro-invertebrates. Gore (in press) argued that even if the fish in an affected stream were not limited by the invertebrate food available, imbalances in benthic community structure with changes in flow could lead to further decreases in invertebrate numbers, with possible reverberations throughout the complex assemblage of biota associated with the river.

The importance of aquatic invertebrates as a food source is well documented. Sterba (1962) commented that out of 67 families of freshwater fishes considered, 42 fed on insects and in 29 of these families insects were the major food item. Aquatic insects therefore contribute significantly to the fisheries production of inland waters. They also provide a varied, balanced source of protein which may make their value as a quality foraging food more important than the actual biomass produced.

A host of other vertebrates from frogs to birds rely directly on aquatic invertebrates or their aerial adults as a high-quality food source. In certain instances man feeds directly on aquatic invertebrates such as freshwater mussels, lake-flies, freshwater crayfish and prawns (Hynes 1984). Not all of their impacts are beneficial, however. For instance, human interference with aquatic habitats can lead to the development of vast populations of a single species, which may pose problems when mass emergence of winged adults occurs. Mosquitoes, blackflies, other biting midges and sandflies are all known vectors of various debilitating diseases affecting man, and stream flow modification can lead to increases in the numbers of such undesirable animals.

Protection of the small aquatic life forms in rivers is also imperative because they are responsible for the "magical" cleansing of polluted water that occurs as it flows down a river. Thousands of small animals and plants in every square meter of riverbed, together with the vitally important micro-organisms, extract dissolved and particulate material from the water column and sediments for use in their own life-processes, leaving the water to flow on purer as a result of their activities. A water manager knows well that polluted water released into a river will become more pure, and would ultimately become reusable, as it flows downstream, but he may not have realized that in order to ensure the continuation of this purification process he must maintain the aquatic biota that provides this service. Consideration of the needs of the mesobiota thus is clearly an important part of any comprehensive management programme of stream flow, and accounting for the needs of all components of the riverine ecosystem would be more effective than a strategy which accounts for any one component.

The subject of quantitative water requirements of riverine biota is considered a grey area in the literature by some lotic ecologists. A few have faced the very real need to supply engineers and planners with figures that they can work with, however, and have attempted to devise acceptable scientific methods for assessing instream flow needs. Almost all of the work has centred on the needs of the fauna, and we found little literature referring to the quantitative water requirements of macrophytes and other mesobiota. Because of the bias in the literature and in our own knowledge, the following account mainly discusses the topic with regard to the biota in general terms, and to the macro-invertebrates in particular.

CHARACTERISTICS OF PLANT/INVERTEBRATE COMMUNITIES WITH REGARD TO WATER QUANTITIES

The composition of riverine communities reflects both the quantity and quality of water available to them, as well as other features of their environment. It is difficult to identify the separate effects of these variables, as in general terms cool, pure waters are linked with the rocky bed and fast, turbulent flow of mountain streams while, in a gradation, warmer, less pure waters coincide with deeper, slower laminar flow and the sandy or muddy substrata of downstream reaches. Thus, it may be difficult to determine if, for instance, the prominence of fringing reed-beds on a lower river is due to nutrient enrichment of the water, the slower flow and sandy substrata present there, or some combination of these and other factors.

Some trends can be identified, however, if one accepts that not every river will meet every generalization. At the coarsest level rivers may be perennial, seasonal or intermittent, with each having a different biota that could be devastated by a change in the flow regime (Hynes 1970; Towns 1985). While the invertebrate fauna of perennial streams may have long life-cycles (or many generations), that of seasonal or intermittent streams will consist largely of species with life cycles that can be completed in the short time during which conditions are favourable. Thus, the invertebrates and aquatic plants of a perennial river would be decimated by the cessation of flow and drying out that may accompany a halt in water releases, with reverberations throughout the food web of that ecosystem. Macrophytes of the same river, however, usually occurring along its lower reaches in open valleys which allow seasonal flooding and drying of bankside areas, can withstand periodic dry periods as long as these are within the limits normally experienced by the system.

At the other extreme, rivers with a tendancy to come down in spate bear a less abundant and less varied fauna. Thus, small tributaries bearing flood waters from limited catchments may have a richer biota than the rivers that they feed (Hynes 1970). Logging, afforestation, urban development and seasonal changes in rainfall all affect the intensity of runoff and thus the abundance and diversity of the riverine biota. In South Africa one manifestation of this is that in the winter rainfall area the riverine fauna is at its lowest abundance in winter, whereas in the summer rainfall area the fauna is richest in winter (Hynes 1970).

Aquatic plants tend to be scarce in the higher reaches of streams, at least partly because the rocky bed and turbulent flow precludes the easy establishment of seedlings. On the other hand, the invertebrate fauna in these reaches may be diverse, with species adapted in a variety of ways to cope with fast flowing waters: hooks, claws, safety nets and ballast are important aids for maintenance of position, and body shapes tend to be flattened and streamlined to keep friction to a minimum (King et al 1986). Because mountain streams, with relatively small annual fluctuations in environmental conditions, are mainly eroding, cool, clean-water systems, their biota is sensitive to small changes in temperature, flow and silt loads and is easily decimated by disturbance. As the waters are also usually oligotrophic growth tends to be slow, as does recovery from disturbance.

As flows slow downstream and the substratum changes from rock through sand to mud, macrophytes and small aquatic plants proliferate and the invertebrate species change to those that can survive in such substrata and can cope with greater extremes of water quality and flow. Both plants and animals are more tolerant of environmental fluctuations than those in the headwaters, but still need to live within certain environmental limits. These limits indicate the resilience of the community, and though usually the limits widen, and thus the resilience of the biota increases, downstream, environmental changes that exceed the limits at any point along a river (such as a drastic change in the flow regime) will cause collapse of the community structure and the establishment of some new, altered structure. Such a new community structure would still be largely unpredictable with our present knowledge, but may include, for instance, proliferation of a pest species.

Where flow is reduced, established riverine communities will respond with changes in size and abundance as well as in structure. Thus, with permanent reductions in river flow, wetlands, floodplains and riparian zones may diminish and eventually disappear. More subtle changes, such as the loss of aquatic plant and invertebrate biomass, will have equally widespread but less detectable effects, affecting, as they will, the whole food base of the complex river ecosystem.

RESPONSES OF THE FAUNA TO CHANGES IN FLOW

Changes in the flow regime of a river almost always mean a reduction in flow, except where unseasonal high-flow discharges are released from a dam or substantial interbasin transfer of water occurs. Alteration of seasonal flow patterns to either a stable year-round flow or increased flows in the dry season and decreased flows in the wet season will result in a marked response from the aquatic biota. Reduced discharges are known to affect aquatic invertebrates through loss of total wetted area and of riffle habitat (with resultant decreases in abundance and biomass), reduced food, dessication (Canton et al 1984), increased drift (Gore 1978) and decreased production (Gore 1983); many other consequences such as reduced upstream migration can be envisaged. Stable year-round flows, or unseasonal high or low flows, can favour some species at the expense of others, causing shifts in community structure and perhaps the loss of some species and the proliferation of others that are pests.

The four instream variables commonly accepted as being directly related to discharge are velocity, depth, turbulence and wetted area. These variables are an integral part of most instream flow models and especially of those that incorporate requirements of the biota. Because of the inherent associations between these and many other variables (Gore and Judy 1981; Morin et al 1986) effects on the biota of changes in one of them are difficult to identify.

Even when it can be shown that animal densities correlate with different values of one of a series of measured variables, with the others held constant, there is no guarantee that more subtle unstudied factors are not involved. Factors such as the availability of ground water (which influences the existence of riparian vegetation and the stability of banks), and the influence of increased silting on instream biotic diversity and community structure also need to be accounted for. Chutter (1969), for instance, pointed out that riverine invertebrate species apparently responding to small changes in depth may well have been influenced by different densities of algae or of predatory fish in the shallower areas, rather than by depth per se. De Moor (1986) reported that between March 1981 and December 1982 ecological conditions at his study site on the Vaal River changed considerably. A long drought had reduced flows and cleared the normally turbid waters. Large mats of *Myriophyllum aquaticum* had appeared and large expanses of rapids had become exposed. The community of *Simulium* species, which had previously been dominated by *S chutteri*, became dominated instead by *S hargreavesi*. Habitat modification had altered rapids ideally suited to *S chutteri* in such a way as to favour other, fortunately less problematic, species.

Despite the inherent difficulties involved in accurately identifying cause and effect, many authors have reported responses of invertebrates to changes in one of a variety of environmental variables. It is impossible to review this wealth of literature here, but some pertinent work is considered below. Details of other work done is contained in many of the references given in this chapter, particularly in Gore (1978) and Orth and Maughan (1983).

Much of the work has concerned reactions of the biota to changes in current speed (see also Cambray et al this volume). Several authors have reported shifts in preferred current speed of species during their life cycles. Kovalak (1978) found that Ephemeroptera living in slow currents were larger than individuals of the same species in faster waters. He attributed the difference to habitat selection controlled by oxygen requirements rather than by current speeds, however. Gore (1983), reported a more direct link between distribution and current speed, finding a significant correlation between mean shell length (vertical projection into the water column) of the prosobranch snail *Elimia potosiensis* and preferred current speeds. Smith and Dartnall (1980) had already investigated turbulence and boundary layer control by Psephenidae while Statzner and Holm (1982) had dealt with morphological adaptations of benthic invertebrates to stream flow; their results had revealed that vertical projections from the body of an animal impaired boundary layer control and restricted it to areas of relatively low current speeds. Gore (1983) supported these conclusions, finding that small individuals of *Elimia potosiensis* occurred in areas of high current speeds while larger individuals were restricted to lower velocities.

Gore (1983) concluded that the present assumption, when compiling flow preference curves for species, that any one species will have similar flow needs throughout its aquatic life may be erroneous. His identification of a double-peaked preference curve for velocity for *E potosiensis* resulted in a figure for recommended optimal discharge that was 25% higher than that based on a single-peaked curve.

Other reported responses of invertebrates to changes in flow are increased drift with fluctuating discharges (Hooper and Ottey 1982; De Moor et al 1986), decreased faunal density of up to 50% in a low-flow year (Canton et al 1984), behavioural adaptations to combat increased current speeds (Hooper and Ottey 1982; Chance and Craig 1986), preferences for certain depths (Gore and Judy 1981) and preferences in particle size (Gore 1983). Many more details can be found in the general limnological literature and literature on regulated streams (eg Ward and Stanford 1979).

More subtle reactions of the biota to flow changes need to be borne in mind. For instance, in the south-western Cape, when flow is low in summer, larvae of many Trichoptera (K M F Scott personal communication), Coleoptera and other species move into the moist banks of rivers and streams to pupate. Successful pupation depends, inter alia, on maintenance of these banks in an undisturbed and sufficiently wet condition. If stream flow remains abnormally low during a number of consecutive summers, then the bank habitats of these pupae will dry out and may be lost. Community changes will inevitably then occur as some species are reduced in number of individuals or lost altogether and the biota as a whole adjusts to this.

Several recent studies have documented responses of the invertebrates at the community level. In these studies, in which those environmental variables that significantly influenced community structure were identified, depth, velocity and/or discharge featured prominently (Furse et al 1984; Wright et al 1984; Bunn et al 1986; King unpublished). In these and other studies, additional variables of major significance were those that would inevitably change as a result of flow changes: water chemistry, temperature, stores of benthic organic matter (BOM) and coarse:fine BOM ratios (Minshall and Minshall 1978; Gore 1980; King 1982; Townsend et al 1983).

On a community level, then, changes in discharges can be expected to affect, inter alia a) substratum composition and water quality, and thus suitable habitats and ultimately community composition; b) the transport and storage or organic and inorganic particles and thus community composition and proportions of functional feeding groups; and c) the length of recovery zones below points of disturbance or pollution. Probably the first change to occur with reduced discharge, all else remaining unchanged, would be a reduction in biomass and numbers due to the loss of wetted area. With further reductions in discharge and/or deterioration in water quality, changes in community composition would occur. As this trend of impacts continued there would eventually be collapse of all but the most coarse ecological functioning. If the river was receiving a heavy load of waste waters, then at this stage it would be little more than a drain, with the biota virtually nonexistant and almost all water purification processes halted.

RESPONSES OF THE FLORA TO CHANGES IN FLOW

Local enquiries on the subject have produced little hard data, and it seems possible that although much is known of the biology of aquatic plants, little, if any, of this relates directly to their instream flow needs. C Boucher (University of Stellenbosch) has been involved in the study of salinity-tolerance levels in aquatic plants. Investigating the freshwater requirements of estuarine halophytes he has determined that they can tolerate salinity levels much higher than those present in sea water (C Boucher personal communication). Similar work is planned on freshwater macrophytes such as *Polygonum* and *Scirpus*, where he will address such questions as how salinity levels affect seasonal rhythms such as flowering. Another reaction of aquatic plants to changes in discharge noted by Boucher is the upstream shift of sand-bed plant communities to displace mud-bed communities, as tides encroached further into estuaries of depleted rivers. As the two types of communities are thought to have different levels of production, such changes could affect the levels of secondary productivity of the estuary as a whole.

Heeg and Breen (1982) reported extensively on the primary producers of the Pongolo floodplain and pointed out the importance of seasonal inundation by flood waters for the continued annual cycling of terrestrial and aquatic plant communities.

In North America Prewitt and Carlson (1980) recorded increased abundance of filamentous algae in years with less than in 20-year low flows, together with the stranding of many aquatic invertebrates in newly-exposed bank areas and a high number of dead, ill or severely parasitized fish. Similar phenomena (except for the fish) have been witnessed in south-west Cape streams (South Africa) during summer low flows exaggerated by water extraction (personal observation). Reduced flows, together with nutrient enrichment, have also encouraged encroachment of macrophytes such as *Typha* and *Rorippa* into stream channels of the region as well as the establishment of exotic pest species such as *Eichhornia crassipes, Salvinia molesta* and *Myriophyllum aquaticum* in the lower reaches of rivers. *Myriophyllum aquaticum* establishes a rooting system in the stream bed and is exceedingly difficult to eradicate, though high winter flows can cause considerable damage (personal observation). The other pest species are free-floating and could possibly be controlled in rivers to some extent by scouring them from the systems with flood waters. *Eichhornia crassipes* has been reported as surviving up to 14 days in sea water, however, and so the potential exists for it to move along the coast and invade a second estuary.

Clogging of the main stream channel by algae and aquatic macrophytes, because of prolonged low flows, has many implications in all zones of a river. While the phenomenon may result in the loss of rare or endemic species from headwaters (many of which are characteristically very sensitive to disturbance), massed aquatic plants covering the water in the lower reaches may, through evapotranspiration, cause greater water loss than from an open water surface, may lead to reduced levels of dissolved oxygen in the water to the detriment of the aquatic fauna and may retard flood waters. Reduced flow may alter the lotic habitat making it more suitable to colonization by mosquitoes (Culicidae) which are potential vectors of various human and livestock diseases.

PROBLEMS ARISING FROM ALTERING NATURAL FLOW REGIMES - CASE STUDIES

Most river ecologists will have knowledge of problems arising from altered flow regimes in rivers. In a country where many feel that all water reaching the sea is wasted, and where multimillion rand projects to transfer water between catchments are increasingly comtemplated, pondering the potential for ecological disasters is disturbing. Most reported flow-related disturbances of rivers would probably concern more obvious features of river systems, such as the demise of fish denied an upstream migratory route or of a wetland or floodplain denied seasonal inundation of floodwaters. Disturbances of small aquatic forms go largely unnoticed and therefore unreported. Two examples of flow-related disturbances to invertebrate communities are discussed here to indicate the forms that these can take.

Instream needs versus canoe races

After completion of the Kleinplaas Dam on the Eerste River (south-western Cape) extra water was released from it annually for a few years, for a canoe race (apparently against the policy of the Department of Water Affairs). Although the canoeists appeared to have no particular preference for the timing of the race the water was released in mid-spring at a time of naturally decreasing flow, presumably because sufficient water had then been stored for the impending dry season. Water was released in a 'tidal wave' down the river, according to a canoeist, at a time when overwintering aquatic insects were preparing for emergence by moving into quiet edge areas of the stream (King 1982). The 'tidal wave' would have left little time for evasive action by the animals and, while unseasonal spates are certainly not unknown in the region, such an abrupt one arranged for roughly the same time every year could be consistently detrimental to some components of the biota. Possible results could be shifts in community structure, decreased numbers and biomass and other reactions resulting from these.

