
ENVIRONMENTALLY-SENSITIVE RIVER MANAGEMENT: ASSESSMENT AND MITIGATION OF IMPACTS ON URBAN RIVERS

MICHAEL KARL LUGER

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ABSTRACT

Urban development and engineering works have resulted in the majority of rivers that drain urban areas being severely degraded, both ecologically and in terms of their potential amenity value. This dissertation explores the reasons for this "spiral of degradation" and it describes the ecological and social impacts on rivers caused by urban development, channelisation and canalisation. It then suggests possible measures to mitigate the impacts at the levels of the catchment, floodplain and river channel. The present cycle of degradation of urban rivers in the Cape Metropolitan Area (and elsewhere) can be halted. In addition, where degradation has already occurred, mitigation and rehabilitation are possible and could restore some of the lost conservation and ecological values, as well as the potential amenity, recreation and education functions.

Early colonisation of Cape Town by Europeans inflicted severe impacts on the rivers surrounding and passing through the city. These included: catchment degradation, water abstraction, the disposal of unpurified sewage and industrial effluents, removal of riparian forests, clearing of instream vegetation and the draining of wetlands. During the 20th century, many urban rivers have been "improved" by straightening or confining within rectangular concrete-lined canals in order to protect urban development in flood-prone areas. The unquestioning faith in technology during this period and the attitude that human ingenuity could "improve nature" are now regarded by the scientific community, together with some local and regional authorities and informed members of the public, as mistakes that resulted in ecological and environmental degradation. These technical solutions merely treated the symptoms of the problem without recognising, let alone attempting to treat, the causes, that is poor catchment and floodplain management. However, there is still a public demand for canalisation of the remaining "natural" rivers in the greater Cape Town area and beyond. At the same time, there has been an increase in environmental awareness, as well as a growing appreciation of the value of holistic and multi-objective planning in the engineering and planning professions.

This dissertation aims to assess the impacts of urbanisation, channelisation and canalisation on the aquatic ecosystem and socio-economic environment of urban rivers, and to develop possible measures to mitigate these impacts. The objectives of this study are :

- to describe the traditional approach and practice of stormwater engineering,
- to understand the factors that have caused the present degraded state of urban river systems generally, particularly those within the Cape Town Metropolitan Area,

- to outline the ecological theories relating to lotic ecosystems and their functioning in order to assist engineers, decision-makers and the public to understand the arguments for ecologically-sensitive river engineering,
- to present a concise summary of the effects of urban development on river flow and water quality in receiving river systems,
- to assess the ecological impacts of urbanisation, channelisation and canalisation on river systems in a manner that is understandable to non-ecologists and which facilitates the implementation of mitigation measures,
- to assess the socio-economic impacts of urbanisation, channelisation and canalisation on river systems,
- to derive a comprehensive set of potential mitigation measures, applicable to the catchment, floodplain and especially the river channel, and
- to illustrate some of the threats to the Liesbeek River system and to demonstrate how mitigation measures could enhance the ecological functioning of the system.

The assessment of the ecological effects of urbanisation, channelisation and canalisation is described in terms of changes in the key abiotic factors. These include an increase in the magnitude and frequency of high flow velocities, a reduction in substrate heterogeneity, a decrease in aquatic, riparian and floodplain area and a deterioration in water quality. These changes may affect each floral and faunal species differently. Species in the upper reaches, together with those that are rare or specialised, are more likely to be affected. Increasing changes from the natural range of each abiotic factor will increasingly affect species and result in the loss of species. Eventually, basic ecological functioning may be impaired and the system will only support those species that are extremely "hardy".

From a socio-economic perspective, the main effects of urbanisation, channelisation and canalisation include aesthetic degradation of the river and corridor, impairment of recreational and educational opportunities, and reduced biological filtering of the water. The conservation value of both the river and corridor is reduced and linkages between fragmented natural habitats are impaired. The stormwater efficiency may, however, be enhanced by channelisation and canalisation.

Environmentally-sensitive river management promotes the aesthetic, recreational, amenity, education and conservation value of urban rivers and corridors by utilising both structural and non-structural approaches. The non-structural approach includes catchment management measures to limit the increase in stormwater runoff and to minimise the deterioration in water quality. This approach also includes management of the floodplain and control over land use zoning. It is argued that it is essential to implement these non-structural measures in order to minimise the impacts on, and potential to engineer the river channel in a sensitive manner.

The structural approach relates to the engineering and management of the river channel itself. The objective is to maximise the physical diversity of the channel. This will maximise biological diversity and thus the conservation value of the river.

Environmentally-sensitive catchment management aims to reduce the volume of stormwater runoff, preferably to pre-development levels. This has a several advantages, such as a reduction in downstream flooding and minimising the need for downstream channel upgrading. It also protects the riverine ecosystem, and improves the quality of stormwater runoff. Measures, including the storage of rainfall on flat-topped roofs or in car parks, stone-filled trenches, porous pavements, grass-lined channels and detention dams are described. Although it is important that the deterioration in water quality supplied to receiving rivers is minimised, it is not water pollution alone that limits the diversity and integrity of the aquatic ecosystem.

Environmentally-sensitive management of the floodplain requires limiting urban development. Flood insurance and disaster relief, beyond humanitarian grounds, meanwhile encourage further development of flood prone areas. Reserving inadequate corridor widths forecloses environmentally-sensitive river channel management options and therefore it is vital for the authorities to acquire a corridor.

Channels are only fully utilised for 0,01% of the time for stormwater and it is therefore argued that they should be designed and managed to fulfil other functions, including amenity, aesthetics and education. Moreover, corridors frequently constitute the only areas of natural or semi-natural habitat within an urban area and have considerable conservation potential. Their linear nature can play an important role in linking isolated patches of terrestrial habitat.

A number of measures can be utilised to mitigate the negative ecological effects of river maintenance, channelisation and canalisation. Most all of these aim to maintain or recreate the diversity of physical conditions, especially flow velocity and substratum, thereby increasing the diversity of organisms.

Environmentally-sensitive river maintenance practices include: reducing the frequency of maintenance activities, disposing spoil material away from the channel, modifying only one bank, leaving patches of aquatic and terrestrial vegetation uncut, or sections of channel undredged, establishing or maintaining terrestrial vegetation, and undertaking work in an upstream direction.

Streambank protection includes indirect methods such as deflecting the flow away from the banks by the use of dikes, jetties or gabions placed perpendicular to the flow. Direct methods on the other hand include the use of plant material, interlocking blocks, fabric and mesh nets, rip-rap or crushed stone and gabions.

There are also mitigation measures for channelised rivers, and these include levees away from the river channel, flood bypass channels or two-stage channels, wetlands on all inflows, retaining severed meanders, pool-riffle sequences, a meandering alignment, asymmetrical cross-sections, low weirs, regrading or creating less steep banks, off-channel bays or wetlands, modifying the substrate and instream habitat devices.

Lined canals offer little habitat diversity and, as a result, support an extremely depauparate flora and fauna. Mitigation measures can, however, enhance the ecological and recreational potential of canals by means of low-flow channels, planting troughs, the creation of pools, substrate improvement, and maintaining sections of natural, or semi-natural channel. Furthermore, means of enhancing the social benefits include pedestrian or cycling paths, or skate-boarding and roller-blading rinks.

Degradation of the Liesbeek River and its catchment began with the Khoikhoi pastoralists, followed by increased impacts by early Colonial settlers on the forests and floodplains. During the latter half of the 19th century, suburban development increased rapidly. The absence of a sewerage or garbage disposal system resulted in the Liesbeek River becoming an open sewer. The 20th century has seen further urban development and associated increases in stormwater runoff. The resultant flooding culminated in canalisation of much of the river in the 1950's and 1960's. Ad hoc river bank stabilisation has been undertaken, and continues to be undertaken by private landowners. Water quality in the Liesbeek River, while not of a high standard, is probably better today than at any time during the last two centuries. Habitat diversity is therefore likely to be the limiting factor affecting the biodiversity of the system, emphasising the importance of physical habitat rehabilitation. Enlightened attitudes are necessary to prevent further degradation as the Liesbeek, like most urban rivers, is under constant threat of further degradation due to increased urban development.

This dissertation shows how urbanisation, channelisation and canalisation have significant negative impacts on the conservation, water quality enhancement and amenity value of urban rivers. It also demonstrates how many of these negative impacts can be mitigated by environmentally-sensitive river management. However, this management cannot be achieved solely by sensitive channel designs, but by control of floodplain land use and of the quality and quantity of stormwater runoff at a catchment level.

Finally, multi-disciplinary planning, appropriate legislation and support for environmentally-sensitive river management by the public and authorities are required. It is necessary to involve all role-players. The often conflicting engineering and ecological requirements need to be reconciled in order to ensure that the selected solutions meet the needs and aspirations of society in an efficient, equitable and sustainable manner. Urban rivers cannot be pristine and without human intervention or management. How we manage urban rivers will determine whether they become assets or liabilities to society.

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TABLE OF CONTENTS

BIBLIOGRAPHY

LIST OF TABLES

LIST OF FIGURES

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FOREWORD

Rivers flowing through urban or semi-urban areas are usually confined to trapezoidal earth channels, 'straight-jacketed' in concrete or buried in underground conduits. These engineered urban 'rivers' and their associated riverine corridors bear the brunt of urbanisation, namely increased flood flows and water pollution. The result is severely degraded riverine ecosystems which support a limited number of extremely tolerant, 'hardy opportunistic' species. In addition, the potential value of urban rivers and their riparian corridors for recreation, relaxation, aesthetics, water purification, micro-climate enhancement, nature conservation and flood mitigation is restricted.

The reason for this state of affairs is twofold: the encroachment of urban development onto flood plains, and stormwater management which aims to remove runoff to the sea as quickly and cheaply as possible. As a result, urban rivers are utilised to dispose of stormwater runoff only and are engineered accordingly. This, in turn, results in a spiral of degradation with rivers beginning to resemble and function as drains. This promotes further abuse in the form of dumping rubble, littering and the illegal discharge of domestic and industrial effluents.

CHAPTER ONE: INTRODUCTION

CONTENTS

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Throughout history, rivers have provided the foundation for human socio-economic development, by providing water for domestic, agricultural and industrial purposes (Purseglove, 1989). For generations, humankind has attempted to regulate and engineer rivers for a variety of purposes. The principle reason for much of the earliest river engineering was to extend arable land. More recently, river engineering works have been undertaken to maximise the area available for urban expansion, to provide flood "protection" for low-lying or riverside development, and to dispose of stormwater runoff from urban areas.

Early colonisation of Cape Town by Europeans inflicted severe impacts on the rivers surrounding and passing through the city. Catchment degradation, water abstraction, the disposal of unpurified sewage and industrial effluents, the removal of riparian forests, clearing of instream vegetation and the draining of wetlands fundamentally changed the affected rivers. In the twentieth century, humankind has caused massive impacts on urban rivers in Cape Town. Many of these rivers were "improved" by straightening or confining within rectangular concrete-lined canals during the 1950s and 1960s, in order to protect urban development in flood-prone areas (Boddington, pers. comm.). The unquestioning faith in technology during this period and the attitude that human ingenuity could "improve nature" are now regarded by scientists, certain local and regional authorities and informed members of the public as mistakes that resulted in ecological and environmental degradation. These technical solutions merely treated the symptoms of the problem without recognising, let alone attempting to treat, the causes, namely poor catchment and floodplain management. However today, the public still demand canalisation of the remaining "natural" rivers in the greater Cape Town area and beyond.

There has been an increase in environmental awareness on the part of the general public, as well as a growing appreciation of the value of holistic and multi-objective planning in the engineering and planning professions (Fuggle and Rabie, 1992). The increased focus on environmental issues is reflected in the widespread acceptance of the Integrated Environmental Management (IEM) procedure (Department of Environment Affairs, 1992). Furthermore, regulations published on 5 September 1997 make Environmental Impact Assessment a legal requirement for certain activities, including major river engineering works. The Department of Water Affairs and Forestry is promoting Integrated Catchment Management, albeit mainly to protect water supply schemes from poor water quality and to ensure appropriate utilisation of this scarce resource. Recently the Water Research Commission, as well as local and regional authorities, have commissioned various studies to improve the environmental management of urban rivers (for example, studies on the Constantia Valley, Kuils River, Disa River, Lourens River and Big Lotus River).

The increase in environmental awareness has also been manifest in the recognition, by some engineers, that environmentally-sensitive river management encompasses catchment, floodplain and river channel management. Such management draws on principles from catchment management, stormwater master planning, urban conservation, natural resource utilisation, metropolitan open space planning and water quality studies. The importance of retaining stormwater onsite has been promoted for many years (Department of Community Development, 1983; Miles, 1984). Land-use planning initiatives in Cape Town, such as the Metropolitan Spatial Development Framework (Cape Metropolitan Council, 1996), and the City Engineers Department's Greening the City (1982) reports recognise the multi-purpose utilisation of riparian corridors. Various authors have recognised the environmental roles of rivers and their corridors, including the recreational and scenic value (Beaumont, 1986; Petts, 1989). Some value conservation in linking otherwise isolated patches of remnant vegetation (Sedell *et al.*, 1990; Cross, 1991; Low, 1991; McDowell *et al.*, 1991; Saunders and Hobbs, 1991), the role as a buffer zone against flooding (Department of Community Development, 1983; Miles, 1984) and the role of rivers in improving water quality (Best and Ross, 1977; Dawson, 1978; Argue, 1994).

Urbanisation results in "catchment hardening" which causes an increase in stormwater runoff and higher flood flows (Dunne and Leopold, 1978). Traditional stormwater engineering aims to speed runoff through the drainage and river systems to the sea as fast as possible. As the river does not construct a channel large enough to convey flood flows (Dunne and Leopold, 1978), let alone the increased flows resulting from urban development, the channel is frequently "improved", thus reducing the frequency of water overspilling the channel and inundating the floodplain. Increasing the discharge is achieved by increasing the channel capacity and/or flow velocity (Swales, 1982). Increased channel capacity can be accomplished by artificially deepening or widening the channel. Alternatively, the hydraulic roughness of the channel can be reduced, thus increasing the velocity of flow. This in turn can be achieved by removing obstructions to flow, straightening the river (channelisation), or by lining the bed and banks of the channel with concrete (canalisation). The traditional approach and practice of stormwater engineering is described in Chapter Three.

As a result of urban development and river engineering works, the vast majority of rivers draining urban areas are severely degraded, both ecologically and in terms of their potential amenity value. This dissertation explores the reasons for this "spiral of degradation". It shows the ecological and social impacts on rivers caused by urban development, channelisation and canalisation. In addition, it suggests possible measures to mitigate the impacts at the levels of the catchment, floodplain and river channel.

The present cycle of degradation of urban rivers in the Cape Metropolitan Area (and elsewhere) can be halted. Moreover, where degradation has already occurred, mitigation and rehabilitation are possible and could restore some conservation and ecological values, as well as the potential amenity, recreation and education functions.

1.2 STATEMENT OF THE PROBLEM

The intimate abiotic and biotic linkages between the river channel, floodplain and catchment require an integrated management approach, as well as consideration of social and engineering aspects. It is proposed that one of the reasons why catchment management, stormwater master planning, urban conservation, natural resource utilisation, metropolitan open space planning and water quality studies have not been totally successful is that they have not adopted a perspective that is fully holistic towards the management of urban catchments. For example, it is only when the stormwater attenuation, water quality enhancement, amenity value, enhancement of adjacent real estate, environmental education and downstream conservation benefits of a constructed wetland or detention pond are considered together, that their true value is recognised. Environmentally-sensitive river management attempts to promote this integration of disciplines at the catchment, floodplain and river channel level.

The preparation of this dissertation was motivated by the following concerns :

- the poor understanding of other disciplines and lack of communication between riverine ecologists, town planners and engineers,
- that engineers, urban planners and local authorities are not fully informed of the implications for river systems of increased stormwater runoff, the deterioration in water quality and urban development in flood-prone areas,
- the low level of public concern about the inequitable, inefficient and unsustainable development that results in degradation of the amenity, recreation and conservation status of rivers and their corridors,
- the lack of a clearly motivated case for environmentally-sensitive river engineering options at the catchment, floodplain and river channel levels, and
- the low level of knowledge, amongst engineers, urban planners, landscape architects, ecologists and local authorities of measures, to mitigate the ecological impacts of urbanisation, channelisation and canalisation and to enhance the recreational and amenity opportunities.

Methods of assessing the ecological effects of decreased flow in rivers due to impoundments have received considerable attention, particularly in North America and in South Africa (Arthington *et al.*, 1991; King and Tharme, 1994). Although river-channel works have been (and still are) widely undertaken in many countries, few studies have been carried out to determine the effects on aquatic life (Swales, 1982). In the intervening years, biologists have concentrated on "pristine" rivers or on specific aspects, such as autecological studies or nutrient processing. In addition, research funding organisations have, in the past, generally not sponsored studies of degraded ecosystems, such as urban rivers.

As a result, the ecological and amenity impacts caused by urbanisation, channelisation and canalisation, as well as possible mitigation measures, especially at the river channel level, have received little attention internationally and almost none in South Africa. These two key aspects of environmentally-sensitive river management form the focus of this dissertation.

1.3 AIM AND OBJECTIVES OF THIS DISSERTATION

1.3.1 Aim

The aim of this dissertation is to assess the impacts that urbanisation, channelisation and canalisation have on the aquatic ecosystem and socio-economic environment of urban rivers, and to develop possible measures to mitigate these impacts.

1.3.2 Specific objectives

The objectives of this study are :

- to describe the traditional approach and practice of stormwater engineering,
- to understand the factors that have caused the present degraded state of urban river systems generally, and those within the Cape Town Metropolitan Area in particular,
- to outline the ecological theories relating to lotic ecosystems and their functioning in order to assist engineers, decision-makers and the public to understand the arguments for ecologically sensitive river engineering,
- to present a concise summary of the effects that urban development has on river flow and water quality in receiving river systems,
- to assess the ecological impacts of urbanisation, channelisation and canalisation on river systems in a manner that is understandable to non-ecologists and which facilitates the implementation of mitigation measures,
- to assess the socio-economic impacts of urbanisation, channelisation and canalisation on river systems,
- to derive a comprehensive set of potential mitigation measures, applicable to the catchment, floodplain and especially the river channel, and
- to illustrate some of the threats to the Liesbeek River system and to show how mitigation measures could be applied to enhance the ecological functioning of the system.