The same release in early winter would have been equally beneficial to the river ecosystem (scouring, cleaning, providing the age-old reset mechanism to which the biota are adapted) and the canoeists. The increasing level of communication between ecologists, managers and other interested parties will hopefully ensure that in future cases such as this all relevant issues will be taken into account before releases are decided upon and ecologically damaging actions thus kept to a minimum.

Proliferation of a pest species in a regulated river

Damming of rivers usually leads to a significant increase in the abundance of aquatic filter-feeding animals downstream of the impoundments. Damming of the Vaal River by the Vaalhartz Diversion Weir resulted in an increase in Simuliidae downstream, where they became the dominant faunal group. The most common simuliid species was *Simulium chutteri*, a species whose adult females feed on bovine blood (De Moor 1982).

In the nutrient- and plankton-rich waters of the impounded river, where regulated flows maintained higher dry season flow and thus sustained a larger aquatic habitat than would originally have occurred, *S chutteri* increased to pest proportions. The normal seasonal decline in the larvae of *Cheumatopsyche thomasetti* (a predator of the larval stages of *S chutteri)* in the late winter allowed an accelerated population growth of *S chutteri* to the detriment of cattle in a nearby extensive farming area (De Moor 1982). Work by De Moor showed that further manipulation of flow, to simulate seasonal cessation of flow of the unregulated river, was a potentially useful tool for controlling simuliid numbers which had increased partly due to flattening (by damming) of seasonal peaks and troughs in flow. Simulating a natural flow regime thus appears to have considerable potential as a technique for maintaining a diverse and reasonably stable aquatic community in a disturbed river.

ALLOCATIONS FOR INSTREAM NEEDS

Assuming that the decision has been made to allocate water for instream needs and the objectives in doing so have been clearly defined, a further decision must be made on the form the allocation will take. Internationally, a fixed annual allocation is usually favoured by water authorities as it can be easily incorporated into plans and administered. An additional advantage is that it implies that a firm commitment has been made to release the water for instream needs. Disadvantages of such a scheme are that neither the volume or timing of releases would necessarily be based on sound ecological principles or would take into account natural fluctuations or extremes in flow. Thus releases may be constant throughout the year or vary between no and high flow; they may vary consistently month by month on an annual basis with no years of exceptionally high or low flow; and they may produce unseasonally high or low flows.

The chances of being able to predict all the flow requirements of a stable, natural riverine community are probably remote. Instead, with regard to the continued ecological functioning of the riverine communities, there appear to be two main options for managing water releases into regulated rivers. The first option is to simulate the natural preregulated flow regime, on the assumption that this is the condition that the biota is best adapted to. Methods exist for introducing allocated water into a river in some such fashion. A well known method is the use of flow data from an upstream unregulated section of the river to calculate proportional releases from a downstream dam. Such a procedure should be reasonably easy to operate and would ensure toned-down flow variability in the regulated river, but would complicate matters for water authorities faced with many users competing for a limited supply of water.

The second option for managing water releases is to attempt to identify those characteristics of the flow regime which have a significant impact on the aquatic biota, and to incorporate them into a new recommended flow regime for the river. In such an approach, for instance, monthly limits for maximum and minimum flows could be set, and flushing floods and high flows for spawning runs specified.

Whichever option is adopted, one would aim to ensure in a country such as South Africa where extremes in flow are natural, that flow varies both from year to year and within years. Provision for major floods should also be made, in order to ensure maintenance of a variety of habitats such as pools and riffles and to flush out litter, pollutants and fine sediments. Armitage et al (in press) discussed the importance of flushing flows both for the long-term maintenance of habitats in regulated rivers and as a reset mechanism in stream ecosystems in general. Gore (1978), for instance, specified for a particular benthic community a habitat with water depth of 28 cm, current speed 76 cm per second and a substratum of medium-sized cobbles. There are little data to indicate if such a habitat could be maintained with a constant flow, or if it would require occasional flushing flows to scour out fine silt and thick epilithic layers. Armitage et al (in press) noted that a six-fold increase in discharge in a Welsh river failed to alter particle size composition of the substratum but did scour out organic detritus; they did not indicate if the failure of the water to scour out inorganic particles was due to it having insufficient force or to the fact that it was already carrying its maximum possible sediment load (ie was not 'sediment hungry').

Decisions on how to apportion releases in any one river should be based on the recognition that during a given time certain flow requirements may override all others. Gore and Judy (1981) pointed out that discharges adequate to maintain the fish or benthos may be inadequate to meet the hydrological requirements of such features as seasonal flushing flows. At other times flows adequate to maintain the benthos might not maintain the high current-speed gravel beds necessary for salmonid spawning or the long-term maintenance of riparian vegetation, which in turn preserves the stability of the stream banks. Water releases should never halt completely in normally perennial streams.

Identifying the flow needs of a studied reach may be insufficient for long-term survival of the conserved aquatic community, no matter how accurate the calculations, if broader issues are not also considered. Gore (in press) stated that because of downstream drift and upstream movement of different life-stages of benthic invertebrates, consideration should be given to the minimum stretch of river for which a specific discharge must be maintained. It could be that maintenance of acceptable flow levels over isolated short stretches would fail to meet the migratory requirements of many species, and resultant shifts in community structure as some species fail could confound the objectives behind the original allocation of water. In the same vein, B Walker (personal communication) favoured a general policy of allocating flows for the conservation of habitats rather than of specific species, and identified billabongs (oxbow lakes) in Australia as 'endangered habitats'.

RESEARCH NEEDS AND KEY QUESTIONS

The following suggestions for research range from the collecting of data nationwide, in order to increase our biological and geographical knowledge of the invertebrate fauna of rivers and streams, to the answering of specific problems regarding flow regulation of rivers:

Distribution patterns and life cycles of riverine invertebrates.

Reactions of riverine invertebrates to flow regulation
- in a variety of rivers nationwide
- at different sites along multiregulated rivers
- at specific sites over a number of years
- their value as indicators of instream flow requirements

The identification of hydrological requirements for the maintenance of aquatic habitats.

Maximum permissible rates of change in flow during releases from dams, in order to avoid devastation of the downstream biota.

The effects on the biota of short-term extreme fluctuations in flow accompanied by large changes in the area of exposed stream bed.

Microhabitat requirements of common or key aquatic riverine invertebrates.

Long-term experimental releases from a dam with uncommitted, stored water, and subsequent monitoring of downstream effects on the biota.

In addition to these research needs, there are many questions - specific, general or philosophical - that are relevant to the topic of instream flow needs. Some of these are presented below to stimulate future thought and discussion.

With reference to Roberts (1983) assessment of future national requirements for environmental managment, and acknowledging that his figure of nine per cent was not meant to literally mean that each river's flow could be reduced to that proportion of its natural flow, would nine per cent of a river's flow satisfy its instream requirements?

If this figure is impracticable, what proportion of flow is considered necessary for instream needs?

Would different kinds of rivers (shallow versus deep rivers; the silt-laden rivers of Natal versus the clear, acid streams of the south-west Cape) require different proportions of their natural flow for instream needs?

Would each river require a separate assessment of allocation, or could we generalize? If generalization is not possible, how much time would be needed for limnological research before flow regulation took place?

Could more or less of a river's flow be allocated for instream purposes depending on its conservation or other importance? What criteria would be used when assessing its importance?

For the maintenance of specific communities and/or habitats, how would we determine the minimum length of river over which a specified flow must be maintained?

How do we address the problem of changing concentrations of pollutants with changes in discharge?

What major hydrological features should be considered when calculating minimum instream flow requirements (eg minimum flow, maximum flow, mean annual flow, seasonal minima and maxima, five-year floods, 50-year floods etc)? Consideration would have to be given to the flow required for habitat maintenance.

Is it feasible to relate releases to flow in an upstream, unregulated reach of the river? Or should those characteristics of the flow regime perceived to have a major impact on the biota be built into a new, recommended flow pattern?

In arid countries such as South Africa and Australia, the importance of large seasonal fluctuations in flow and of flushing floods have been emphasized. Such characteristics of the hydrograph would be relatively easy to build into a new regulated flow regime, but how important to the biota are minor day-to-day fluctuations in flow?

Many rivers will have to be maintained at functional rather than pristine levels. Having determined the desired status of a river, which component(s) of the biota would be the most useful for assessing and monitoring an instream allocation: the invertebrates, fish, riparian vegetation, some other component, or must we look at them all; single key species or complete communities?

CONCLUSIONS

River ecologists are likely to have to make an increasing number of decisions and recommendations concerning flows in rivers. Advances in knowledge in the last 10 years have enabled such procedures to be followed much more confidently than was possible then. In South Africa, nevertheless, we are only beginning to address the topic of instream flow needs, and are working from a pathetically poor database. Information on the taxonomy, biomass and distribution of the local freshwater biota is scarce, and that on life cycles, critical life-cycle stages and environmental requirements of the mesobiota is virtually nonexistant. Only for those species that are economically or medically important do we have more comprehensive data.

Though the database on the South African riverine biota is poor, the international literature gives many general guidelines on issues to consider, techniques to use and the kinds of recommendations to make when addressing the topic of instream flow requirements of rivers. Most of these techniques have been developed in North America and it is not known at this stage how applicable they are to South African rivers; the indications at this stage are that they may provide recommendations for flow that are too high for the rivers of more arid climates. Local initiatives in the development of suitable techniques are outlined in Chapter 8.

Increased research into the flow requirements of South African rivers would greatly enhance the ability of river ecologists to contribute to effective stream management. In order to do this, however, such scientists would need the same planning and research time as other professionals involved in, say, the construction of a dam. Only then would they be able to make positive, well informed recommendations concerning dam design and water releases into the downstream river.

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CHAPTER 6. FLOW REQUIREMENTS OF FISH

J A Cambray, D J Alletson, C J Kleynhans, M O G Petitjean and P H Skelton

INTRODUCTION

It is usually agreed that given the appropriate water quality, the distribution and number of fish in a stream are primarily controlled by the flow regime and its associated factors, such as timing, velocity, depth, substrate and cover (Mosley 1983). Also of importance are temperature, flood occurrence, food supply, competition, predation, dissolved oxygen, nutrients, stream morphology and sediment. These are the criteria that should be used as a framework for the analysis of the flow requirements of fish.

Fish require an instream flow which provides adequate useable habitat, expressed in terms of an acceptable water quality and quantity for all life stages (Figure 6.1). Different flow allocations and timings will either provide the correct microhabitat for such critical times as spawning and incubation, or result in the loss of an entire year class. Acclimatization of a species to a new set of instream flows can only occur within tolerance limits which are mainly set by the genetic composition of the individual. Once the instream flow characteristics are outside the individuals tolerance limits, the organism will be excluded from the habitat.

There is a worldwide increase in interest in flow allocations. Man's needs in South Africa are competing with lotic systems for existing flows, more so than in many countries. Unfortunately, in South Africa there has been very little research to quantify the effects of river alterations on fish populations (O'Keeffe 1986). Very few lotic systems have had good pre-impoundment or pre-abstraction fish studies completed on them. One is severely handicapped in attempting to establish realistic instream flow figures without before-and-after comparisons of species composition, population dynamics, growth rates, recruitment, biomass and movement patterns of fish.

In the South African Red Data Book on fishes (Skelton 1987) over 80% of the 24 endemic freshwater fish listed are threatened by reduced stream flow. Such rheophilic species as the Incomati rock catlet (Chiloglanis bifurcus) are threatened by increasing water utilization for agriculture and industry. It has a conservation status of "vulnerable", which means that populations of this species have been seriously depleted and its ultimate security is not yet assured. "For a specialized rheophilic species like C bifurcus, the trend of increasing regulation of water supply is of major concern" (Skelton 1987).

In the United States 60% of the fish listed as endangered or threatened are obligate riverine species, and in Australia 30% of the freshwater fish species are in jeopardy. This indicates the failure of water planners to deal with the major threats to aquatic ecosystems (O'Brien et al 1983).

Ecologists require methods and techniques that enable them to put forward effective management strategies for river systems. There are a number of methodologies available for determining instream flow requirements of

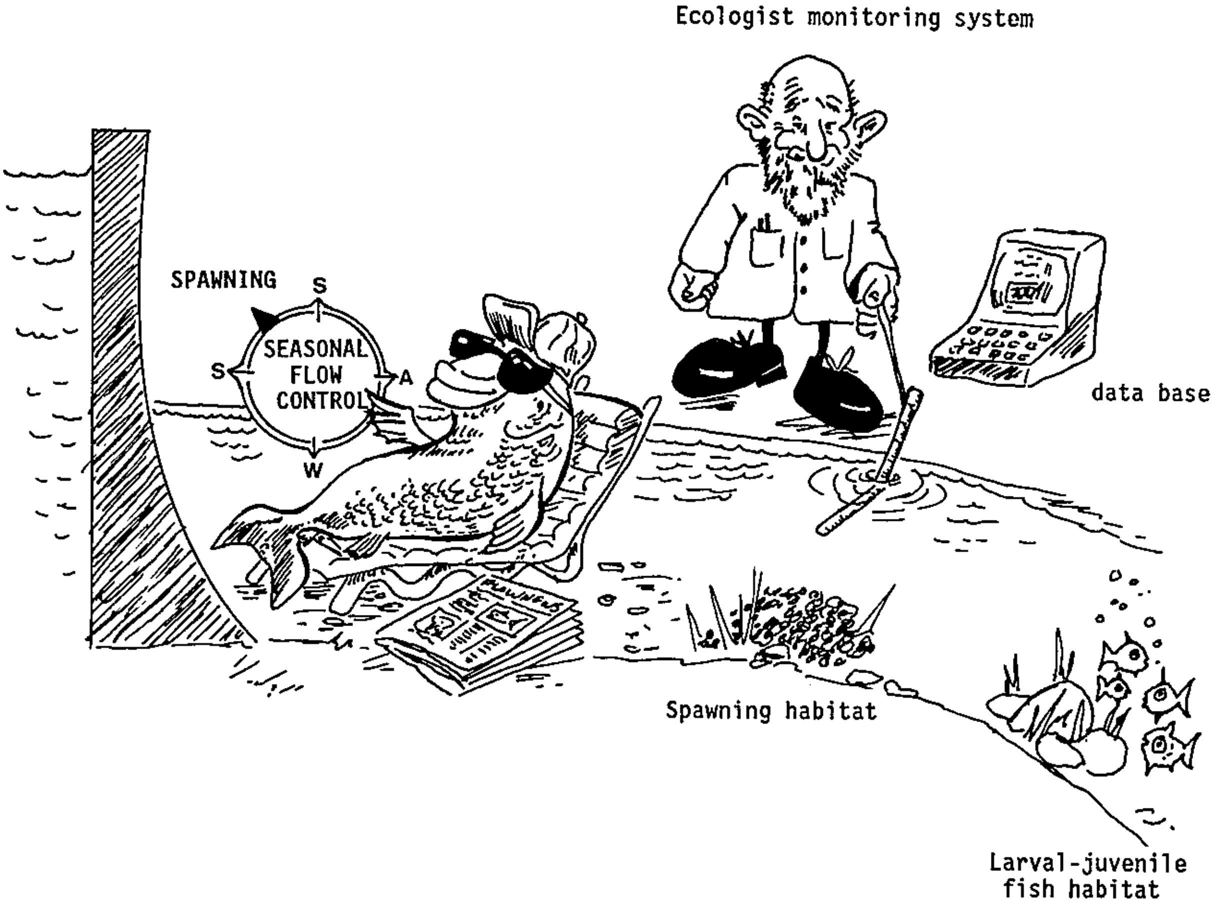

FIGURE 6.1. Fish require an instream flow which produces habitat expressed in terms of an acceptable range of depth, velocity, substrate and temperature for all life history stages. (Drawn by G Marx, Albany Museum).

fish. In the United States many of the methods used to quantify instream flow requirements are based on the life phases of salmonids in cold water systems (Wesche and Rechard 1980). Recently more sophisticated methods using computer modelling, include more species and habitats (Bartholow and Waddle 1986). These methods have to be modified for South African conditions and must be tested in the field. The extent of the physical effects of an altered instream flow are not easy to predict and the long-term impact that any change may have on fish stocks is even more so. Ideally one needs to be in a position to recommend suitable flow regimes to maintain all habitats on both a seasonal and a species basis rather than having to recommend a single "minimum flow" value (Wesche and Rechard 1980).

An analysis of microhabitat/flow rate relationships requires knowledge of the life histories of the species concerned and the ecology of the stream under study. These analyses also require the determination of hydrological conditions in the various microhabitats utilized by a species during the course of its life cycle. For the majority of South African fish species very little is known about their microhabitat needs, with regard to velocity, depth and substrate type. Research is needed in this field so that river ecologists can make a contribution to instream flow recommendations based on sound methodology and data. The overriding concern is that for adequate research, time and funding are prerequisites. The river ecologists must be included on the early planning team and not called in at the last minute to simply provide an estimate. The correct allocation in terms of quantities and timings of water could ensure the proper maintenance of the lotic system in question, and still provide water for offstream uses. Negotiation and compromise are important aspects of instream flow recommendations. Optimal flows are desirable but in many streams river ecologists and river managers will have to negotiate on flows somewhere between optimal and minimal.

CHARACTERISTICS OF FISH WITH REGARD TO WATER FLOW

Many authors have reported that the addition or replacement of species along a river system is a function of stream order, stream size, altitudinal gradient, or other descriptors of environmental gradients (Burton and Odum 1945; Heut 1959; Sheldon 1968). These studies consider the longitudinal changes in community composition as a function of variables such as mean depth, mean velocity, water quality, or other characteristics exhibiting gradational change. This perspective is defined as a macrohabitat approach to riverine ecology (Bovee 1982). Certain macrohabitat characteristics such as water quality or water quantity define the tolerance limits for different species. If these characteristics change so does the distribution and possibly the viability of the species in the system. However, fish and invertebrates do not respond directly to the physical macrohabitat characteristics, they respond to microhabitat conditions (Bovee 1982).

Riverine organisms utilize a variety of microhabitats at different times. The microhabitat used by a species during one of its life history phases is a reflection of its evolutionary history. Size, shape, swimming performance, feeding strategy, predation and competition all combine to define the suitability of a microhabitat, as well as the limits of tolerance. Small fish are often found in shallower, slower water whereas larger fish inhabit the more open waters. Larger fish and many of their aquatic invertebrate food items select microhabitats that optimize their abilities to feed efficiently.

Many of these species are morphologically adapted to live in a particular type of microhabitat. Fish species which occur in swift-flowing, rocky-bottomed mountain streams require specific adaptations to resist turbulence (Welcomme 1986). Some fish have enlarged pectoral spines (eg Amphilius species) or suckers derived from a modified mouth (eg Chiloglanis species) which they use to cling to rocks. Their bodies are usually elongated and dorsally flattened, with a humped longitudinal profile; pectoral fins and spines are usually enlarged, serving as downward-raking hydroplanes. These species are obligate rheophiles and rock-living forms which are very sensitive to river regulation. Other fish species living in mountain streams such as eels (Anguilla species), take refuge from the current in rock crevices. Another less specialized adaption to these turbulent habitats is the ability to swim fast and with agility. These are generally small, streamlined species which occur in the pools of the riffle-pool systems. An example is the redfin minnow, Barbus afer which occasionally makes forays into the swift flowing riffles in search of prey. This group is not as sensitive to current changes as are the fish with suckers and enlarged pectoral spines.

In systems which are seasonal, there may be a higher percentage of fish which have their branchial cavity divided into two surface types. One is for aquatic respiration, the gills, and the other is an epithelium for aerial respiration. In the sharptooth catfish, Clarias gariepinus, the epithelial surface is elaborated as a cauliflower-shaped suprabranchial organ. Reduced flows may favour such species as C gariepinus whereas the more riverine fish will fall prey to them because of a loss of cover and inability to cope with lower oxygen levels.

In river systems the natural spawning grounds of many fish species are subjected to considerable changes, which lead to fluctuations in population numbers from year to year. The bottom of riffle areas are important spawning grounds for many stream fishes (Cambray 1985a; Cambray and Meyer 1987). The riffles are also important areas for the production of insect food. Pools are important for many stream fishes as post-hatching nursery areas. Fish food in the pools includes drift from the riffles and terrestrial insects. The early larval fish often occur in the quietest pools and backwaters. Instream flow requirements for these different life history stages must be taken into consideration along with the requirements for adults.

FISH RESPONSES TO FLOW MODIFICATIONS - CASE STUDIES

Cambray (1985a) has suggested that Labeo capensis and Clarias gariepinus can now breed earlier in the year in the lower Orange River due to flow modification. Before the completion of the Hendrik Verwoerd Dam in 1970, the natural flow in the lower Orange River would have been too low for spawning in early spring. Cambray (1984) has also suggested that the rare riverine minnow, Barbus hospes (Namaqua barb) in the lower Orange River has actually benefited from more constant flows since regulation. In contrast, the more pool-loving minnows such as *Barbus paludinosus* and *B trimaculatus* have reduced populations correlated to constant flows. Below the P K le Roux Dam, hydroelectric discharges can result in the river rising and falling two metres in a short period of time (up to 400 cumecs, sometimes for only a few minutes). These rapid water level and flow fluctuations expose adhesive eggs (such as those of the sharptooth catfish, *Clarias gariepinus* and the substrate spawning cichlid, *Tilapia sparrmanii)* or wash out nonadhesive eggs (such as those of the Orange River labeo, *Labeo capensis)*. In contrast, *Pseudocrenilabrus philander* is a mouth brooder and can move its eggs. Skelton and Cambray (1981) recorded that *P philander* was more abundant in the lower Orange River than *T sparrmannii* which would be a direct result of river regulation. The riffle inhabiting rock-catfish, *Austroglanis sclateri* (a Red Data species) could be used as an indicator species for instream flow recommendations in the Orange River because their habitats are sensitive to stream regulations.

Tomasson et al (1984) found that the unseasonal releases of cold water to the Orange River below the Hendrik Verwoerd Dam caused poor reproductive success of the smallmouth yellowfish, *Barbus aeneus*, and subsequent poor recruitment to commercial fish stocks. Water discharged from a thermally stratified impoundment can either be warmer or colder than natural riverine temperatures. These temperature changes can result in disruption of the life cycles and dynamics of downstream biota as well as changes in community structure.

In the Outiniqua-Langeberg mountain areas, in the rain-shadow zone of the little Karoo, there are normally perennial streams which are completely abstracted. The Red Data species, the slender redfin (*Barbus tenuis)* only occurs above weirs. Below these weirs, abstraction results in total absence of flow at certain times of the year. These populations are now isolated from each other and their long-term genetic viability must be in some doubt.

There is concern about fish populations immediately below the Braam Raubenheimer storage dam, on the Incomati River system. At the end of winter, which should be the dry season, there are unseasonal floods due to the release of water for Lowveld irrigation. In addition, peak summer floods are now controlled which has enabled several fish species to invade the river below the dam, eg *Kneria auriculata*, *Amphilius natalensis* and *B anoplus*. *Tilapia sparrmanii* has increased in numbers and it is foreseen that some species such as *Chiloglanis bifurcus* may disappear if the managed low summer flows persist. Both *K auriculata* (rare) and *C bifurcus* (vulnerable) are Red Data species (Skelton 1987).

River modification can also have an effect on alien angling species. In the Umzimkulu, spawning sites are sometimes exposed in mid to late June because of water abstraction. The result is that many of the eggs and young of winter breeding species such as rainbow trout (*Parasalmo myukiss)* are desiccated. The poor recruitment reduces the number of fish available for the angler.

Although most South African rivers have poorly developed floodplains, several rivers such as the Pongolo have important floodplain fish populations. A total of 48 fish species have been recorded from the Pongolo floodplain (Heeg and Breen 1982). Several of these species are important as human food and are exploited at a subsistence level by the local population. The Pongolo pans have been extensively studied since the late 1960's (eg Pott 1968; Coke 1970; Kok 1980; Heeg and Breen 1982; Stallard et al 1986). The pans are now strongly influenced by the manipulation of the Pongolapoort Dam discharges and investigations of the effects of different flood levels have led to an understanding of the water requirements (amount and timing) necessary for the functioning of the floodplain fauna and flora. As an ecosystem, the Pongolo floodplain is totally dependent on sufficient water and its timely release from the Pongolapoort Dam to maintain its integrity and to ensure the continued survival of its flood-dependent biota.

Kok (1980) studied 13 fish species in the Pongolo floodplain pans and described their life history and their dependence on flood conditions to trigger migration and spawning. To inundate the floodplain to high water level requires a water release of approximately 126×10^{6} m^{3} yr ^{1} which is almost 15% of the mean assured yield from the dam (Kok 1980). Heeg et al (1980) suggested a system of temporary weirs placed strategically along the river which may possibly still give satisfactory flood conditions and would demand an estimated release of only 42×10^{6} m^{3} yr^{-1} of water from the dam.

Kok (1980) noted that the most important aspect demanding immediate attention was to find a suitable flooding regime, whereby as large an area as possible of the floodplain could be inundated during summer to accommodate fish spawning, and for sufficient duration to facilitate flushing of accumulated salts and for assimilation of the hot-lines energy input. Such fish species as the tigerfish and catfishes appear to be totally floodplain-dependent. These floodplain dependent species will gradually disappear from the system without controlled floods from the Pongolapoort Dam.

FLOW ASSESSMENT METHODS BASED ON FISH DATA

Over the past 30 years a number of methods have been developed to quantify the relationship between flow variation and the suitability of fish habitat for passage, spawning, incubation and rearing and to other instream flow uses (see Estes and Orsborn 1986; Bartholow and Waddle 1986). Present guidelines for selecting one of the many methods to determine instream flow requirements and evaluating the results from a particular method are inadequate (Peters 1982; Estes and Orsborn 1986). Many of the methods were initially designed for salmonids in North American coldwater streams, and have a single-species approach.

In general, instream flow methods are based on three principal components. First, the physical criteria which include geomorphic and/or hydrological data to predict a range of hydrological and related conditions such as water depth and velocity as a function of flow. Secondly, there is a fish habitat criteria analysis which involves the determination of the behavioural responses of fish to channel morphology or flow related variables. Lastly, there are fish habitat projections, which combines the first two components to project the availability (area) and/or quality of habitat for the species or stage (eg spawning) under investigation, as a function of flow (Estes and Orsborn 1986).

Wesche and Rechard (1980) summarized and assessed a range of instream flow methods for fisheries (their Figure 6.1). One group of methodologies is based on manipulation, synthesis and interpretation of streamflow records, these are the "office" methods. The other group of methodologies is based on the collection of field hydrological data and the subsequent application of available fish habitat criteria to determine flow/habitat relationships, these are the "field/office" methods. The majority of these methods were developed for salmonids in cold-water streams and are not applicable to South African conditions. The first group requires low time and financial inputs while the latter yields a flow recommendation of higher resolution and at least partly considers the biological needs of the fish population involved. "When possible, field methodology should always be preferred over strictly office methods" (Wesche and Rechard 1980). Recent work on evaluating several methods in one system substantiates this claim (Estes and Orsborn 1986).

Mosley (1985) divided the large number of methods for analysis of instream flow into three main groups (Table 6.1). The simplest is the 'discharge methods group' which is similar to the office group of methodologies of Wesche and Rechard (1980). The best example is the Montana Method (Tennant 1975, 1976) (Table 6.2). The 'habitat methods' are the second type (Table 6.1). These methods consider the relationships between discharge and stream habitat character, but with little consideration of the requirements of instream uses (Table 6.2). The third group of methods are called the 'biological response methods' (Table 6.1). These have been developed from the second group and employ suitability criteria for selected species or instream uses (Table 6.2). The most sophisticated are the network habitat analysis and instream flow incremental methodologies (IFIM) (Table 6.2).

The predictions resulting from IFIM analysis can be used in developing management recommendations to preserve, restore or enhance fish habitat. The IFIM is versatile as it is designed to give as sophisticated an analysis as the decision-making process demands. This method has been extensively investigated and applied both in America and New Zealand (Orth and Maughan 1981, 1982; Glova 1982; Jowett 1982; Mosley 1983; Moyle et al 1983; Tsai and Wiley 1983).

Bartholow and Waddle (1986) point out that the methods used in network habitat analysis provide a consistent framework for communication among investigators and decision-makers which helps everyone concerned to understand the problem and identify and evaluate the alternative scenarios.

The value of network analysis is that it takes into consideration the possibility that multiple developments, such as the many impoundments and weirs along the Orange-Vaal River system, may have cumulative and synergistic effects on habitats distributed throughout the basin. Network analysis is also designed to take into consideration the effect of water

TABLE 6.1 Comparison of the three major groups of methods used for instream flow analysis

Major method group	Distinguishing characteristics	Cost/Benefits	Limitations and applicability in South Africa
Discharge methods (office) eg Montana method (Tennant 1976) 11% for conservation (Roberts 1983)	- office approach - simplest - requires little knowledge of actual instream uses. - requires flow data or synthesize from rainfall records - little consideration of physical character of stream - no need to visit river - no geomorphological or biological data needed	- low cost - interpretation should be - based on expert opinion on relationship between biota, habitat and discharge.	- should be restricted to reconnaisance level planning. - should be modified to include seasonality in South Africa. - uncritical application leads to incorrect decisions.
Habital methods (office plus field) eg Swank and Phillips 1976.	- collection of geomorphological and hydrological data at same time. - establishes relationships between discharge and stream habitat character. - measurements made at one flow and predicted at other flows. - modification does multiple flow measurements.	- medium cost - also requires biological expertise to assess flow changes.	- little consideration of requirements of instream uses. - may be useful as interim measure while biological data is collected.
Biological response methods. eg IFIM (Bovee 1986)	- includes habitat method as well as suitability criteria for selected species or instream uses. - requires most detailed hydrological, geomorphological and biological information.	- high cost - highest accuracy - as with other 2 methods biological expertise, as well as the biological data, is still required for interpretation.	- use for Red Data Book species. - at present there is a lack of the required biological information.

TABLE 6.2 Applicability of several instream flow methods under South African conditions

Method	Distinguishing characteristics	Cost/Benefits	Limitations and applicability
Discharge group			
1. One-flow method (Sams and Pearson 1963)	- based on aerial photographs - no other records available	- relatively inexpensive	- useful only at early planning level - designed for optimum flow for spawning salmonids - not applicable
2. Tennant method or Montana method (Tennant 1975, 1976)	- simple - quick and easily applied - based on mean annual flow - 8 flow classifications each a percentage of MAF - 7 for fish and wildlife habitat - 1 for flushing flow (200% of MAF) - select desired classification (%) and multiply by MAF	- low time and personnel inputs. - calculations from existing database.	- percentages not universal - since flow fluctuations and seasonality are not accounted for, it is of little use for South Africa - however, method can be modified to account for seasonality - reconnaissance level surveys - Tennant (1976) recomended field evaluations of selected percentages - uncritical applicaton can lead to incorrect decisions
3. Hoppe method (Hoppe 1975)	- based on percentile levels of flow duration curve and various life history characteristics of fish species present	- quick if flow data and some biological data available	- South African modification may be useful
4. NGPRP method (NGPRP 1974)	- based on existing hydrological records - estimates stream flow needs based on average hydrological conditions for each month - has provision to estimate flow needs for extremely dry period	- low cost - quick	- applicable for South Africa as it includes seasonality
Habitat group			
1. Maximum spawning area flow (Orsborn 1982)	- estimates discharges at which the maximum spawning area occurs from existing information on basin and streamflow characteristics	- medium cost - quick	- limited capability for assessing flow recommendations because they only evaluate one flow condition - could be used to assess spawning area available for endangered fish eg Barbus Capensis
Biological response methods			
1. A wide variety of methods (see Wesche and Rechard 1980, their Figure 3).	- developed for single species - mainly salmonids in cold-water streams	- methods vary widely in manpower and data requirements	- not applicable in South Africa

TABLE 6.2 (Continued)

Method	Distinguishing characteristics	Cost/Benefits	Limitations and applicability
2. Idaho method (White and Cochnauer 1975)	- determines maintenance flows for fish passage, spawning and rearing in large rivers - workers must identify stream reaches which are critical areas for spawning, rearing and passage - uses Water Surface Profile computer programme - can create habitat discharge plots from combining habitat criteria and hydrological data.	- high cost of fieldwork - high accuracy	- possibly useful for establishing discharges for fish passage, eg mullets in the eastern Cape.
3. Bovee method (Bovee 1975)	- assess minimum discharge for warmwater fisheries for fish passage, spawning and rearing - field transects done in critical areas for fish passage, spawning, incubation and rearing. - wetted width, depth and velocity readings taken.	- high manpower requirements - accurate for single species.	- method to calculate incubation flow is weak (ie 2/3 of spawning flow) - single species orientated - could be used for single endangered fish species - improvement (see Washington method (Collings 1972, 1974)) which requires assessment of different discharges at transects.
4. Instream flow incremental method (IFIM and physical habitat simulation system approach (Bovee 1982, 1986)	- this is one of the most sophisticated methods. - quantifies habitat capable of supporting targeted species as a function of selected flows - combines open channel hydraulics and behavioural responses of fish.	- requires hydrologist and biologist. - resource intensive. - requires extensive hydraulic data collection to simulate available hydraulic conditons (physical model) - requires fish habitat criteria.	- able to evaluate a series of specified flows within range of hydrological model. - use on target species, eg endangered fish. - use when competition for water is high. - problem with braided channels.
5. Network habitat analysis (Bartholow and Waddle 1986)	- evaluation of entire river basin (=network) - predicts habitat responses to alternative management regimes - input biological and hydrological components - includes micro- and macro-habitats.	- high resource requirements	- provides best framework for communication between investigators and decision-makers - considers problem of multiple projects which may have cumulative and synergistic effects on habitat eg Orange-Vaal River impoundments and weirs - considers effect of diversion facilities (eg Lesotho Highlands Scheme).

diversion facilities which can shift flows from one tributary to another (the Lesotho Highlands scheme is a good example). In addition, the effects of combined reservoir operations (eg Verwoerd and P K le Roux Dams), can be directly shown using network models. One very important aspect of the IFIM is that, unlike other methods, it allows for incremental evaluations of any flow within the calibration range of the hydrological model developed for the site. In the United States it has been shown that in some cases, just having a model that provides an estimate of cause/effect relationships has proven to be a powerful ally in negotiating water and habitat management issues.