1.4 APPROACH AND METHODOLOGY

Literature on hydrology and river channel hydraulics was reviewed in order to develop an understanding of the traditional approach and practice of urban stormwater management and river channel engineering.

In order to appreciate the historical context and early impacts of agriculture and urbanisation on river systems, a review of the historical literature of the Liesbeek River catchment was completed. Numerous trips along the Liesbeek River and visits to other rivers in the Cape Town Metropolitan Area were undertaken in order to gain an understanding of the range of threats, impacts and opportunities which affect urban rivers.

The ecological theory of river ecosystem structure and functioning was reviewed in order to derive an understanding of the key concepts and aspects which could be impacted by urban development and river channel engineering works.

An extensive literature review was undertaken in order to ascertain documented ecological and amenity impacts resulting from urbanisation, channelisation and canalisation. In a holistic environmental study of this nature, it was not possible to adopt a quantitative approach to the assessment of impacts. Instead, use was made of the findings of the few available case studies and the ecological theories were applied in order to assess the likely impacts on the river ecosystem. Further details of the assessment methodology are presented in Chapter Four. In addition to the ecological assessment, social and engineering criteria were also included to provide an inclusive perspective of the impacts on urban rivers. The basis for this component of the assessment is presented in Chapter Four.

To appreciate the philosophy and practice of environmentally-sensitive river management, a comprehensive literature review was undertaken. This included documentation of the range of measures available to mitigate the negative ecological and amenity impacts on urban rivers. A number of recent river management projects in the Cape Town Metropolitan Area were also visited to ascertain whether any environmentally-sensitive features had been incorporated into the project. The potential mitigation measures focused on the river channel, as opposed to the floodplain and catchment levels.

Lastly, potential threats to the Liesbeek River are listed and possible mitigation measures to address selected impacts suggested.

1.5 LIMITATIONS OF THIS DISSERTATION

Although this dissertation is multi-disciplinary in nature, the focus is on the impacts of urbanisation, channelisation and canalisation on the aquatic ecosystem. The motivation for this emphasis is provided in Section 1.2. The amenity and social aspects are considered in less detail, with only the salient points described in order to present an integrated perspective of the impacts and possible solutions.

A complex and evolving field pertaining to urban rivers relates to administrative and legal issues, such as local and regional authority jurisdictions and responsibilities, private property rights, ownership of the river banks and bed, water rights, determination and enforcement of receiving water quality standards, and land use controls. The new Water Act, and the possible formation of catchment management authorities, is likely to have significant impacts on the management of urban river systems (Department of Water Affairs and Forestry, 1995; 1996a,b). Although these legal and administrative issues are likely to play a major role in how urban rivers are managed, these issues are not covered in this dissertation.

On account of the dynamic nature of aquatic ecosystems and complex interrelationships between the various abiotic and biotic factors which affect the ecosystem, it is extremely difficult to predict the specific impacts. As a result, the ecological assessment presented in this dissertation is merely an indication of the general impacts that can be expected.

The range of mitigation measures and their benefits as described in Chapter Seven are at a generic level. The selection and design of mitigation measures requires detailed site investigation and input from a range of disciplines, including hydraulic, hydrological, legal, administrative, cost and maintenance issues. Therefore, the possible mitigation measures, as suggested in Chapter Eight, to alleviate selected impacts in the Liesbeek River, only illustrate the potential ecological benefits.

1.6 STRUCTURE OF THIS DISSERTATION

This dissertation is presented in nine chapters. Chapter One provides a background and introduces the problem to be addressed. The aim, objectives, limitations and structure of the dissertation are then described.

Chapter Two presents a conceptual framework of the ecological theory of river ecosystem structure and functioning. It describes the typical abiotic and biotic characteristics of the various river reaches and then summaries the concepts underlying the current understanding of river ecosystems. It is argued that the riverine community is mainly determined by abiotic characteristics. These include current velocity, substrate and area, as well as water quality. This theory is utilised in Chapter Four in the assessment of the impacts associated with urbanisation, channelisation and canalisation.

Chapter Three explains the general effects of urban development on the quantity and quality of stormwater runoff. Changes in these two factors, combined with the effects of urban development in flood-prone areas, are responsible for much of the ecological and amenity degradation of urban rivers. The methods of increasing the discharge of natural river channels, such as clearing obstructions, channelisation and canalisation, are explored.

Chapter Four assesses the impacts of urbanisation, channelisation and canalisation on the ecological, amenity and engineering functions of urban rivers. This assessment draws on the ecological theory and engineering principles described in Chapters Two and Three respectively.

Chapter Five explores the background to environmentally-sensitive river engineering. It explains the history, provides some international case studies and notes the increase in public awareness of environmental issues. It also introduces the three spatial levels of environmentally-sensitive river management: catchment, floodplain and river channel management.

Chapter Six derives possible measures to mitigate catchment and floodplain level impacts. In particular, these refer to regulating the quantity and quality of stormwater runoff and the control of land uses within the floodplain.

Chapter Seven contains a comprehensive set of potential mitigation measures to reduce the significance of the river channel impacts described in Chapter Four. The mitigation measures are illustrated where possible and the environmental benefits described.

Chapter Eight outlines the history and characteristics of the Liesbeek River and describes potential threats to the ecological integrity and amenity value. In addition, there are examples of possible mitigation measures that address selected impacts.

Chapter Nine contains conclusions and recommendations based on the findings of the dissertation. This final chapter highlights the ecological theories which underlie the assessment of ecological impacts and the benefits of mitigation. The impacts of urbanisation, channelisation and canalisation are then summarised and possible mitigation measures at the level of the catchment, floodplain and river channel are described. Recommendations for environmentally-sensitive river management are also suggested.

CHAPTER TWO: ECOLOGICAL THEORIES OF RIVER STRUCTURE AND FUNCTIONING

CONTENTS

CHAPTER TWO: ECOLOGICAL THEORIES OF RIVER STRUCTURE AND FUNCTIONING

2.1 INTRODUCTION

> *"A major barrier to the inclusion of nature conservation requirements in river engineering is that often neither engineers nor ecologists are fully informed about the concepts, techniques and limitations which govern the other's work"* (Lewis and Williams, 1984, p11).

Odum (1969, p 262) defined an ecosystem as "any unit that includes all of the organisms ... in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles ... within the system". Rivers are closely linked to, and influenced by the floodplain and catchment. The boundaries of the river ecosystem correspond with the catchment boundary, or the area bounded by watersheds, within which water moves towards a river system.

This chapter provides an overview of the ecological principles and limnological concepts which form the theoretical base of river ecosystem functioning. In Chapter Four, these theories are applied, together with case studies from literature, to predict the effects that urbanisation and various forms of river engineering may have on river ecosystems. In Chapter Six, and especially in Chapter Seven, these theories are again utilised to inform the mitigation measures that constitute environmentally-sensitive river engineering.

2.2 RIVER ZONATION AND GENERAL CHARACTERISTICS

The physical, chemical and biological features of streams change along their courses. In the ecological literature this is recognized in various schemes of river zonation (Harrison, 1965; Illies, 1961; Noble and Hemens, 1978). Each zone has a distinct physical and hydrological character, and a distinct biota (O'Keeffe *et al.*, 1989).

Table 2.1: Idealised features of the three reaches of rivers as interpreted from the perspective of the river continuum concept (after Ward, 1992)

CHARACTERISTIC	REACHES		
	UPPER	MIDDLE	LOWER
Temperature	Cool, low variation	High variation	Moderate variation
Production to respiration ratio	Less than one	Greater than one	Less than one
Energy source	Terrestrial detritus	In situ primary production	Transported detritus
Nutrient availability	Low	High	Low

Attached algae		Sparse	Abundant	Sparse
Submerged angiosperms		Absent	Abundant	Sparse
Plankton		Absent	Absent	Present
Leaf litter		Abundant	Sparse	Negligible
Invertebrates :	Shredders	Co-dominant	Rare	Absent
	Collectors	Co-dominant	Co-dominant	Dominant
	Grazers	Sparse	Co-dominant	Absent
	Predators	Low	Low	Low
Environmental heterogeneity		Low	High	Low
Biotic diversity		Low	High	Low

For convenience, a generalised river can simplistically be divided into three zones, namely upper, middle and lower reaches. A typical stream would have bedrock, boulder, and cobble bed in the upper reaches, an alluvial gravel bed in the middle reaches, and an alluvial sandbed in the lower reaches. However, streams that originate in regions with moderate relief may have little or none of the boulder and cobble channel form, but a gravel bed in their headwaters. Similarly, streams originating in lowlands, for example, the Kuils River on the Cape Flats, will generally have a sandbed channel form throughout their length (Resh *et al.*, 1988). The abiotic and biotic characteristics of these three generalised zones are described below.

2.2.1 The upper reaches

The upper reaches are characterised by cool, clear, turbulent, well-oxygenated, nutrient-poor water and stony beds. There is often abundant canopy-like riparian vegetation, which reduces light penetration and thus limits aquatic macrophyte (the larger plants) development. Furthermore, instream macrophytes are limited by the high flow rates and associated scour.

The primary energy base available to aquatic invertebrate consumers in mountain-stream ecosystems comprises allochthonous food. This material is manufactured outside the river channel (Cummins, 1974). Stream ecologists have measured the amount of terrestrial litter entering streams (Gosz *et al.*, 1972; Fisher and Likens, 1973; Winterbourn, 1976; De La Cruz and Post, 1977; Blackburn and Petr, 1979; Conners and Naiman, 1984 cited in Stewart and Davies, 1990), the retention of this litter by the stream bed (Anderson and Sedell, 1979; Bilby and Likens, 1980; Rounick and Winterbourn, 1983; Speaker *et al.*, 1984; King *et al.*, 1987a,b cited in Stewart and Davies, 1990), and the breakdown of leaves, wood and bark by bacterial and fungal activity (Bärlocher and Kendrick, 1975 cited in Stewart and Davies, 1990). This allochthonous material consists largely of leaves and fruits derived from the riparian zone and is gradually broken down from course particulate organic matter (CPOM) to fine particulate organic matter (FPOM) by animals, bacteria and fungi.

Headwater reaches are dominated by invertebrate organisms adapted to living in fast-flowing water, and include the nymphs or larvae of mayflies (Ephemeroptera), stone flies (Plecoptera), caddisflies (Trichoptera), as well as the young and adult stages of beetles (Coleoptera) and bugs (Hemiptera). The most numerous invertebrates are shredders, which feed by breaking up or shredding CPOM. Food is usually scarce, resulting in slow growth rates and low productivity. The availability of litter falling into a stream as a food source for the biota of oligotrophic (nutrient poor) headwaters depends directly on the effective retention of leaf litter in the system. Prochazka *et al.* (1991) noted that the most retentive features were riffles and backwaters, while cobble substrata was the most retentive substratum.

In the South Western Cape, benthic (on the bottom or bed of the stream) organic matter ("leaf packs") reaches maximum values during summer and early autumn (King *et al.*, 1987). Early winter spates completely scour the bed, leaving a winter minimum. In summer, the very high densities of shredding amphipods (such as *Paramelita nigroculus*) and crabs (for example *Potamonautes perlatus*) have a significant effect on leaf breakdown, thereby lowering the expected amount of benthic organic matter (King *et al.*, 1987; Hill and O'Keeffe, 1992).

It has frequently been suggested that the life cycles of stream invertebrates are synchronised to maximise the use of allochthonous inputs (Vannote, *et al.*, 1980). However, studies of low-order (small tributary) streams in the South Western Cape have shown no such autumnal pulses of organic input from indigenous vegetation, but rather a protracted spring and summer fall (Day *et al.*, 1979; King, 1982; King *et al.*, 1987; Britton, 1990). This scarcity of food appears to account for the low productivity of the mountain streams of the region. The food available to the stream biota of South Western Cape rivers therefore fluctuates, but is temporally predictable, and the stream biota are presumed to be adapted to these regimes (Davies *et al.*, 1993).

The upper reaches support rare, often endemic species, whereas more hardy cosmopolitan types occur in the lower zones (O'Keeffe *et al.*, 1989). This is supported by King (1982), who found that macro-invertebrates endemic to the fynbos biome inhabit high-altitude headwaters and that a more widespread element becomes proportionately numerically larger downstream. This is presumably because the environmental influences affecting cool, clean high-altitude streams are fewer and less complicated than those affecting mature rivers which are influenced by larger, more varied and more disturbed catchments (O'Keeffe *et al.*, 1989).

In general, the riverine invertebrate fauna are dominated by insects. Other invertebrates only become apparent in the more sluggish and polluted waters of the lower reaches (King, 1982).

Headwater stream species are normally able to survive only a very narrow range of environmental conditions and any disturbance could eliminate these sensitive species (O'Keeffe *et al.*, 1989; Dallas and Day, 1993). Moreover, because of the longitudinal nature of rivers, any activity on a river, or in its catchment, will affect downstream sections of that river (Vannote *et al.*, 1980). A disturbance near the source could have a greater overall impact than one situated lower down the system. Neuhold (1981) argues that redundancy of organisms (that is when the function of an organism is performed by other organisms) increases downstream. Therefore, upstream ecosystems have less inertia, which is the ability of an ecosystem to recover from damage by replacing the function of one organism with another, and therefore are more sensitive to disturbance.

Typical fynbos species found along the upper courses of mountain streams in the South Western Cape include mosses, sedges (such as *Isolepis prolifer* and *Scirpus digitatus*), restionaceae (for example *Elegia capensis*), and shrubs (for example *Metrosideros angustifolia* and *Psoralea pinnata*). The larger and more permanent streams support riparian trees such as *Brabejum stellatifolium* (wild almond), *Brachylaena neriifolia* (Water white els), *Cunonia capensis* (Red els), *Ilex mitis* (Cape holly) (Boucher, pers comm).

2.2.2 The middle reaches

In the middle reaches, the stream widens, flow rate decreases, oxygen concentration decreases and there is an increase in temperature and turbidity. Riparian vegetation no longer forms a dense canopy so that more sunlight reaches the water. This, together with the reduction in flow rate, results in an increase in aquatic plant biomass. The bulk of food for riverine animals is autochthonous (generated within the stream) and consists of bacteria, fungi, algae and aquatic plants. The invertebrate community is dominated by collectors (which gather FPOM by erecting nets, sieves or strings of saliva) and grazers (which feed on the algal layer of rocks), with a few scrapers (Vannote *et al.*, 1980; Davies and Day, 1986; Cummins, 1992).

The channel is typically meandering and contains pool-riffle sequences, which increase the diversity of biotopes by providing standing and flowing water with a wide variety of substratum and flow characteristics. Conditions, such as temperature, vary more in the middle reaches than they do in the shaded headwaters. As a result, most species of invertebrates cannot survive year-round but occur either in summer and autumn or in winter and spring (Davies and Day, 1986). These seasonal communities replace each other, with the missing set of animals surviving the "unfavourable" period as eggs or minute larvae deep in the river bed (Cummins, 1974; Minshall *et al.*, 1985 cited in Ryder and Pesendorfer, 1989). On account of the variety of physical conditions, species diversity is maximised in the middle river reaches (Platts, 1979; Vannote *et al.*, 1980; Minshall *et al.*, 1983 cited in Brussock, 1985).

The suite of plant species typically associated with the middle reaches includes stands of ferns (such as *Pteridium aquilinum*), cyperoids (such as *Prionium serratum* (palmiet)) and shrubs and trees (such as *Brabejum stellatifolium* (wild almond), *Brachylaena neriifolia* (water white els), *Metrosideros angustifolia* and *Rhus angustifolia*.

2.2.3 The lower reaches

As rivers flow into the lowlands, they widen and the flow rate decreases, resulting in the settling out of fine organic and inorganic matter which forms a relatively uniform sandy or silty layer on the river bed. The water becomes less oxygenated, while mineral and nutrient loads increase leading to increased plant growth (Holmes and Newbold, 1989). The increased sunlight and lower flow rates encourage the growth of phytoplankton and zooplankton.

Amongst the invertebrates, collectors dominate, while deposit feeders also become abundant. Bottom-dwellers of many invertebrates tend to be worm-like in shape for burrowing into the substratum. The main refuge of aquatic non-burrowing forms is the semi-submerged backside vegetation (Davies and Day, 1986). The riverside reeds also provide shelter for birds who feed on the abundant aquatic life, while bottom-feeding fish increase the diversity of the fauna.

Table 2.2: Generalised physical and chemical characteristics of each reach (modified after Dallas and Day, 1993)

CHARACTERISTIC	UPPER REACH	MIDDLE REACH	LOWER REACH
PHYSICAL			
Slope	Steep	Gradual	Very gradual
Velocity	Fast, erosive	Slower	Slow, depositing
Substratum	Mainly boulders	Mixed boulders and sand	Sand and mud
Temperature	Normally cool	Slightly warmer	Warm
Riparian vegetation	May be canopy	Concentrated on banks	Only on banks
CHEMICAL			
Dissolved oxygen	High	Intermediate	Low
Nutrients	Low	Intermediate	High
Conductivity	Low	Medium	High
pH	Low	Medium	High

The presence and abundance of the aquatic flora found in the lower reaches of the river depends on the magnitude and velocity of floods, which can scour out even perennial species (King, pers comm). Aquatic vegetation that may be found in protected backwaters of South Western Cape rivers includes *Aponogeton distachyos* (water blommetjie) and *Nymphaea capensis* (water lily). Species along the water's edge include *Cyperus marginatus*, *Isolepis prolifer*, *Junkus kraussii*, and *Polygonum salicifolium,* together with grasses, such as *Cynodon dactylon* (kweek) or *Sporobolus virginicus*. *Prionium serratum* (palmiet), together with the cosmopolitan *Phragmites australis* (fluitjies riet) and *Typha capensis* (bulrush), are found where silt accumulates.

2.3 BASIC CONCEPTS OF LOTIC ECOSYSTEM FUNCTIONING

2.3.1 Introduction

In the development of a scientific discipline, the emphasis changes from basic data collection to prediction via the formulation, testing and refinement of concepts (Hart and Allanson, 1984).