In general, these models assemble the appropriate knowledge in an organized manner and provide a dependable approximation based on the best information available. At the present time in South Africa there would be problems using these models, in that the information is not available to make the models comprehensive and detailed enough to represent how the natural systems function. However, the IFIM advocates warn that the models should not be too complex or data-intensive to be applied. The IFIM or modifications of this network system should be a goal for quantifying instream flow requirements of fish in South African rivers. In the interim we will probably have to modify one of the other existing, less data-intensive approaches.

The requirements of most flow assessment methods based on fish data, consist of habitat criteria defined in terms of the water depth, velocity and substrate requirements of a species through all its life history stages. Curves are then drawn for each species, identifying the range and preference of each life history stage for the hydrological parameters of depth and velocity, as well as substrate and temperature.

Estes and Orsborn (1986) caution investigators, and note that one should review basic hydrological characteristics of a study area to assess whether the hydrological components of an instream flow analysis fall within the expected range of natural hydrological conditions. It is worth noting here that it is the dry end of the range that is important, ie the drought years. Also the biological criteria must be representative of the species and system evaluated (Hunter 1973). Therefore each system must be studied in its own context as generalizations will probably give unreliable flow predictions.

HYPOTHETICAL FLOW MODIFICATION SCENARIOS AND RESPONSES

We have considered above how one would obtain an instream flow recommendation for the following three categories of rivers or river zones.

1) First/second order streams
2) Perennial streams (mid-order)
3) Intermittent streams

It must be stressed that the figures used in this section are only hypothetical and should not be used for real systems. We also fully realize that it may be dangerously misleading to make generalizations when there is great bioclimatic variation between river systems. Thus the following three cases are given to stimulate thought and to present rough guidelines for instream flow management.

First/second order streams (ie mountain streams)

Examples are:

Cape Province - Wit River (Gamtoos system)
Rondegat River (Olifants system)
Natal - Umkomaas River (Vergelegen Nature Reserve)
Transvaal - Upper section of Blyde River (Farm In-die-diepte)

This category of stream has riffles connecting pools. The fish community will be simple, usually only a few species. These species can be divided into small residents (less than 15 cm total length) such as the redfin minnow, *Barbus afer* in the Wit River, and medium sized migrants (less than 40 cm total length). The migratory fish will usually be breeding adults moving into and out of the area on a seasonal basis from riffle areas lower down in the system.

The habitat most sensitive to flow manipulation in this section of the river is the riffle areas. To maintain species living in this habitat an average depth of 15 cm is suggested (Figure 6.2). Seasonal flooding is also necessary to enable fish to move up the river, to flush the spawning beds and to provide enough flow to maintain the habitats for embryo and larval fish development.

A minimum-management approach is recommended for flow regulation in these first/second order streams. In many cases these rivers are fairly inaccessible or located in protected Mountain Catchment Areas. No flow regulation is necessary unless the riparian vegetation has been severely disturbed. The main problems for these streams are small weirs and water abstraction from pools which could lower the riffle depth below 15 cm.

Scenario: If mean water levels are lower than 15 cm in riffles, the sensitive riffle-loving species die out first. There will be reduced or no spawning habitat for migrants and thus recruitment will be poor to the lower sections of the river. In addition, there will be a reduction in embryo and larval fish habitat. Man-made barriers such as weirs might require design alterations to allow fish migration.

Perennial streams (mid-order)

Examples are:

Cape Province - Groot River (Cockscomb Forest area) Gamtoos system
Natal - Umkomaas River (Hella-Hella area)
Transvaal - Elands River (Crocodile-Incomati system)

This section of a river is characterized by deeper pools and connecting riffle areas. Again, management for a specified riffle depth will accommodate the requirements of pools. The fish community is now a multispecies complex with lentic components (small and large fish) such as cichlids, clariids and certain cyprinids and many small species components such as catlets and certain minnows.

In this section there is a good chance of medium to large dams being built for water storage. Management is therefore likely to have greater impact here than in the first case. The riffles are again identified as the most sensitive habitat and therefore the species that inhabit this area, such

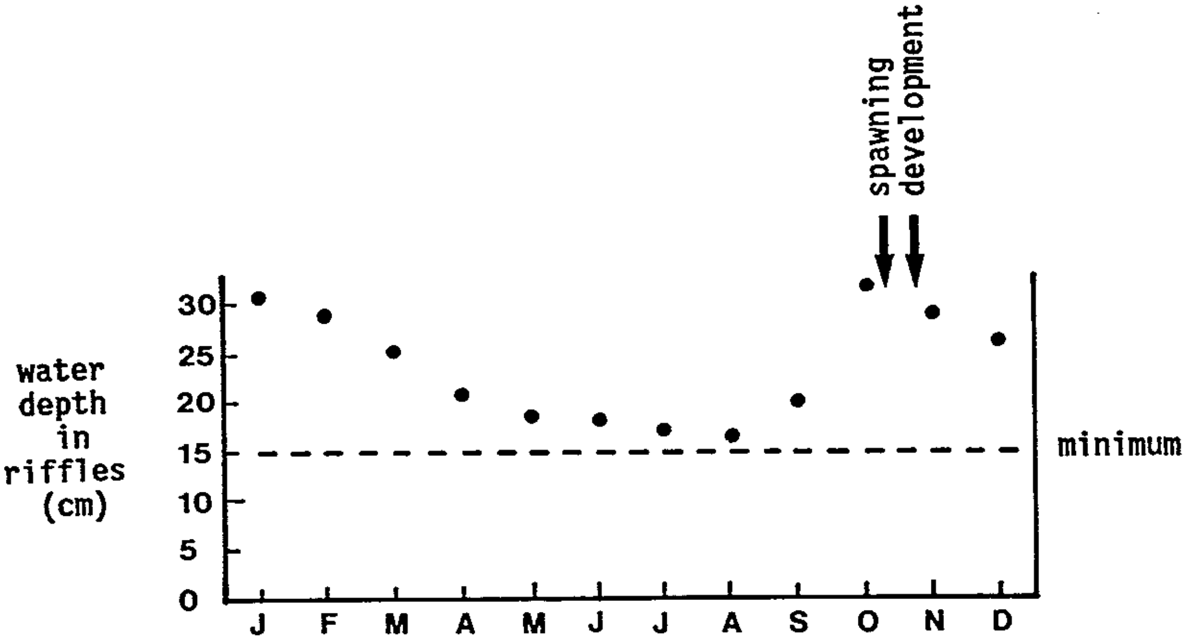

FIGURE 6.2. Hypothetical water depths required in the sensitive riffle areas in first/second order streams, on a seasonal basis, summer rainfall area.

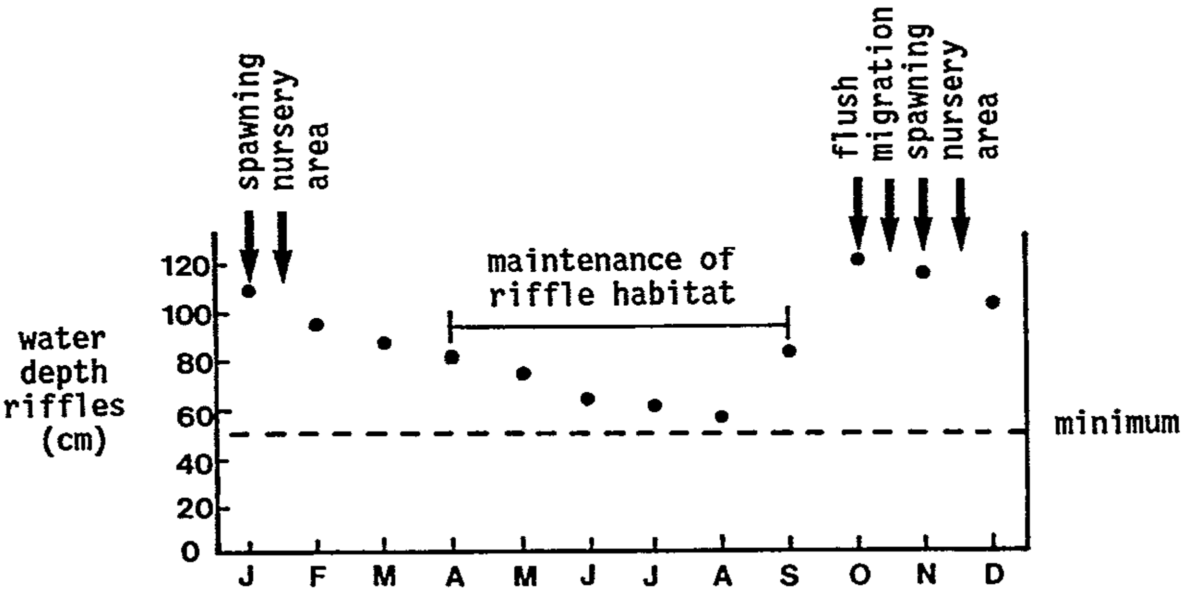

FIGURE 6.3. Hypothetical water depths required in the sensitive riffle areas of perennial (midorder) streams, on a seasonal basis, summer rainfall area.

as *Amphilius* species and *Chiloglanis* species are termed sensitive (indicator) species. An average depth in the riffles of 50 cm is recommended (Figure 6.3), which will maintain the riffles for the breeding and survival of sensitive species.

The primary management concern would be to keep the river perennial. One also needs to know the minimum stimulus flow (MSF) that will allow species to move laterally or longitudinally for spawning migrations. Floods, simulated if necessary, will inundate terrestrial vegetation and provide suitable spawning areas. These flood waters must be of adequate duration to provide about 10 cm of water on the spawning grounds while embryos are developing and until they become mobile larval fish.

The biologist will require time to study this area due to the complexity of the system and the impacts of management options. It is recommended that the instream flow incremental methodology (IFIM) be investigated and used in this area on one or two of the sensitive species (including studies on all their life history stages). This information will help to generate real instream flow recommendations for these species.

Intermittent streams (ie nonperennial)

Examples:

Cape Province	- Groot River (Karoo area) (Gamtoos system)
Natal	- White Umfolozi
Transvaal	- Limpopo

It is assumed that in this case one is dealing with naturally seasonal systems and that flow is intermittent and irregular. The main management option is to maintain pools as refugia, and there is little concern for the riffles except during the breeding season (Figures 6.4a and b). If there are any short-lived species (ie less than three years life span) which spawn only in the riffle areas, then there should be a 20 cm depth in the riffles during the breeding season at least once a year for at least two weeks. In normal years the managed riffle flows could be more frequent during the spawning season to allow for multiple or serial spawning.

This example provides a good opportunity to simulate nature, ie the flow regime that would naturally occur in any specific year. The biologist would have to assess whether the impoundments act as refugia for all species. For the riverine pools a management strategy would be to release water to top-up pools along the system, not to create riffle areas (except during the spawning season). This is completely unlike the previous two cases. Minimum pool depth should be one metre but in this case one also has to consider adequate volumes. Pools of at least 50 m in length, with a width of at least 10 m, should be maintained. The release of water should be gradual, but of sufficient volume and duration to fill all the pools.

The fish community consists mainly of generalists, which are also opportunists. The concern of biologists is that if the "top-up" of refuge

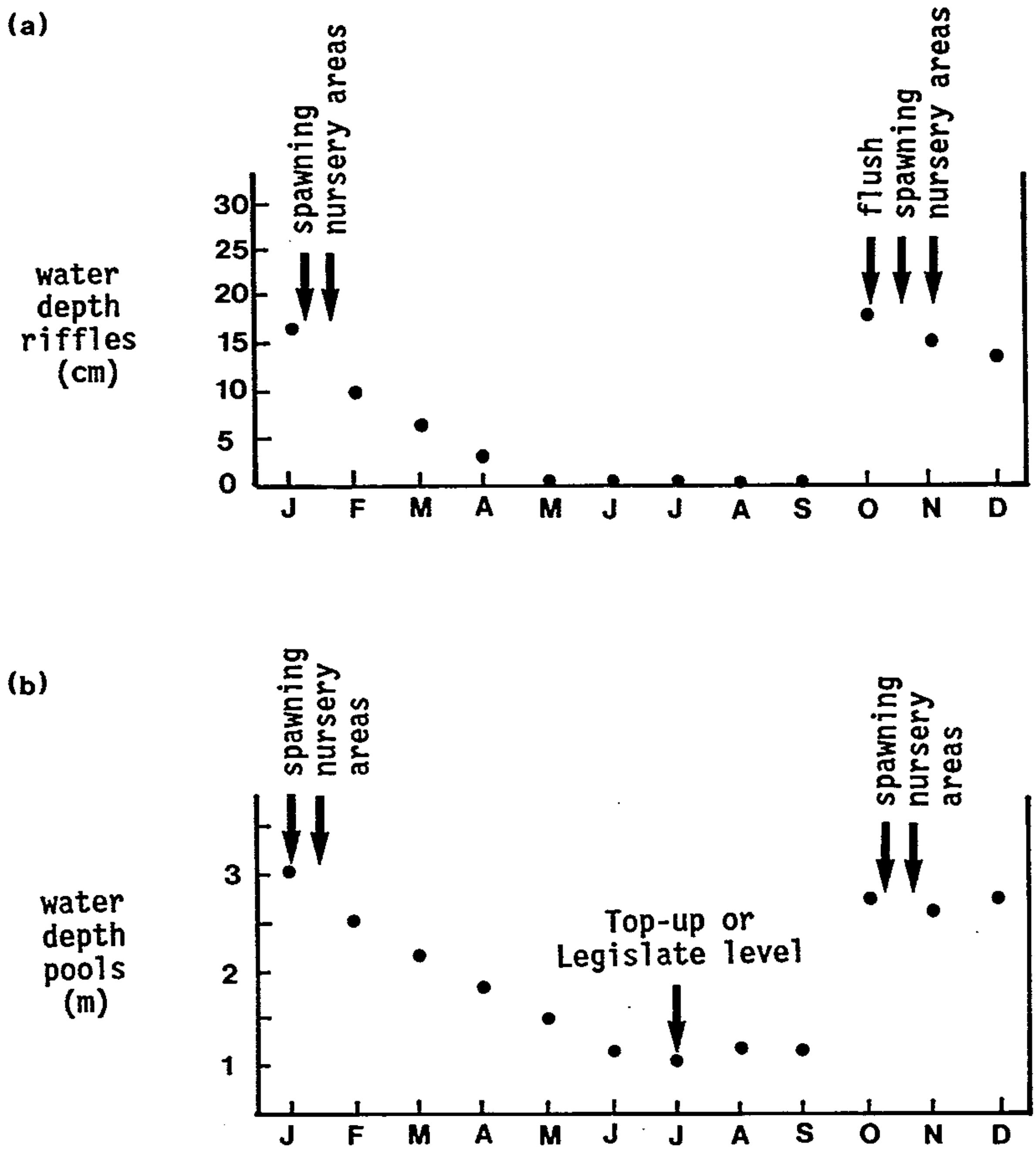

FIGURE 6.4 Hypothetical water depths required in intermittent streams on a seasonal basis - (a) riffles (b) pools.

pools is not possible during drought years, then farmers should be prevented from pumping them dry. To facilitate this, certain pools in the river under question should be identified as "Legislated Pools", where water abstraction would be prevented below a certain level. This one could call the TULP method (for, Top-up or Legislated Pool) which would ensure refuge areas and permit the biota to survive in normal years by topping up, and in dry years by legislative means.

MANAGEMENT RECOMMENDATIONS AND OPTIONS

If instream flows are to accommodate the ecological requirements of river biota then the first management requirement is to invite ecologists to join the planning team at an early stage in all scheduled developments.

In impounded rivers, it is possible to simulate the natural flow regime on a daily, seasonal or annual basis, as well as on a drought/wet cycle. It is up to stream ecologists to predict the consequences of over exploitation (Cambray et al 1986). Stream ecologists require biological information on the particular system before they can suggest the amount and timings of releases to minimize ecological impact.

The river manager might consider a particular instream flow pattern to be of greater economic or recreational value than a simulated natural flow pattern (Roberts 1983). A solid information base is needed before these decisions can be made with confidence.

The demands on water resources may result in flows that are insufficient for the critical life stages of certain species. Conservation agencies, in deciding whether to translocate rare or endangered species, should if possible conduct impact studies on the proposed recipient streams before the translocation takes place.

The stream ecologist may suggest the development of fish hatcheries to replenish fish stocks in a regulated river. An alternative option, and possibly a more economical one, would be to adjust the instream flow to suit the species' requirements rather than to build and operate a hatchery. Tomasson et al (1984) made such recommendations to improve the *Barbus aeneus* habitat below the Hendrik Verwoerd Dam.

The stream ecologist may also recommend habitat improvement schemes which would increase breeding sites and nursery areas in rivers, where these areas have been reduced because of altered flow regimes (Gore 1985). Portable weirs for filling pans have been suggested for the Pongolo River floodplain (Heeg and Breen 1982).

Careful siting of structures such as dams, weirs, tunnels etc may obviate their consequent ecological impact. Damming a section of river where a Red Data species occurs may be avoidable by choosing an alternative site.

If any Red Data species is put at risk because of a decrease in water flow in a river the conservation authorities could initiate a voluntary conservation programme with adjacent landowners. If this is not feasible, then an alternative would be to purchase the aquatic habitat in order to protect the endangered species. Cost is obviously a limiting factor.

RESEARCH AND MONITORING NEEDS

The existing instream methods should be evaluated to determine their applicability to South African rivers. Short courses are given on the use of these methods at Colorado State University. It would be valuable for a South African stream ecologist to attend these courses to assess the transferability of the American methods.

It is necessary to identify all local fish species with a low tolerance to habitat change, ie adversely affected by river regulation. The Red Data Book (Skelton 1987) is a step in the right direction and provides guidelines on fish species and habitats which require urgent study.

The more base line information there is on fish species and other macrobiota, the better will be the output of the methodology (ie the instream flow recommendation. More information is required so that tables similar to Tables 6.3 and 6.4 can be compiled. These tables include basic life history information as well as habitat criteria, such as depth, flow velocity, temperature and substrate required for spawning. Cover is also a habitat parameter of paramount importance and is directly related to stream flow. Once the data are available then curves for each species may be drawn to identify the habitat preferences for each life history stage (ie spawning, incubation, embryos, larvae, juveniles and adults).

It is sometimes assumed that flows which are adequate for spawning are also adequate for incubation (Stalnaker and Arnette 1976). Is this true for South African fish species? Fieldwork is required at spawning and incubation sites to test this assumption.

The Tennant Method (Tennant 1976) recommends 200% of the average flow as an adequate flushing flow for most streams in North America, but there are no data to support this suggestion (Wesche and Rechard 1980). Stream ecologists in South Africa must establish how important flushing flows are to stream quality. If they are important then a methodology should be developed for recommending flushing flows for streams that are to be subjected to water development projects. Spring flushing flows are probably necessary in certain systems for stream quality, to clear silt, organic debris and in some cases toxic substances. The Drakensberg minnow, *Oreodaimon quathlambae*, which is listed as endangered (in danger of extinction) by Skelton (1987), breeds in midchannel, amongst boulders and requires a clean gravel/boulder substrate for breeding and incubation (Cambray and Meyer 1987). Flushing flows may be necessary below the reservoirs in the Lesotho Highlands scheme to clean gravel beds for successful breeding of this minnow.

The habitat requirements of early life history stages are usually distinct from those of adult fish. In the United States, it was not until the recent interest in the impact of nuclear power stations that all stages of fish were studied. It was realized that there were very little data on the early life history stages of fish, especially those from lotic environments. There is a distinct lack of specific ecological data for most of the early life history stages of freshwater fish in South Africa (Cambray 1983, 1985b). In many cases it is not known where the species spawns. A solid base of information is required on these highly vulnerable early life stages. Loss or alteration of larval fish habitat by installation and operation of dams or major water withdrawals is the most typical environmental impact.

TABLE 6.3 Life history information of six southern African freshwater fishes

Species	Distribution (specific system)	Habitat (adult)	Spawning time	Spawning temperature °C	Fecundity -greatest-	Egg incubation time - days
Barbus aeneus	Orange River	Pools	October to March	19 to 24	90 000	Not known
Barbus natalensis	Tugela River	Pools	Not known	Not known	Not known	6 at ± 18°C
Barubs afer	Wit River	Riffles and pools	October to February	18 to ?	1 300	3 at 20°C
Clarias gariepinus	Orange River	Pools	October to February	20 to 30		1 at 19-24°C
Chiloglanis anoterus	Sabie River	Riffles	November to April	20 to ?	420	Not known
Kneria auriculata	Crocodile River (Incomati system)	Pools and small Riffles	Not known	Not known	Not known	Not known

TABLE 6.4 Depth, velocity and substrate spawning criteria of six southern African freshwater fishes

Species	Depth (cm)	Velocity (cm/sec)	Substrate	Remarks
Barbus aeneus	Not known	Not known	Gravel	- Quantitatively we know very little about spawning criteria for our fish species.
Barbus natalensis	Not known	Not known	Gravel	
Barbus afer	10 to 20	Not known	Boulders	
Clarias gariepinus	10 to ?	0 to ?	Boulders and grass	
Chiloglanis anoterus	20?	19?	Boulders	
Kneria auriculata	10 to 20	14	Boulders (small)	

The NGPRP Method (NGPRP 1974) of assessing instream flow requirements assumes that water presently flowing past recording gauges represents the flows supporting present levels of aquatic resources. It is probable that this is not necessarily so. In South Africa, some of these resources are already stressed, and the trend or rate of change of fish communities is poorly known. To continue with the present flow regime in these cases may result in the loss of some presently threatened species.

The opportunity exists to study streams in which the river ecosystem has not been considered and the river has been used merely as a cheap channel to transport water from one offstream user group to the next, eg the Eerste River in the south-west Cape.

Is the best instream flow model one that mimics nature, given that there is now only part of the natural volume of water available for instream uses?

To what extent do fish species adapt to habitat changes imposed by river regulation? This is a key question to be answered in pursuit of the goal of maintaining the diversity of fish communities in regulated rivers.

The following two hypotheses are suggested as general themes for testing by means of both field data collection and experimental research techniques:

i) All macrobiota dependent on rivers, including mammals, birds, reptiles, amphibians, invertebrates and plants will generally be accommodated by the flow requirements allocated for the survival of fish communities. Also within the fish communities, it is probable that certain key or indicator species may be present.

ii) Certain species, by reason of their greater sensitivity to habitat change, may be termed key or indicator species in monitoring for change in biodiversity in rivers.

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CHAPTER 7. WATER QUANTITY REQUIREMENTS OF RIPARIAN VEGETATION AND FLOODPLAINS

K H Rogers and D W van der Zel

INTRODUCTION

Riparian vegetation plays a direct, key role in the functioning of river systems through the effects it has on water quality and flow rate. Riparian vegetation colonizes the source areas of streams, river banks and floodplains and in these areas it retards the flow rate, improves water quality, stabilizes river banks, controls water drainage and plays a major role in water use through transpiration. The riparian zone is particularly susceptible to encroachment by alien plants which variously modify its role in catchment process.

Studies of natural riparian vegetation are few, especially in semi-arid areas such as occur over most of southern Africa, and the understanding of their water requirements is extremely poor. As a result, there is no established theoretical basis on which to develop useful discussion in this chapter. There is also little point in attempting to review the literature. Instead, the intention of this chapter is to develop a conceptual framework for addressing problems of the riparian zone in general and its water requirements in particular.

The approach adopted here, after proposing a definition and basic description, is to present preliminary conceptual models of the determinants of the water balance and vegetation communities of riparian zones. These models provide a basis for describing the many interactions between the biota and environmental factors such as hydrology and fire. It is foreseen that more detailed submodels of various component processes can also be developed to provide clearer, testable hypotheses for research purposes. Refinement and quantification of the models will ultimately help the manager in his task of developing techniques and of assessing the impact of management actions.

Definition

The riparian zone of a river is the three dimensional strip along the banks of the channels and in places the wider floodplain, that is influenced by riverine hydrological processes. These influences are derived from those river channel processes that have been described in some detail in earlier chapters.

The definition adopted is:

The riparian zone is that area of a river or floodplain in which water availability, determined by fluctuations in river flow or floodplain level, regulates plant growth and species distribution.

The riparian zone should be distinguished from the phreatic zone, a concept used by forest hydrologists to describe the area adjacent to water courses in which "plants (trees) have constant access to freely available water" (Bosch and Versfeld 1982).

GEOMORPHOLOGY

The characteristics of the riparian zone depend on the geomorphology of the valley and the nature of the substratum over which the watercourse runs. Where the slopes are flat and the soils have a high water holding capacity the riparian zone will be wide, such as a floodplain or permanent marsh. On steeper slopes and with a rocky or highly porous substratum, riparian vegetation will be little more than a narrow strip along the edge of the water channel.

The ecological development and significance of the riverine strip is usually related to stream order, being more developed and biologically diverse along mature rivers (stream order >5). Exceptions to this rule of thumb are the source-area sponges and ground water forest patches on many of our first order streams.

The possible combinations of river morphology and soil type are too great to illustrate fully but some examples are given in Figure 7.1. An example of type 1 would be a first or second order stream in deep volcanic ash soil (Pereira et al 1962); type 7 a floodplain on a graded river such as the Pongolo (Heeg and Breen 1982) and type 8 a braided channel system such as the Sabie River flowing through the Kruger National Park. In the latter system, mounds between channels are colonized by riparian vegetation similar to that on the fringing floodplain.

VEGETATION

Riparian zones vary from narrow, grass or sedge covered strips along the banks of deeply incised rivers which seldom overtop their banks, to floodplains adjacent to large mature rivers which have attained grade and regularly overtop their banks. Floodplains may be homogeneous grassland or forest strips or highly heterogeneous mosaics of grassland, forest, swamp and open water as occurs on the Pongolo River floodplain (Figure 7.2).

All substantial riparian zones may also be classified as wetlands. Swamps, marshes and vleis in which the water supply is at least temporarily in contact with the river, fall within this category. Water availability in the riparian zone thus ranges from permanently inundated or permanently waterlogged soils, to periodically inundated or waterlogged soils, at least to the depth of root penetration.

Some riparian zones, especially in semi-arid areas, experience short seasonal floods and long dry seasons when water availability is low, at least for shallow-rooted plants (Furness 1981). Thus a continual supply of water is not a diagnostic feature of riparian zones as is the case with phreatic zones. Riparian plant communities and species differ widely in their forms, their response to water supply and their life history characteristics (Menges and Waller 1983) but comprise essentially emergent

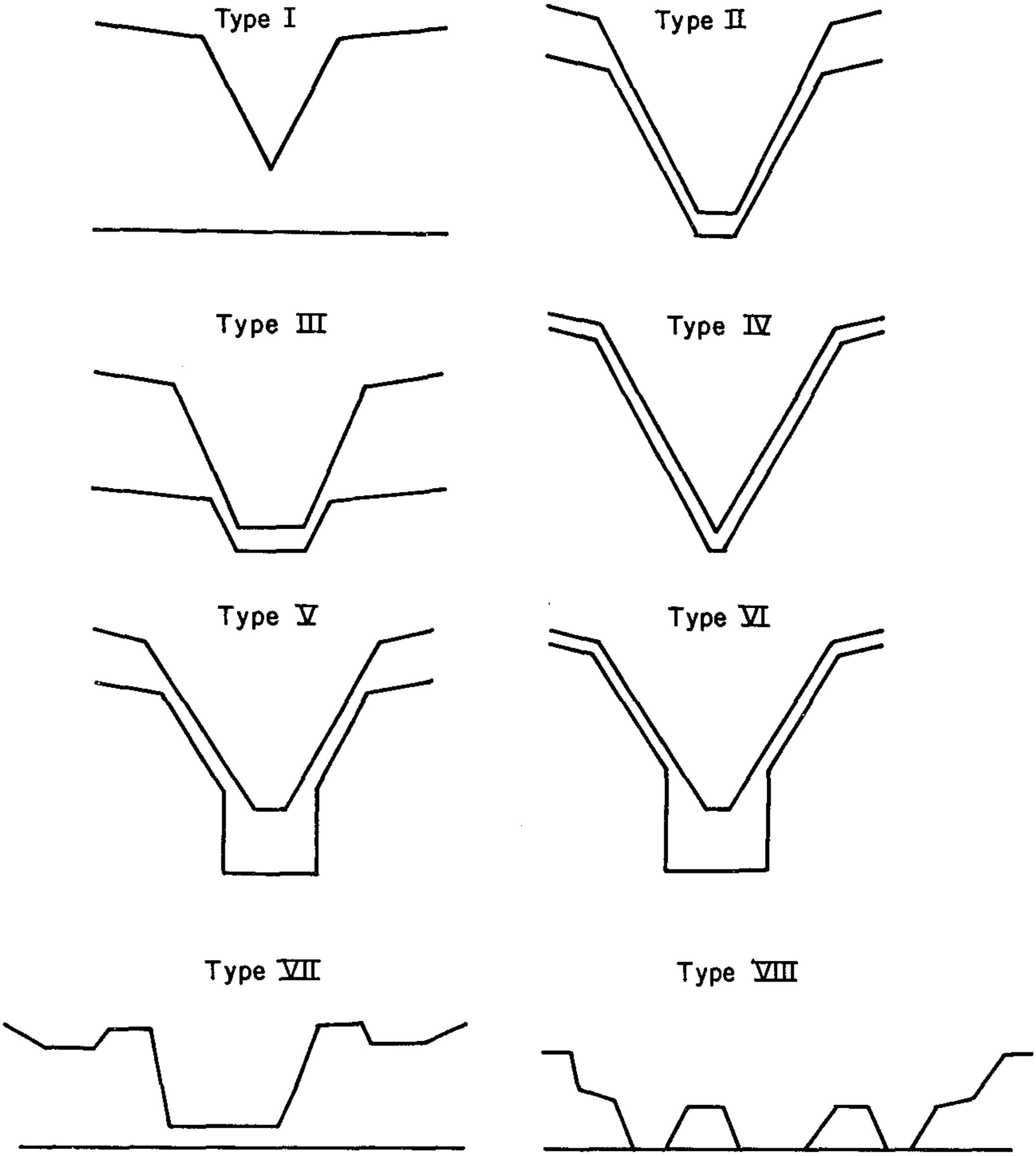


FIGURE 7.1. Examples of river channel and soil mantle cross-sectional morphology.