Ecology in general, and limnology (the study of freshwater ecosystems), in particular, is a young science and the conceptual basis for stream studies is therefore not well established (Hart and Allanson, 1984). The following concepts represent the current understanding of the functioning of lotic or running water ecosystems:

- the River Continuum Concept (Vannote *et al.*, 1980);
- the Nutrient Spiralling Concept (Newbold 1987, 1992);
- the Serial Discontinuity Concept (Ward and Stanford, 1983a);
- the resilience of rivers (Hynes, 1966, 1970; Webster *et al.*, 1983 cited in Boon, 1992);
- the Intermediate Disturbance Hypothesis (Connell, 1978; Ward and Stanford, 1983b), and
- the Flood Pulse Concept (Junk *et al.*, 1989).

In addition to these concepts, lotic ecosystems are subject to general ecological theories. Rivers represent complex four-dimensional systems, and the above theories have been assigned to longitudinal, lateral, vertical and temporal components.

Rivers are influenced by, and interact with, the surrounding landscape (Hynes, 1975; Ward, 1989). To perceive rivers as ecosystems necessitates an integrated spatio-temporal framework that includes:

- a longitudinal dimension from headwaters to the sea;
- a lateral dimension extending beyond the channel boundaries (including the riparian and floodplain zones);
- a vertical dimension encompassing the ground water system, and
- a temporal dimension (Ward and Stanford, 1989).

The following sections describe the theories relating to each of these dimensions.

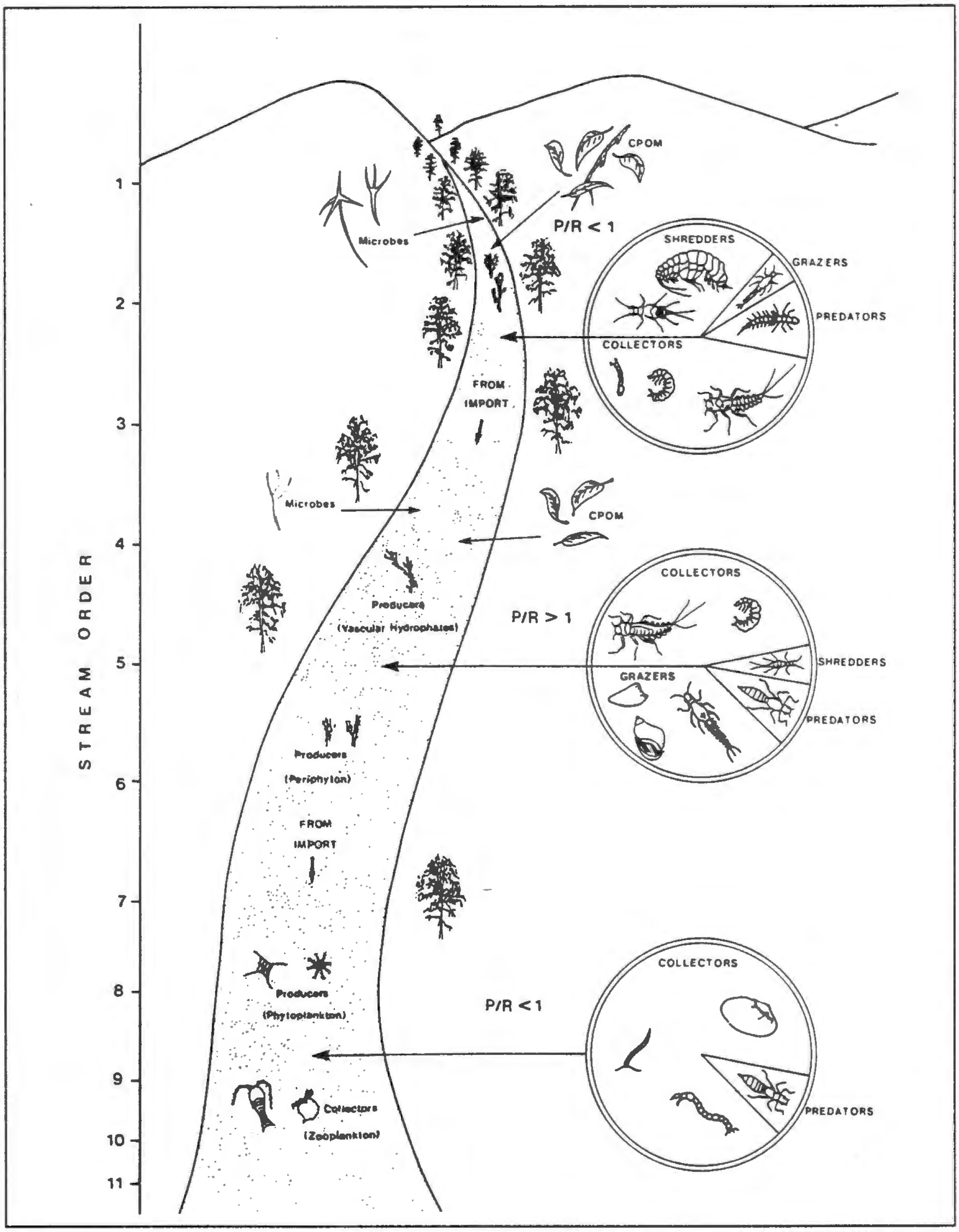
2.3.2 The longitudinal dimension

The following concepts relate to the longitudinal nature of river ecosystems: the River Continuum Concept, the Nutrient Spiralling Concept and the Serial Discontinuity Concept. These are important because they stress that impacts at some point are likely to have upstream and especially downstream implications.

a) <u>The River Continuum Concept (RCC)</u>

The River Continuum Concept (RCC) was formulated by Vannote *et al.* (1980) in an attempt to provide a coherent description of the various morphological and biological changes that occur during progression downstream from small streams to large rivers (Welcomme *et al.*, 1989). The RCC suggests that plant and animal communities adjust to spatial resource gradients imposed by downstream changes in environmental conditions. The biological adjustments are evident in the changing balance of production and decomposition and in changes of species composition (Hart and Allanson, 1984).

Figure 2.1: Some general features of the River Continuum Concept (after O'Keeffe, 1986)



Furthermore, the concept proposes that changes in community composition will be expressed as a downstream succession of "functional feeding groups". Leaf material imported to the headwaters of a stream is subject to the action of "shredders", and plant material produced within the stream is utilized by "grazers". The general pattern is of a continuum, whereby coarse particulate organic matter (CPOM) is progressively reduced to fine particulate organic matter (FPOM) by the successive actions of these functional groups, or "litter processors" (Minshall *et al.*, 1983). Thus, the processes in downstream reaches are directly linked to those upstream (Cummins, 1979; Minshall *et al.*, 1983; Cummins *et al.*, 1984; Ward and Stanford, 1987.

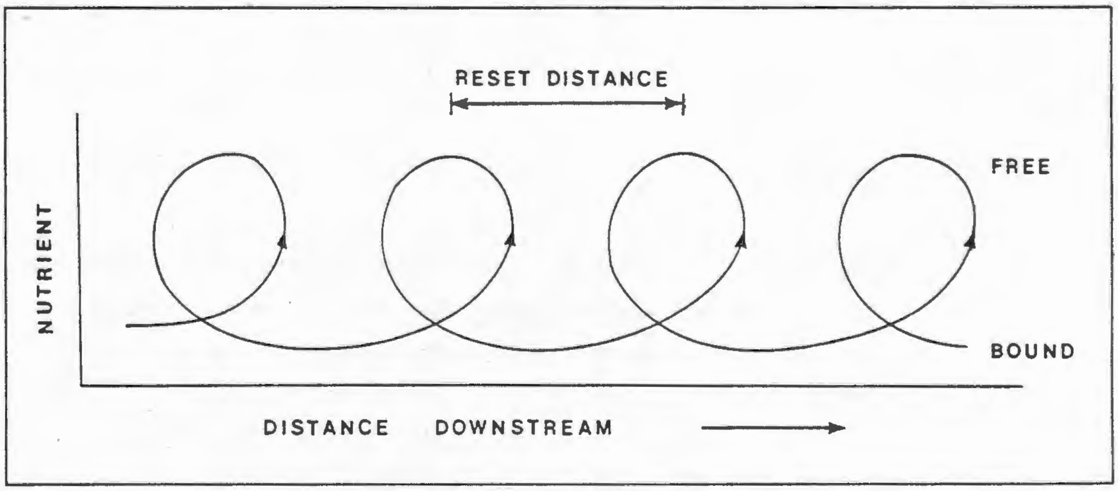
b) The Nutrient Spiralling Hypothesis (NSH)

The theory of stream ecosystem structure and functioning has come to emphasise the origins and fates of organic resources and inorganic nutrients (Cummins, 1974; 1975; 1977; Hynes, 1970; 1975; Cummins and Spengler, 1978; Minshall, 1978 cited in Cummins, 1979). Studies of detritus dynamics in headwater streams have shown the importance of organic inputs from the riparian zone (Fisher and Likens, 1973; Cummins, 1974; Sedell *et al.*, 1975; Cummins *et al.*, 1979; Karr and Schlosser, 1978 cited in Swales, 1982). However, it is generally considered that the upper reaches of most streams and rivers are predominantly heterotrophic (dependent on organic matter supplied from outside the river) (Hynes, 1970).