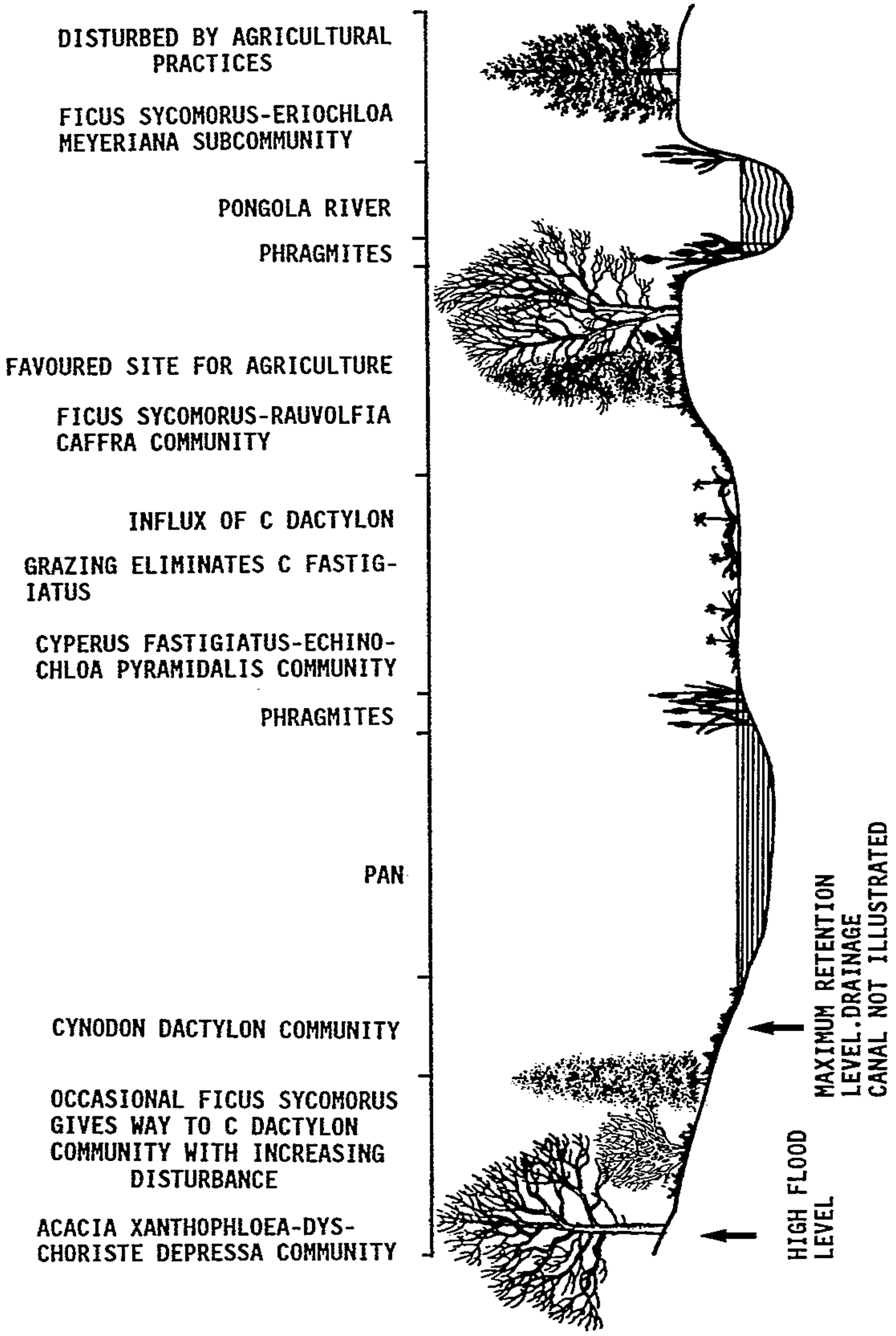


FIGURE 7.2 Cross-section of the Pongolo River floodplain showing the distribution of seasonally flooded plant communities (after Furness 1981).

aquatic or inundation tolerant species. The riparian zone may be devoid of vegetation on rapidly eroding or building river banks.

River bank morphology and substratum are important factors affecting the width of the riparian zone and species distributions change markedly with distance from the river in response to changes in depth to the water table and inundation. This concept has been well illustrated by Menges and Waller (1983) for a temperate forest system and by Furness and Breen (1980) for the subtropical system of the Pongolo River floodplain (Figure 7.1). Riparian vegetation will also change with river size as the gradient and local geology change from the headwaters to the coast (Day et al 1986).

Man has altered much of the natural riparian vegetation, by planting agricultural crops, orchards and plantations and other forms of development. As these monocultures and alien communities can and should be strictly controlled by legislation (both by the Conservation of Agricultural Resources Act and the Forest Act), the balance of this paper is concerned with natural riparian vegetation along and in river channels and floodplains.

In the recent review of biological invasions of southern Africa (Macdonald et al 1986) numerous authors noted that riparian zones are particularly susceptible to encroachment by invasive plant species. Macdonald and Richardson (1986) suggest that seed dispersal by stream flow is a major cause and Brown and Gubb (1986) demonstrate that seasonal watercourses are by far the most susceptible to invasion of all habitats in arid areas, other than those influenced by urban and agricultural development.

FUNCTIONS OF THE RIPARIAN ZONE

Decisions by water resource managers on the necessity or otherwise of providing water to sustain riparian zones must be made with the knowledge of the role which the zone plays in the river ecosystem and the catchment as a whole. The specialized communities which comprise riparian zones perform a variety of general functions which include the following:

Flow based functions
1) control of water velocity, slowing and spreading flood waters
2) control of erosion of riverbeds and banks
3) water retention, thus increasing evapotranspiration and groundwater recharge

Physico-chemical functions
4) increased deposition rate, of organic and inorganic suspended solids
5) nutrient retention, increased by means of 3 and 4 above
6) sink for pollutants, also enhanced by 3 and 4 above

Biological functions
7) enhancement of biotic diversity, aquatic and terrestrial
8) enhancement of heterogeneity (patchiness) of the habitat or landscape with effects such as, natural veld fire control, thermoregulation by shading of shallow streams etc
9) resistance to invasion by alien species

Human use functions
10) provision of food and resources for man and livestock
11) provision of prime recreation sites of high commercial value

The one negative factor often attributed to riparian vegetation (trees and shrubs) is that it utilizes water which would otherwise flow down the river (Bosch and Versfeld 1982). The removal of riparian vegetation will, however, create serious water quality and quantity problems for downstream users, in addition to many other related socio-economic problems, far in excess of the transpiration losses. Hewlett (1961) has proposed the variable source concept as a way to interpret and explain storm and base flows from forested upland catchments. The concept has since gained headway through various efforts of soil physicists, geographers, agricultural engineers and forest hydrologists who applied the concept in their local situations.

HISTORY OF MANAGEMENT POLICY

In southern Africa, land owners and planners, be they farmers, foresters, developers, engineers, bridge builders or of other profession, have mostly regarded riparian zones as a hindrance to efficient water use. The riparian zone has thus continually been subjected to abuse and development and specific legislation has been necessary to alleviate the problem. More than 65 years ago the Drought Commission pointed out the importance of the vegetated riparian strips. When, the Forest Department accelerated its afforestation programme in the 1920's, the alleged reduced water yield of rivers provoked public anxiety.

A policy was adopted, in 1932, prohibiting afforestation of a 66 foot strip (later 20 m) on both sides of perennial streams, vleis and other surface water on State Forest lands. This rule was not obligatory for private land owners, although since the Soil Conservation Act of 1946, the following General Provision applicable to all land owners prevailed:

1) "No vegetation, excepting proclaimed weeds and other noxious plants, shall be destroyed within ten (10) metres of the edges or banks of or in rivers, brooks, springs, vleis, marshes, dongas, water courses, or earth channels".

2) "Within ninety (90) metres of the edges of marshy water sponges, under average rainfall conditions and twenty (20) metres horizontally and vertically from the edges of water sponges, brooks and rivers, no plantations shall be planted or re-established for commercial purposes or regrowth allowed after existing plantations have been thinned out or completely felled".

Because this was a directive and not a law, only seven prosecutions were achieved over more than 30 years and these rules were not effective in stopping damage to sensitive streamside zones. In contrast this rule effectively protected most riverine vegetation in state forest areas from both disturbance and management and, since afforestation alters local environmental conditions, uncontrolled invasions by alien weeds such as bramble, poplar, wattle and bugweed have often occurred.

The afforestation permit system has applied since 1972. As a first condition on every permit it is stated that no afforestation is allowed within the 20 m strip on both sides of perennial streams, and that all alien vegetation in these strips should be cleared annually. This enforceable piece of legislation is applicable on both state and private land and is being actively administered by regional forest officers with considerable success.

While the old Soil Conservation Act (1948 now repealed) focused on prevention of soil erosion, the Forest Act emphasises efficient water use. The new Conservation of Agricultural Resources Act (1985) seems to emphasize the elimination of obstructions in the river channel, "that will disturb the natural flow pattern of runoff water". It also has a number of regulations controlling cultivation within 10 m of the high flood line of a water course.

Legislation has therefore been negative in the sense that it seeks to control alien riparian vegetation, but does not encourage or enforce proper management of indigenous riparian vegetation.

CONCEPTUAL MODELS OF RIPARIAN DETERMINANTS

The particular characteristics of riparian vegetation are the expression of the individual plant's responses (a function of life histories) to the local climate, and the interactions between physical and chemical conditions at the channel margin. The vegetation in turn "feeds back" to further alter conditions such as soil structure and erodability, flow resistance and the light climate. This complex set of interactions is best illustrated by means of conceptual models of riparian water balance and vegetation processes.

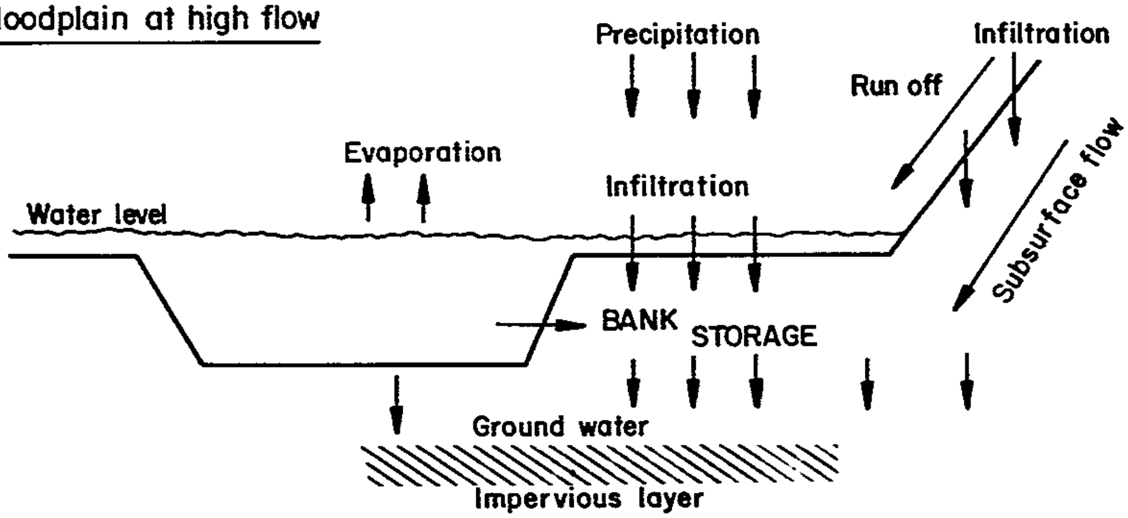
When interpreting these models for research or management purposes it is important to remember that river systems have properties in four dimensions; longitudinal (source to sea), vertical and horizontal (cross sectional profile at any point), and temporal (the time continuum) (Ward and Stanford 1987). The significance of individual components of the models will therefore depend on the position of a particular river section in these four dimensions.

Riparian water balance

For the purposes of this discussion, riparian zones can be separated into two hydrologic types: (i) the floodplain type in which inundation, whether permanent or periodic, is a major determinant of structure and functioning and (ii) the bank-storage type in which inundation is absent or infrequent and the ground water level is the major determinant.

In both types, inputs of water are from the river itself and from surface and subsurface flows from the adjacent landscape. Losses are to evapotranspiration and to ground water which may return to the river channel (Figure 3). The most important factors affecting riparian water balance

A. Floodplain at high flow



B. Floodplain - low flow
or "BANK STORAGE" riparian - all flows

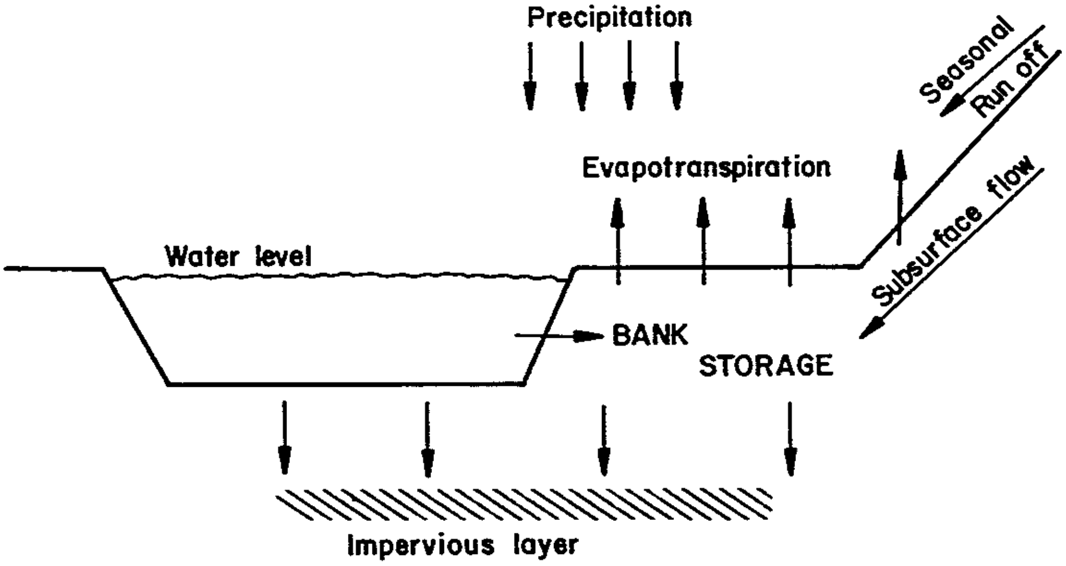


FIGURE 7.3 Basic patterns of water movement into and out of floodplain and "bank storage" type riparian zones.

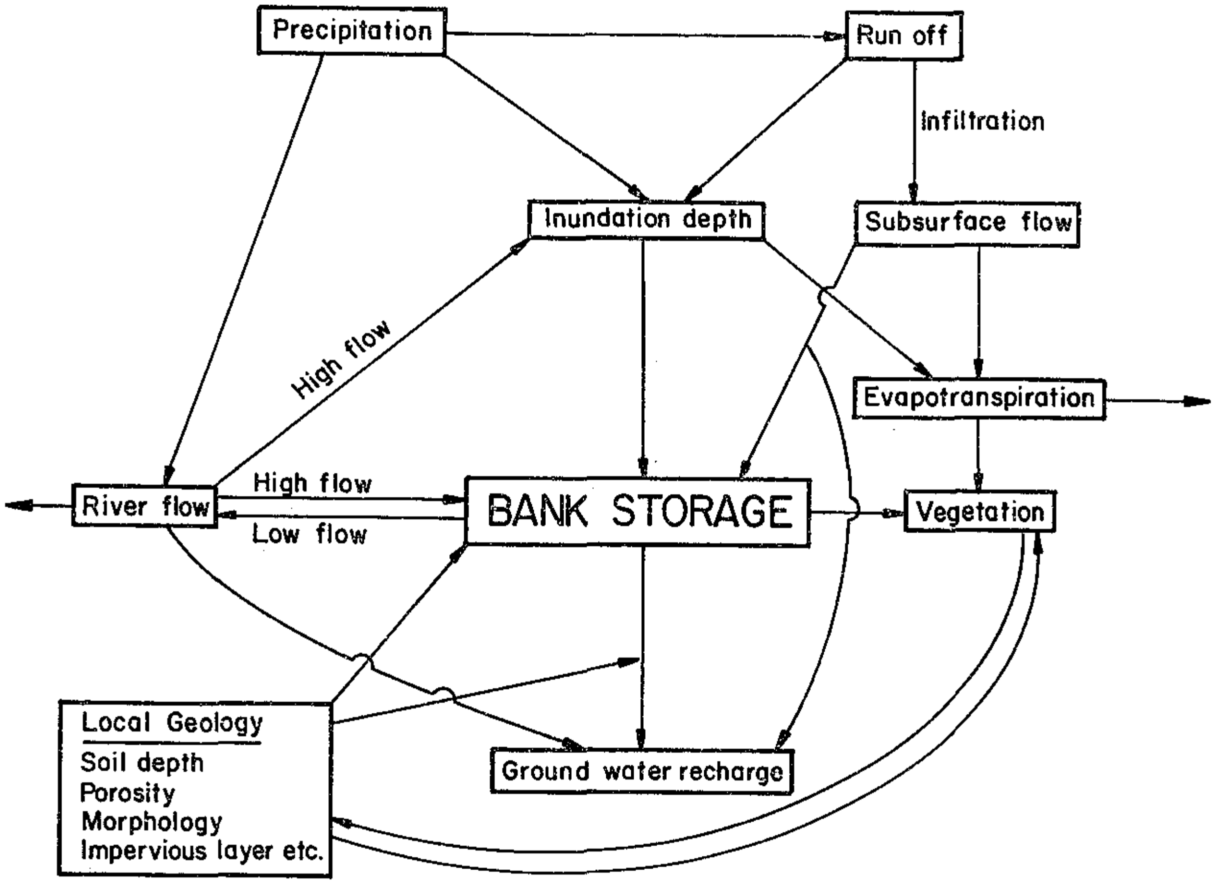


FIGURE 7.4 Conceptual model of factors affecting depth of inundation and bank storage dynamics of riparian zones.

in any one river section are therefore, the magnitude and timing of surface inundation and bank storage recharge, which in turn will be dependent largely on sectional morphology and the depth and porosity of the soil mantle. A preliminary conceptual model of how all these factors interact to determine inundation depth and bank storage volume, is presented in Figure 4.

Forest hydrologists, more concerned with catchment processes affecting storm and base flows in rivers than with the riparian zone itself, have developed different perspectives which could be usefully integrated into models of riparian water balance.

The variable source area concept for example, (Figures 5 and 6) recognizes that neither stormflow nor baseflow, is uniformly produced from the entire surface or subsurface area of a catchment, as visualized in the alternative Morton-Sherman concept (Figure 6). Instead, the flow of water in a stream at any given moment is under the influence of a dynamic, expanding or shrinking source area, normally representing only a few per cent of the total catchment area. The variable source area concept visualizes the response of the channel system to precipitation rates as far more crucial to the upland hydrograph than presumptive specifications about infiltration rates of "excess" rainfall over the basin. Overland flow is treated as an expansion of the perennial channel system into zones of low storage capacity and thus rapid subsurface seepage into small draws, swampy spots, and intermittent channels. This expansion is aided by rain falling directly on these wetted areas. Subsurface stormflow, the bulk of the average upland storm hydrograph (Figure 6) is viewed as feeding the expanding channel from below while rainfall feeds it from above. In this way the channel can grow to many times its perennial width and length.

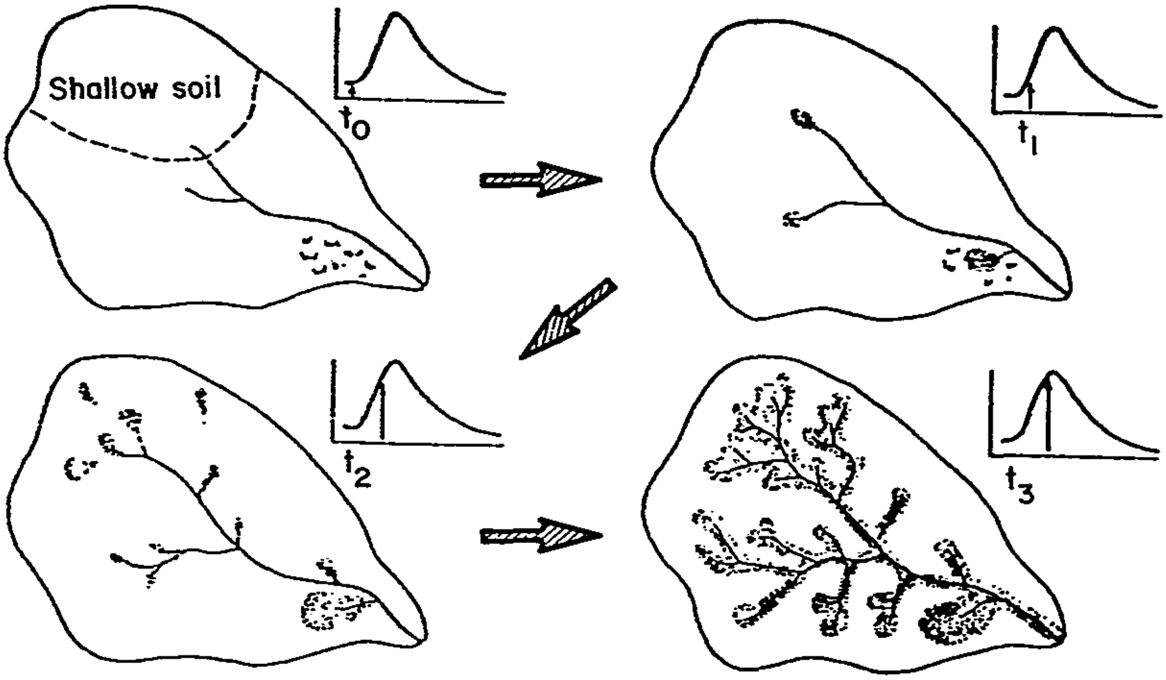


FIGURE 7.5 A plan view of the expansion of the source area during storm flow in a first order catchment.

A crucial feature of the variable source area system is the expanding channel network, since by this means the channel reaches out to tap the subsurface flow systems which, for whatever reason, have overridden their capacity to transmit water beneath the surface. As the source area network shrinks, the channel is reduced back to its perennial length; slowly if the soil mantle is deep or the slopes long; rapidly if shallow or slopes short. The limits to which the source area can swell may well determine the extent of the riparian vegetation zone.

The variable source area concept emphasizes the four dimensional properties of river systems. It recognizes that the condition of a river, at any point along the continuum, including the riparian zone, is a reflection of all the characteristics of the upstream parts of the catchment. Efforts to broaden it and incorporate inundation and bank storage in the riparian zone should prove very useful to ecologists and managers.

Riparian vegetation processes

The major determinant of riparian vegetation processes is water. Local community structure is inevitably a function of the manner in which water

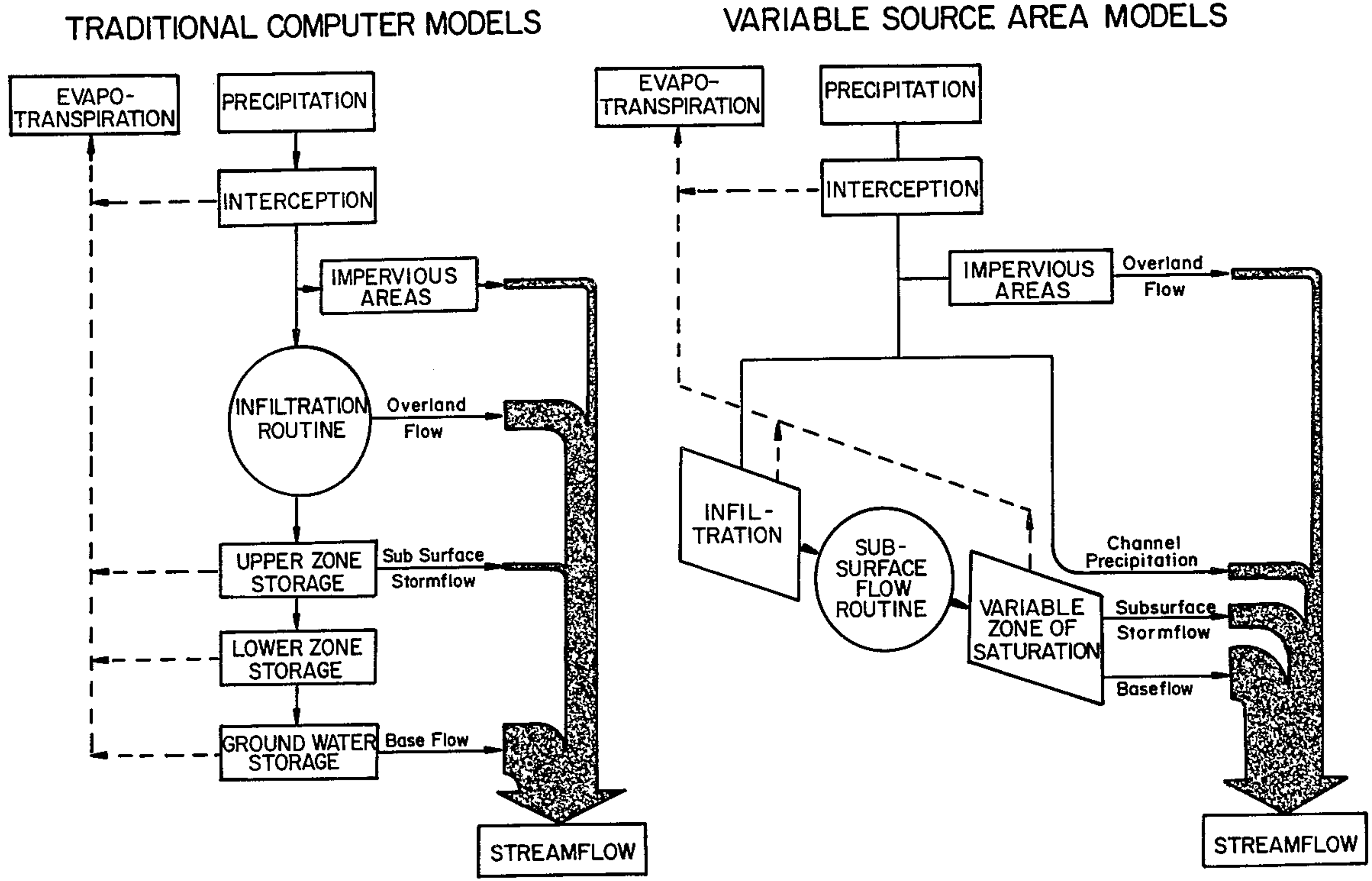


FIGURE 7.6 Models of the runoff process, reflecting various views of how source areas generate streamflow. The main difference between traditional and variable source area models lies in the role of infiltration (after Hewlett 1982).

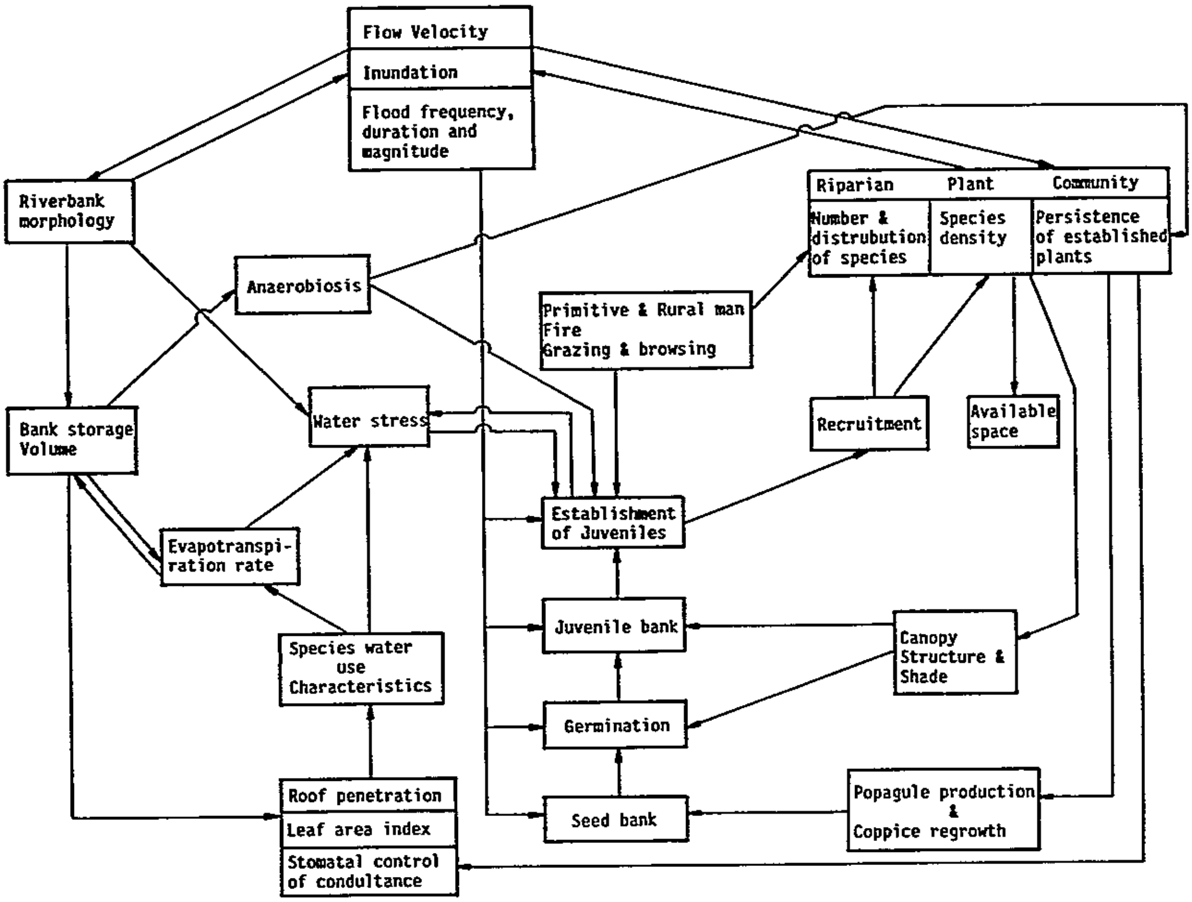


FIGURE 7.7 Conceptual model of the determinants of riparian vegetation community structure.

availability interacts with all other aspects of the environment (climate, fire etc) and the life history characteristics of the plants (growth, differentiation and reproduction). Bank storage and inundation interact with vegetation in different ways (Figure 7.7), but both have major effects on regeneration and recruitment to existing populations.

The main effects of bank storage are a result of either anaerobic conditions when the soil is saturated, or water stress which occurs during the dry season or droughts. Each species will respond characteristically to changes in bank storage in both time and space, according to its life history but the juvenile stages will be most sensitive since their root systems are shallow and poorly developed.

Four characteristics of inundation affect the structure and functioning of the riparian strip:

(i) Velocity
Turbulent floods will uproot plants and thus regulate their density. While severe floods may appear destructive, the loss of adult plants does act as a stimulus for establishment of others of the same or different species. Floods are therefore important in the maintenance of habitat heterogeneity, regeneration and biodiversity.

(ii) Duration
The longer the period of inundation the more anaerobic the soils will become, which in turn will affect the survival and establishment of plants, especially juveniles. The duration of inundation will also affect seed storage, distribution and germination in both space and time.

(iii) Frequency and (iv) magnitude
The high frequency and large magnitude of floods will amplify the effects of both velocity and duration and may have special relevance for the biological periodicity of riverine communities.

Inundation acts on riparian vegetation as a "disturbance" - an ecological phenomenon receiving much attention in recent literature as a process fundamental to the structure and functioning of communities (Sousa 1984; Picket and White 1985).

The variety of ways (stress, physical disturbance, stimulus for reproduction) that water acts on riparian plants must be clearly recognized. The notion that the water-needs of riverine vegetation can be related simply to evapotranspiration (cf Bosch and Versfeld 1982) or continuous water supply (the phreatic zone) is simplistic. Floods (disturbance), drought (water stress; cf Monteif 1975) and soil saturation (anaerobiosis; cf Armstrong 1982) are all fundamental determinants of the structure and functioning of riparian communities.

ESTIMATES OF WATER QUANTITY REQUIREMENTS

There are many studies of water use by riverine vegetation but very few have quantified results that may be applied to the problem of deciding on in stream flow needs. One exception is Nänni (1972), who studied the effect of removal of woody riparian vegetation at Cathedral Peak Forest Research Centre in Natal and concluded that for every meter of vegetation removed, daily water flow increased by 12 litres.

Results of current field experiments from the Eastern Transvaal (Witklip Forest Research Area) indicate that riverine vegetation with high biomass and deep rooting characteristics, has a significantly higher water demand and hence influence on small-stream flow characteristics than does herbaceous vegetation. The effect of vegetation clearing or poisoning on stream flow, is proportional to the length of time the river banks remain devoid of live vegetation; the effect being lost or even reversed when the riverbanks become revegetated. Horton (1973) provides a seven hundred reference abstract bibliography, which includes the more quantitative studies and those carried out for forest production purposes in manipulated ecosystems.

It is concluded that for agricultural/silvicultural purposes, adequate estimates can be made from several models of water use by riparian vegetation. Of these the most well known are the Penman, Thornthwaite and Blaney-Criddle models, where climatic data are available. Several adaptions have been made, while computer applications are also available. For southern Africa, Louw and Kruger (1968) published tables and figures of calculated short and tall crop evapotranspiration using the Penman equation. The authors warned, however, that these estimates should be compared to measured values. At the time few such measurements were taken in South Africa but this has substantially changed since then.