Proponents of the River Continuum Concept (RCC) view downstream changes not as zones, but as resource gradients along which the biota are predictably structured (Vannote *et al.*, 1980). The RCC emphasizes that downstream communities are a function of upstream processes (Ward and Stanford, 1989) and that the quantity and quality of detritus in a given reach is influenced by the allochthonous inputs, autochthonous production, microbial and animal processing, and retention characteristics of upstream areas.

The dependence of downstream communities on upstream processes implies that communities in each successive stream order are dependent upon the inefficiency or "leakage" from the preceding orders (Cummins, 1979). This storage-cycle-release nature of lotic ecosystems is embodied in the Nutrient Spiralling Hypothesis (NSH) (Webster, 1975; Wallace *et al.*, 1977; Webster and Patten, 1979; Elwood *et al.*, 1983 cited in Ward and Stanford, 1983a). The NSH is concerned with the unidirectional and biologically mediated recycling (spiralling) of nutrients along the river continuum.

Figure 2.2: The Nutrient Spiralling Concept (after Hart and Allanson, 1984)

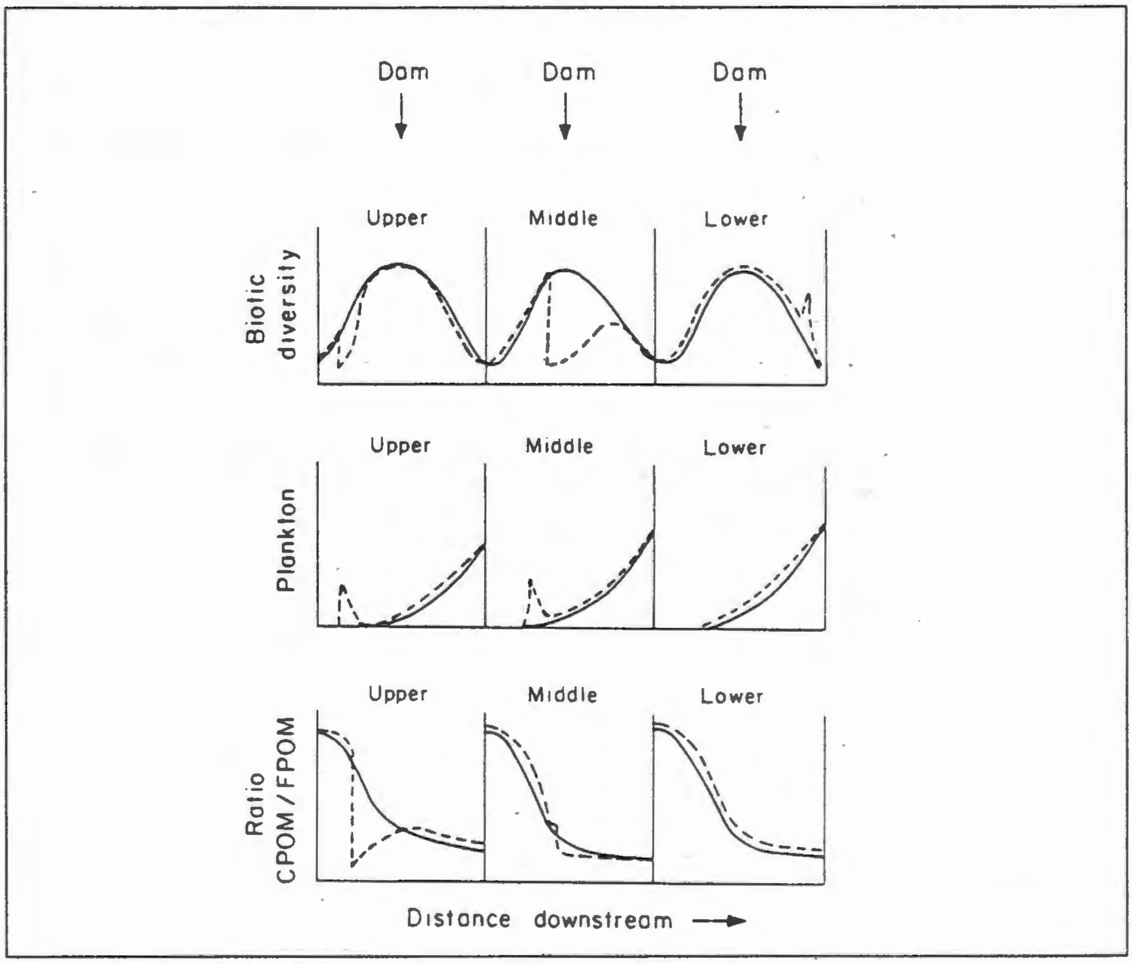


In a "closed" system, such as a lake, nutrients are cycled, being taken up by living organisms and returned to the environment in the process of decomposition. In streams, a more "open" system operates. As the nutrients are cycled, they are continually displaced downstream, so that they are said to traverse an imaginary spiral, or more correctly, a helix (Hart and Allanson, 1984).

c) The Serial Discontinuity Hypothesis (SDH)

The Serial Discontinuity Hypothesis (SDH) was developed in recognition of the major interruption of longitudinal gradients caused by dams and the downstream changes in abiotic and biotic characteristics that may occur (Ward and Stanford, 1983a). The hypothesis assumes that the RCC and NSH are conceptually sound and that their underlying assumptions are valid. Given that river communities do represent a continuum, the construction of a dam creates a discontinuity. The effect on any given characteristic may be visualized, and quantified, in terms of a "reset distance", the distance downstream of the perturbation required for the characteristic to return to its original value (Hart and Allanson, 1984).

Figure 2.3: The Serial Discontinuity Hypothesis showing the relative changes in variables downstream of a dam in the upper, middle and lower reaches (after Hart and Allanson, 1984)



The SDH stresses the significance of dam placement along the longitudinal profile. The effect of impoundment on a given variable depends on the pre-impoundment condition of that variable, which in turn changes along the longitudinal profile (Ward and Stanford, 1989). The clarifying effect of impoundments, for example, will have little influence on the transparency of already clear water in the upper catchment, whereas a dramatic alteration will occur if the lower reaches of a turbid river are dammed. The SDH can be applied to physical parameters such as temperature, and biological phenomena at the population (e.g. species abundance patterns), community (e.g. biotic diversity), or ecosystem levels (e.g. photosynthesis/ respiration) (Ward and Stanford, 1983a).

2.3.3 The lateral dimension

Interactions along this dimension include active and passive movements of organisms between the channel and the adjacent riparian/ floodplain system, and exchanges of nutrients and organic matter (Ward, 1989). In addition, many less direct interactions occur, such as the influence of the flood regime on the composition, productivity, and successional state of riparian vegetation. This in turn, influences channel morphology, aquatic temperature and light regimes, habitat heterogeneity, and the quality, quantity and temporal nature of allochthonous inputs (Ward, 1989).

a) The Flood Pulse Concept

The ecological significance of exchanges between rivers and their flood plains is encapsulated by the Flood Pulse Concept (Junk *et al.*, 1989), which suggests that flooding is the major "driving variable" in the dynamics of lowland river ecosystems. The emphasis on lateral exchanges complements the RCC with its emphasis on longitudinal transport.

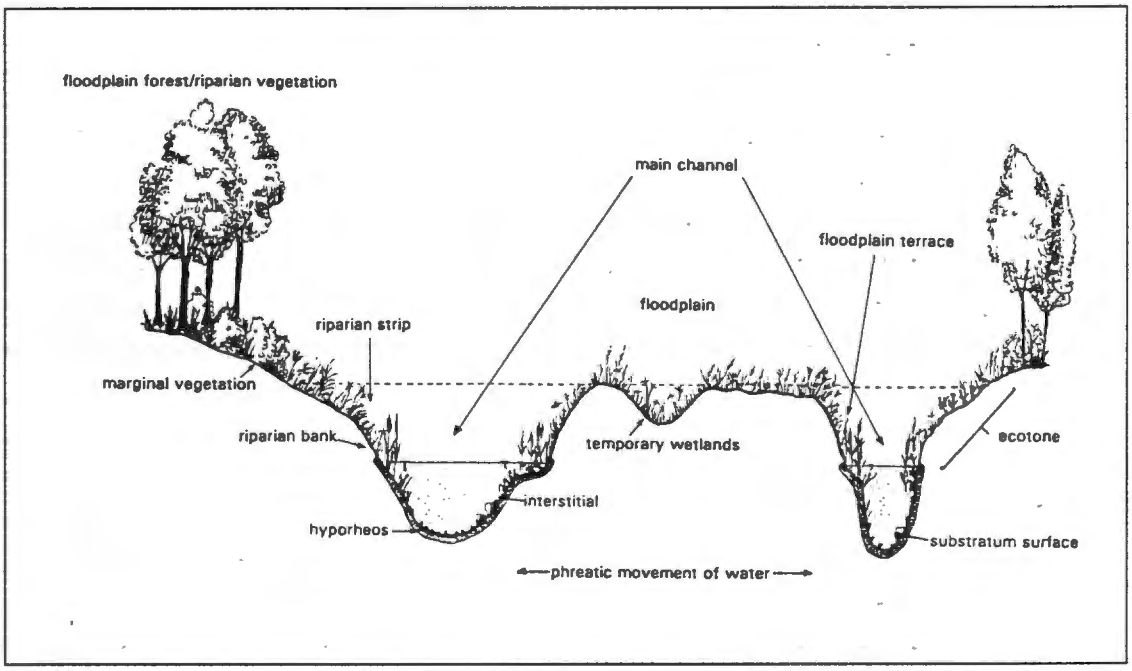
Vegetation succession is the process whereby a plant community, in time, becomes increasingly complex with regard to species composition, abundance, and interrelationships (Odum, 1971). Channel migration and flood events cause disturbance to the succession so that at any given time the floodplain contains several successional stages and therefore exhibits a high level of habitat diversity.

The Flood Pulse Concept applies particularly to large rivers with seasonally inundated flood plains (Junk *et al.*, 1989) and is therefore not applicable to rivers in the South Western Cape.

b) Boundaries or ecotones

A boundary, or ecotone, is defined as a zone of transition between adjacent ecological systems. Naiman *et al.* (1988) list the characteristics of ecotones as being areas with an abundance of certain resources (Blake and Hoppes, 1986) and a relatively high biological diversity (Lynch and Whigham, 1984). The tendency for ecotones to support more dense and diverse faunal communities is known as the "edge-effect" (Leopold, 1933 cited in Naiman *et al.*, 1988; Shields and Nunnally, 1984). This could be because ecological diversity, in term of species numbers, is often related to environmental heterogeneity (MacArthur, 1972 cited in Ryder and Pesendorfer, 1989). Davies *et al.* (1993) conclude that the spatial and temporal patchiness of ecotones contributes to the comparatively high biodiversity.

Figure 2.4: The major riverine habitats showing the ecotone between the aquatic and terrestrial environment (after Davies *et al.*, 1993)



The river-edge zone is an important ecotone linking the river channel and floodplain environments, and it also plays a crucial role in maintaining the structure and functioning of the river ecosystem (Naiman and Decamps, 1990, Ferrington and Goldhammer, 1992 cited in Davies *et al.*, 1993). Riparian vegetation influences the character of the river by reducing local current velocity, stabilising the river banks, shading of the channel, reducing temperatures, controlling the sediment input and retaining detritus (Cummins, 1992). Moreover, riparian vegetation influences the nature of autochthonous (for example the degree of shading) and allochthonous organic inputs such as type, quantities and season (Cummins *et al.*, 1984).

Vegetated riparian zones can provide a corridor of scarce, high-quality habitat through agricultural and urban areas (Johnson and Jones, 1977 cited in Shields, 1982b). However, corridors tend to favour edge-dependent species rather than those requiring large, undisturbed areas of habitat (Risser and Harris, 1989).

Backside habitats act as a buffer zone between the river and the adjacent land, helping to protect the river from human disturbance (Lewis and Williams, 1984). Buffer strips of natural habitat also protect the river from polluted runoff by precipitation, flocculation, or adsorption. In addition, pollution may be consumed or converted biologically by the plant and microbial communities found in such buffer strips (Petersen *et al.*, 1992).

2.3.4 The vertical dimension

Rivers are in intimate contact with ground water aquifers which contain a much greater volume of water than that contained in the river channel. The exchange of water between the river channel and the ground water, the "vertical" dimension, exerts a significant influence on river ecosystems (Danielopol, 1980; Hynes, 1983 cited in Ward and Stanford, 1989). In the following sub-section, the characteristics and function of the hyporheos are described.

a) The hyporheos

The hyporheic zone is the interstitial (the area between sand and gravel particles) habitat between the water in the river channel and the adjoining ground water (Orghidan, 1959 cited in Ryder and Pesendorfer, 1989). Various studies have shown that the hyporheic zone of small streams frequently extends only a few metres horizontally from the channel (Williams, 1984 cited in Sedell *et al.*, 1990). In contrast, the hyporheic zone in gravel-bed rivers may include extensive floodplain aquifers that are connected to the channel (Stanford and Ward, 1988). An important feature controlling the size of the hyporheic zone is the size and porosity of the substrata. Large cobbles, that have been sorted by fluvial processes, usually have greater interstitial spaces (25% to 40% of the aggregate volume) which allows more water to flow through them than compacted gravels, sands, or bedrock (Sedell *et al.*, 1990). The hyporheos therefore extends deeper below these coarser materials.

Hynes (1983) found that the density of invertebrates is sometimes higher at a depth of 5cm to 10cm below the stream bed. Ward and Stanford (1988) conclude that the volume of hyporheic habitat may be more than ten times that of the channel and that the biomass might well exceed the benthic biomass of the river.

Many investigators have found that the hyporheic zone provides a refuge for zoobenthos that migrate into the substratum to avoid adverse surface conditions during times of floods (Hynes, 1972; Ward and Stanford, 1989); during severe drought (Hynes, 1968; Imhof and Harrison, 1981 cited in Sedell *et al.*, 1990), and to avoid predators and extreme temperatures (Ward and Stanford, 1987). The hyporheos therefore mitigates against unfavourable conditions and provides a reservoir for invertebrate colonists (Ryder and Pesendorfer, 1989). In addition, the hyporheic zone provides suitable and predictable conditions for immobile stages such as eggs, pupae and diapausing nymphs and provides incubation sites for fish eggs and larvae.

The hyporheos supports a permanent specialized fauna (Sedell *et al.*, 1990). It also supports larval stages, especially of insects, that return to the main channel to emerge and complete their life cycles (Stanford and Ward, 1988).

The hyporheic zone serves as a sink for organic matter and is important to carbon cycling in running waters (Hynes, 1983). Husmann (1978 cited in Hynes, 1983) stressed that loose gravel in well-oxygenated situations is a biologically active zone, and that it may be significant in the purification of organically polluted ground water. The interrelationships between streams and the hyporheos indicates that nutrient processing may be more complicated than the Nutrient Spiralling Hypothesis. Davies *et al.* (1993) hypothesised that during winter, when discharges are high in the South Western Cape, alternative sources of energy may become available to the invertebrate and decomposer communities, due to the flushing of ground water/ hyporheos nutrient accumulations. The frequently observed production of spate-generated brown foams which coat the rocky substrata and banks support this hypothesis. These foams could provide an extremely important food resource for stream invertebrates during winter, which would normally be regarded as "lean times" for the invertebrate and decomposer communities.

2.3.5 The temporal dimension

The importance of biological interactions in structuring stream communities is currently a matter of controversy. Some scientists maintain that physical and chemical factors are more important in determining the distribution and abundance of stream invertebrates (Rabeni and Minshall, 1977; Minshall and Minshall, 1978; Stout, 1981 cited in Townsend, 1989). Other scientists maintain that competition or predation are more important (Peckarsky and Dodson, 1980; McAuliffe, 1983; Hemphill and Cooper, 1984 cited in Townsend, 1989).

Traditional community ecology theory states that competition is the most important force in structuring communities. The co-existence of species was predicted according to the Competitive Exclusion Principle, which states that co-existing species must differ in their trophic niches. More recently, attention has shifted away from this simple deterministic model to give non-equilibrium and stochastic or random factors more prominence (Townsend, 1989). The increased emphasis on disturbance is particularly relevant to stream ecosystems. Disturbance acts as a reset mechanism and is defined as "any relatively discrete event in time that is characterized by a frequency, intensity, and severity outside a predictable range, and that disrupts ecosystem, community, or population structure and changes resources or the physical environment" (Resh *et al.*, 1988, p 433). Disturbance may be rapid (for example a spate), or a prolonged change (such as a drought) in the physical environment that exceeds the normal range of conditions experienced by a substantial number of organisms resulting in their death and/or removal (Minshall, 1988). The most common natural disturbance associated with streams is related to an increase in discharge accompanied by increased velocities and bed movement.

Characteristics of disturbance include magnitude, frequency, predictability, duration and rate of change. These characteristics will affect various groups of organisms differently as a result of differences in mobility and life cycle factors (Statzner, 1987; Statzner *et al.*, 1988 cited in

Minshall, 1988). Furthermore, they will affect the rate and dynamics of recovery, particularly the mechanisms by which recruitment occurs (Minshall, 1988). While small-scale spatial disturbance is expected to enhance species diversity and trophic structure, disturbance at larger scales (reach or catchment) may have an adverse effect on communities because of the lack of colonists (Minshall, 1988). Anthropogenic activities can disrupt the natural temporal patterns that structure riverine ecosystems (Ward and Stanford, 1989). Temporal disruptions result in altered predator-prey, competitive and trophic interactions, and affect fecundity, recruitment, growth, and mortality.

Ecosystems accommodate natural perturbations or disturbances of some magnitude and intensity (Regier *et al.*, 1989). Mature ecosystems are resilient and have a variety of alternative ways of maintaining basic functions even though external pressures may be harsh (Likens and Bormann, 1974). This is referred to as the "assimilation capacity" of an ecosystem, and reflects the ability of the system to "hide" or to avoid short-term effects (Likens and Bormann, 1974).