All these studies, however, focus on loss of water by transpiration, while our knowledge of how water acts as a determinant of vegetation processes remains negligible.

RESEARCH AND MANAGEMENT RECOMMENDATIONS

Research

There is a general need for information on the ecology of riverine vegetation, both in terms of inventory and classification and in terms of ecological structure and function. The former is already being addressed as a priority by researchers interested in wetlands, with progress being limited at this stage to Natal (Begg 1986), the Kruger National Park and the western Cape. The value of remote sensing imagery should be fully investigated in this regard. The latter requires a set of detailed studies on sites, selected to cover a full range of bioclimatic regions in southern Africa.

A logical priority that should accompany the inventory and classification exercise would be a comprehensive attempt to devise quantitative estimates of water requirements by specific categories of riverine vegetation. Reference to Louw and Kruger (1968) and to the variable source area concept of Hewlett (1982) should assist, and estimates expressed in simplified units such as those used by Nänni (1972) are recommended.

However, as should be evident from the conceptual models, the detailed water requirements of riparian zones cannot be established without knowledge of how riverine vegetation responds to different hydrological conditions. In other words, how factors such as inundation depth, timing and frequency and bank storage dynamics, act upon different species to determine community structure. There is therefore a need for detailed site-specific investigations of plant-life histories, hydrology and the interactions which structure riparian plant communities.

Management

1. The riparian zone should be clearly delineated as a specific land management zone with explicit, enforceable land-use constraints.

This could be done in terms of the Environmental Conservation Act's new proposals on environmental impact assessment.

2. The "polluter pays" principle should be applied in the case of damage to riparian zones as a result of poor land-use practices.

3. Management objectives, practices and constraints need to be drawn up for different riparian and land-use categories.

4. Special attention should be given to minimizing the impact of all civil engineering structures and works in these zones.

5. Since riparian zones are longitudinal systems which dissect catchments, and their structure and functioning are inseparable from land-use practices in general, it is essential that their management be approached on a catchment basis. Catchment management committees with appropriate private and public sector membership are the only effective means of achieving such management aims.

6. The use of historical records to propose a suitable hydrological regime for any riverine area is to be encouraged in the initial management phase. However, changing catchment conditions (erosion, eutrophication, salinity etc) and site specific objectives will mean that such regimes may not be appropriate in the long term. Furthermore historical records may be absent from some catchments or may only date from some time subsequent to man-induced modification. In such cases or where objectives dictate, more detailed knowledge of riparian determinants must be sought in site specific research.

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CHAPTER 8. LOOKING TO THE FUTURE – SOUTH AFRICA'S REQUIREMENTS

J M King and J H O'Keeffe

River ecologists in South Africa have a wealth of international literature to refer to when assessing instream flow requirements of rivers but, to date, little practical experience. Detailed knowledge of the biota and ecological functioning of the rivers is also poor, when compared to that of many countries now attempting the task of allocating water for ecological purposes. Time is limited, for most of South Africa's major rivers are already regulated, or will be by the turn of the century. With a burgeoning population to provide for, the planning and development of water resources cannot be postponed until relevant research is complete, but instead must proceed based on the best available information.

If information on the instream flow requirements of rivers is not forthcoming, development of water resources will go ahead without this input, and as the competition for water between different users is continually increasing, it would be difficult to regain a 'share' of the water for a river once it had been totally committed elsewhere. Instead, strong motivation for an instream allocation needs to be made at an early stage of the development of a river's water, if it is wished to maintain some semblance of the past ecological functioning of that river.

In the light of these facts, we describe here guidelines for presenting to the Department of Water Affairs applications for instream flow allocations, and two different approaches devised locally this year for the speedy calculation of instream flow needs.

AN OUTLINE OF THE INFORMATION NEEDS OF THE DEPARTMENT OF WATER AFFAIRS REGARDING INSTREAM FLOW ALLOCATIONS

Compiled by F van Zyl, A Rooseboom and K Rogers

This guide should be used by researchers providing the Department with recommendations for the flow regime that would be necessary to maintain a regulated river in some predetermined condition. The information supplied must be practical and quantitative, in order to allow the Department to calculate weekly, monthly and annual water allocations for instream needs.

The information should:

- include details of water requirements for the river in drought (ie a declared drought), normal and wet periods;
- for each of the above categories, specify the conditions of flow required. Thus, quantified information would be needed on the minimum periods and frequencies of specific flow rates: when, how often, how long, how much, how irregular, rates of change etc;
- give approximate standards of water quality relating to different discharges; and
- indicate, where possible, the split between consumptive and non-consumptive water requirements.

Total annual discharge of a regulated river will differ (usually being lower) from that of the river before regulation, but should incorporate key features of the unregulated flow regime (eg seasonal fluctuations, important flood peaks) in order to simulate the latter's major impacts on the ecosystem. Recommendations made should take into account that:

- water management takes place on a catchment basis;
- releases from dams are subject to:
  limited storage capacity
  limited sluicing capacity (discharge rate)
  lack of control of major floods
  downstream losses of water (extraction, evaporation etc)
  downstream gains of water (tributaries, seepage etc)

One suggested approach for determining the required flow regime is to identify certain levels (ie depths) of water which would fulfil different ecological requirements (Figure 8.1). Water depth at each level can be converted into discharges and linked with the recommended timing and duration of that discharge to provide figures for the required volume of water. To establish the recommended timing and durations of a particular dscharge, the requirements of key biotic processes at each level (eg regeneration of riparian vegetation; inundation of floodplain; maintenance of fish migratory route) would need to be identified. This was basically the approach employed in the Skukuza method (see below).

Alternatively, calculations of instream flow requirements could be based on the historical flow data. Using these data, major features of the flow regime could be identified and incorporated into the altered flow regime. This was basically the approach used in the Cape Town method (see below).

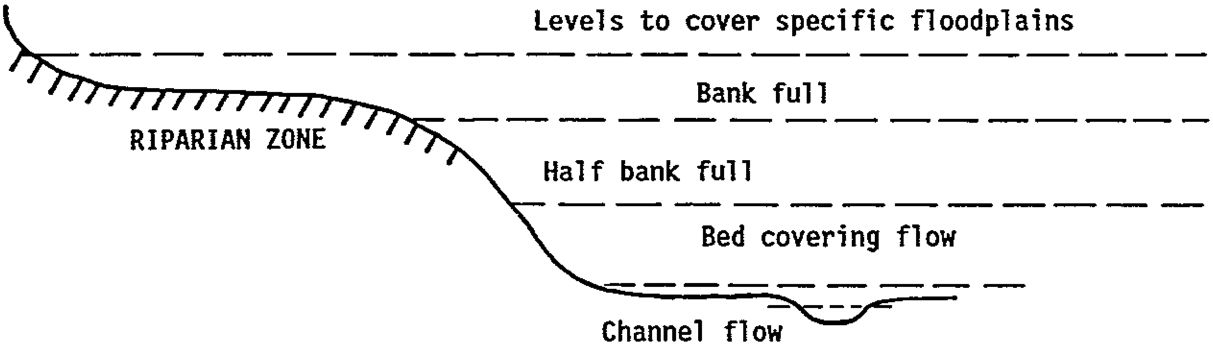


FIGURE 8.1 Suggested levels of water in a river that fulfil different ecological requirements. These levels can be converted into discharges and integrated with time to produce required volumes.

LOCALLY DEVELOPED APPROACHES TO INSTREAM FLOW CALCULATIONS

The following two approaches allow a quick preliminary assessment of the approximate instream flow requirements of a river. They cannot provide the refined level of accuracy of indepth research, and should wherever possible be used in conjunction with such research. Indeed, for a river with a high conservation status such research would be imperative.

The Skukuza method

At a workshop held at Skukuza in March 1987 (Bruwer 1987), ecologists and hydrologists were required to estimate the ecological water requirements of the main rivers which feed the Kruger National Park. This was a short-term exercise in response to imminent management plans to exploit the water resources of these rivers upstream of the Park. The recommended flows which emerged were necessarily only rough estimates, since data on the rivers' ecological functioning were mostly lacking. However dubious the actual figures were, it was felt that the protocol adopted to define water requirements of the rivers was successful and could act as a framework for future attempts to determine the instream flow requirements of rivers.

The first step in the method is to identify the consumptive and non-consumptive users of water in a river ecosystem (Table 8.1). Quantities of water are then assigned to each of the consumptive components, using the guidelines described by van Zyl and Rooseboom (see above), and the best available information or 'best guesses' of relevant specialists. The consumptive requirements are summed and added to the largest non-consumptive requirement (Table 8.2), the assumption being that by satisfying this largest nonconsumptive requirement all other nonconsumptive requirements will also be met. To the resulting base flow requirement for the river are added any additional requirements for increased flows and flushing floods. The final total can then be allocated at an appropriate level for each season in order to mimic major features of the natural flow regime. Because variability of flow is an outstanding feature of South African rivers and thus may be important ecologically, due allowance for this should be made in the final flow recommendation.

The advantages of the Skukuza method are that the important components of the riverine ecosystem are clearly identified, and their individual flow requirements can be modified and corrected in the light of future additions to the data base. Only the critical nonconsumptive flow requirement need be assessed accurately, limiting the need for intensive data-gathering.

It must be emphasized that the Skukuza method is only a set of guidelines which does not in itself suggest methods of assessment for each component. These assessment methods will depend on the existing database and the resources and time scale of the proposed flow modification project, and might well include some of the methods outlined in earlier chapters. Certainly, no-one would suggest that the figures arrived at in the Kruger Park exercise (Bruwer 1987) are the final accurate instream flow requirements.

TABLE 8.1 The Skukuza method - consumptive and non-consumptive water users. The list gives examples of likely components and is probably not exhaustive

Consumptive requirements:

water surface evaporation
- ground seepage loss
- riparian evapotranspiration
- floodplain inundation

Less:
- direct rainfall and runoff
- floodplain return flow

Non-consumptive requirements:

- estuarine maintenance
- flushing of sediments
- maintenance of fish communities
  invertebrate communities
  waterfowl habitat
  water plants
  other biota
  channel morphology
  natural temperature regimes
  water quality

TABLE 8.2 Procedure employed in the Skukuza method

Step one:	Identify the important consumptive and non-consumptive water requirements for the ecosystem
Step two:	Quantify these requirements
Step three:	Sum the consumptive requirements
Step four:	Add the volume required for the largest non-consumptive requirement
Step five:	Define the timing and size of any additional floods
Step six:	Allocate the required flow seasonally, maintaining viability of flow if possible

The Skukuza method is a flexible and comprehensive approach which can be used to give either a first estimate or a detailed calculation of the ecological flow requirements of rivers. Because many aspects of the biology of rivers are often poorly understood, however, we would recommend that two alternative approaches should always be used in the assessment of flow needs, to act as a check on each other. The hydrological method described below is a suitable alternative method in this context.

Flow Record Simulation approach

At the workshop reported in this document and at a subsequent workshop in Cape Town river ecologists and hydrologists considered the potential for using the historical hydrological data when determining instream flow requirements of rivers (King et al in preparation). The method is still at a formative stage, but basically two assumptions are made: that nothing is known of the river except for the flow data provided by the water authorities, and that as the riverine communities have coped with conditions in the river over a long period of time, identifying and incorporating the major characteristics of that flow regime into a new regulated discharge pattern should allow some semblance of the previous ecological functioning of the system to continue.

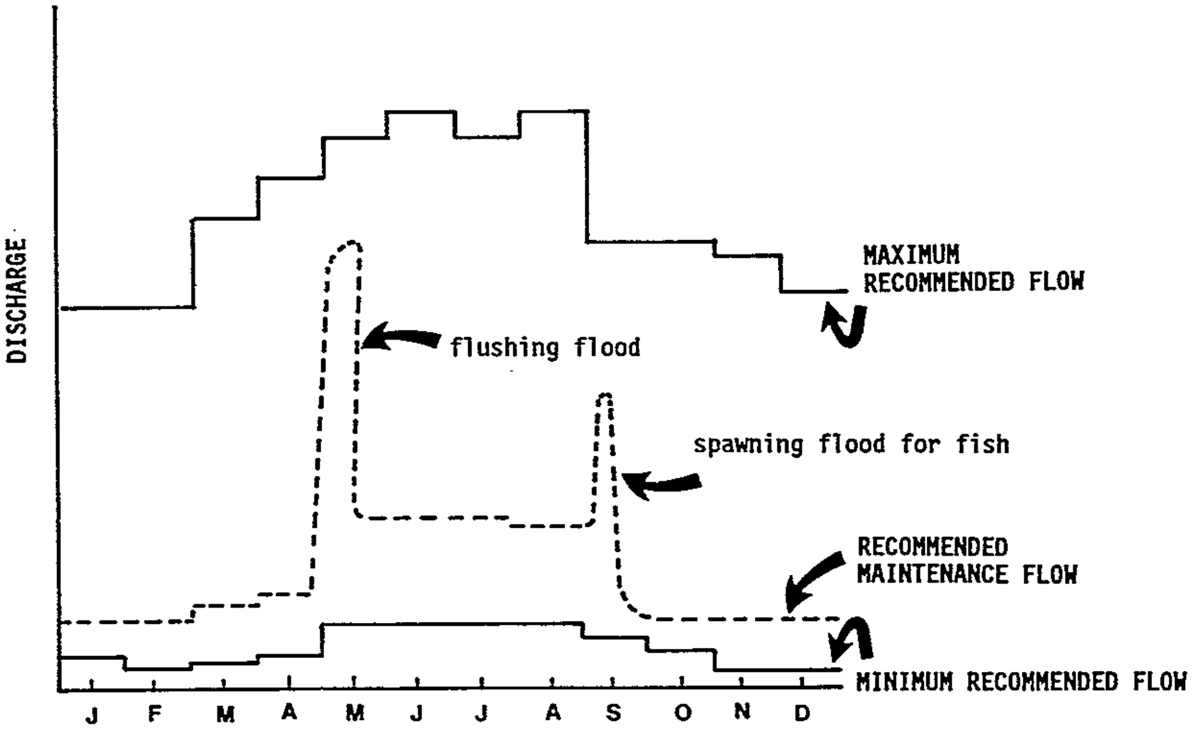
The first step in the method is to identify recommended minimum and maximum flows for each month of the year, based on records of DAILY flow of the unregulated river. For each month, the data on daily flow are plotted (eg a 50 year database would give 50 x 31 data points for the January graph) and the minimum and maximum flows that occur regularly/ often re identified (see King et al in preparation for details). These flows, listed month by month, become the limits within which discharges must be held through the year (major floods would not be contained by the regulatory structure and would occur as before). Maintenance flows are then identified within these limits and requirements for floods superimposed to give detailed monthly and annual water requirements (Figure 6.2). It is envisaged that recommendations resulting from the use of this method will be quantitative and sufficiently flexible to allow the water manager to meet the requirements of other water users as well.

A detailed description of the theory and practice of the method forms part of a more comprehensive document presently being compiled by ecologists to aid the water authorities in developing and managing the water resources of South African rivers (King et al in preparation).

CONCLUSION

It is worth repeating that the two methods described above will provide only a first estimate of the instream flow requirements of a river. When making flow recommendations the methods should, at the very least, be used in conjunction with a synthesis report of all present ecological knowledge of the river. If the river is deemed sufficiently important to warrant more than a first estimate of its instream flow needs, then time and finances should be allocated for the necessary indepth research.

On the other hand, if experience in these methods is acquired over the next few years, it should eventually be possible to make some generalizations concerning the flows necessary for regulated rivers. Such



The flow Record Approach

FIGURE 8.2 The Flow Record Simulation approach. An example of the kind of flow regime that could be recommended for a regulated river in the winter rainfall region. The maximum and minimum limits between which flow must be held are shown for each month, together with the recommended maintenance flow. Two floods are incorporated. At times specified by local river ecologists, in order to simulate major impacts of the natural system.

generalizations might allow flow recommendations to be made, for instance, for a river with no ecological or historical flow data, providing that some idea of its flow regime is available (eg from rainfall data) and that a 'first estimate' of instream flow needs was deemed sufficient for that river. At the moment we do not know what kind of generalizations may be possible, even less what they would be, but the little local work done on the subject shows considerable promise and should be supported.

Equally important is to bear in mind the wealth of international expertise regarding instream flow allocations. River ecologists in North America, for instance, have more than a decade of experience in calculating instream flows, and though much of their methodology is research-intensive their general knowledge on the subject must be extensive. Efforts should therefore be made to communicate and work with them and other relevant experts.

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