The following four sub-sections describe the ecological concepts of succession, resilience, the intermediate disturbance hypothesis and the dynamic equilibrium model.

a) Succession

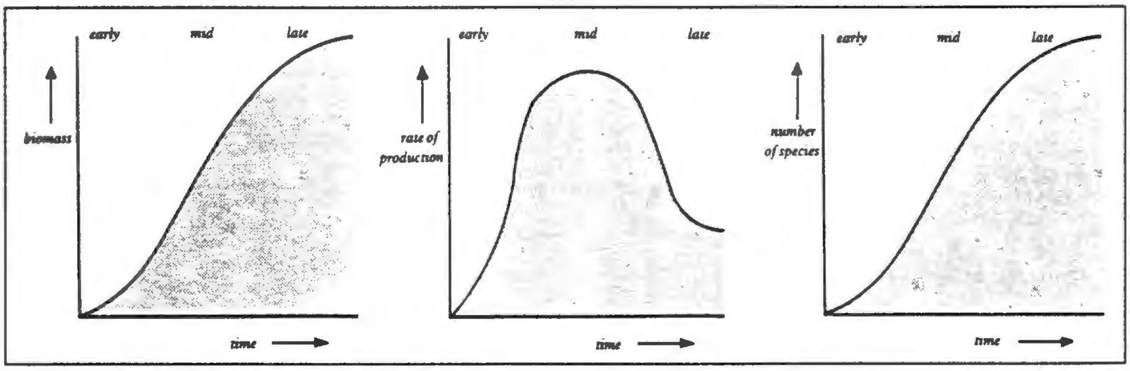
Communities undergo change, so that the age of a community (since its last disturbance) is vital to its structure and composition (Lewis and Williams, 1984). This change is called ecological succession. Odum (1969) defines succession as having three parameters:

- it is an orderly process of community development that is reasonably directional and, therefore, predictable;
- it results from modification of the physical environment by the community; that is, succession is community-controlled even though the physical environment determines the pattern and rate of change, and
- it culminates in a stabilised ecosystem.

The first colonisers (pioneers) to a bare site must be able to survive the rigorous physical conditions, but have the advantage of no competition for light, space or resources. Over time, the pioneers are ousted by more specialised species, and the biomass and number of species increases (Figure 2.5) (Lewis and Williams, 1984).

Different streams, particular reaches or areas within a reach may support different types of communities because they are subject to different disturbance regimes. Stream benthic communities occurring under "flashy" discharge regimes, tend to be occupied by "weedy", fugitive, or r-selected species (Townsend, 1989). In contrast, stable or predictable river ecosystems support predominantly K-adapted species, which are characterised by long-lived, "specialist" species, typical of late successional stages.

Figure 2.5: Graphs showing how biomass, rate of increase of biomass and species diversity change as succession proceeds (after Lewis and Williams, 1984)



Greenslade (1983 cited in Minshall, 1988) indicates that K-selected communities would have a higher species diversity. This is because the complexity of food chain interactions and available habitats is greater in later rather than in earlier stages of succession (Lewis and Williams, 1984).

b) <u>The resilience of rivers</u>

Stream organisms are adapted to both regular and irregular disturbances or resets, and recuperate quickly through the use of one or more adaptive mechanisms (Minshall *et al.*, 1985 cited in Ryder and Pesendorfer, 1989). Resets are essential to the maintenance of normal community structure in streams (Cummins, 1977; Cummins and Spengler, 1978 cited in Ryder and Pesendorfer, 1989). The presence of refugia (such as backwaters, pools, riparian zones and flood plains), passive and active migration into the hyporheos, as well as flexible life histories and effective recolonisation mechanisms enable the benthos to persist and recover from frequent, temporally unpredictable disturbances (Scrimgeour and Winterbourn, 1989; Fisher, 1990).

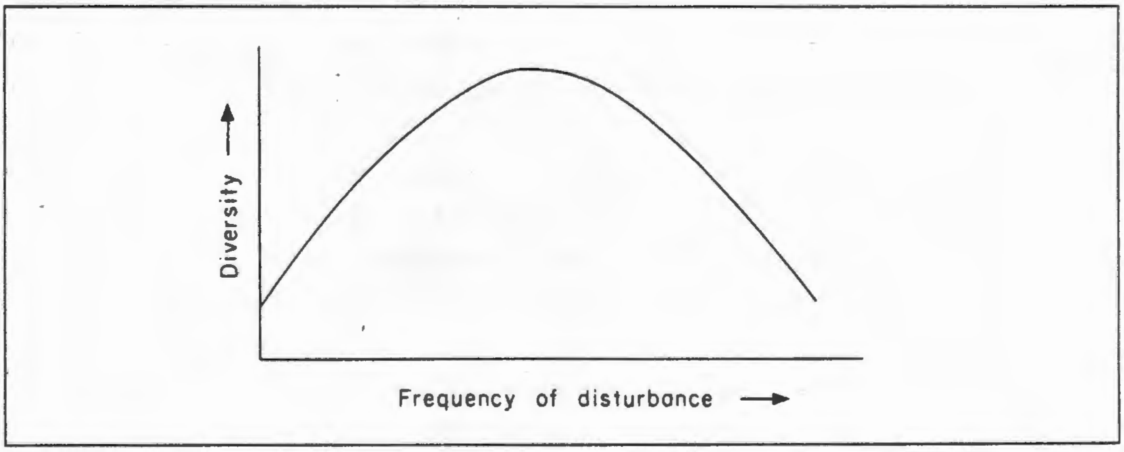
Even after major spates, when a major proportion of the biota is lost, recovery to near pre-spate community composition can be rapid (Townsend, 1989). For example, Reice and Smith (unpublished cited in Reice *et al.*, 1990) found that, following a spate, total animal densities were reduced by 48% in cobbles and by 79% in sand-gravel. Within two weeks, animal densities rebounded to 240% in cobbles and 510% in sand-gravel. These data are consistent with the hypothesis that both the magnitude of change and the resilience of the community are greater for sand-gravel than for cobbles (Reice *et al.*, 1990). Biological communities in sandbed channels are probably least affected by physical disturbances, such as increased velocity, because even moderate flows are able to move sand. The biotic community, which has had to adapt to these conditions, is therefore less affected by increased movement of this type of substratum (Reice, 1985 cited in Resh *et al.*, 1988).

Biotic communities in gravel bed channels may be affected most by an increase in flow velocity (Resh *et al.*, 1988). Pools are likely to experience the greatest physical disturbance during flow reversal events. This is because during normal flows pools are depositing environments, but during high flows they become eroding environments. The opposite prevails in riffle areas. During flow reversal events (which are bed-forming flows), the upstream slopes of riffles are the least disturbed. This may explain the upstream biased distribution of most invertebrates within riffles (Mason, 1976; Lamberti and Resh, 1978; Godbout and Hynes, 1983; Brown and Brown, 1984 cited in Resh *et al.*, 1988).

c) The Intermediate Disturbance Hypothesis (IDH)

The IDH is a non-equilibrium model of disturbance and community structure. It was developed by Connell (1978) to explain the high species diversity in tropical rain forests and coral reefs. It presumes a competitive hierarchy of species and that the superior competitors are the more efficient occupiers of space (resident species) (Resh *et al.*, 1988). In the absence of disturbance, superior competitors will eliminate those that are inferior, reducing the species richness of the system. On the other hand, if disturbances are too frequent or of too great a magnitude, the resident competitors will be eliminated and colonizing species (inferior competitors) will dominate the system. However, under a disturbance regime that is intermediate in frequency and intensity (and area), resident species will persist in the system, along with a continuing supply of colonising species (Connell, 1978) therefore yielding maximum species richness.

Figure 2.6: The theoretical relationship between biological diversity and environmental disturbance



The application of the IDH to streams is discussed by Ward and Stanford (1983b) and Reice (1984). The theory is supported by studies in Sweden (Badcock, 1953b); Bavaria (Engelhardt, 1951); Wales (Jones, 1948), and North America (Nevin, 1936 cited in Hynes, 1972). These studies showed that streams which are more liable to spates had less abundant and less varied faunas than rivers that were not (Hynes, 1972).

d) The Dynamic Equilibrium Model

The Dynamic Equilibrium Model of Huston (1979 cited in Reice *et al.*, 1990) regards community structure as a trade-off between growth rates, rates of competitive exclusion of species, and frequency of population reductions. Huston proposed that if the recurrence interval of disturbance was shorter than the time necessary for competitive exclusion, then species that were poorer competitors would persist in the system. This would serve to increase species richness, unless disturbance was severe or frequent enough to eliminate those with long life cycles. "Diversity is determined not so much by the relative competitive abilities of the competing species as by the influence of the environment on the net outcome of their interactions" (cited in Reice *et al.*, 1990, p 648).

In streams, the continuous redistribution of benthos, due to invertebrate drift and colonization of denuded substrata, reduces the role played by predation and competition (Resh *et al.*, 1988). Different species have different propensities to drift and recolonize, depending on local physical and biological conditions (Townsend, 1980; Minshall and Petersen, 1985; Brittain and Eikeland, 1988 cited in Townsend, 1989). Furthermore, upstream movements of organisms and upstream flight by ovipositing adults (Williams and Hynes, 1976 cited in Townsend, 1989) add to the dynamic process. The net result is that the effects of local species interactions are swamped and community composition, at least on a small scale, is largely determined by disturbance and colonization dynamics within a patchy environment (Townsend, 1989).

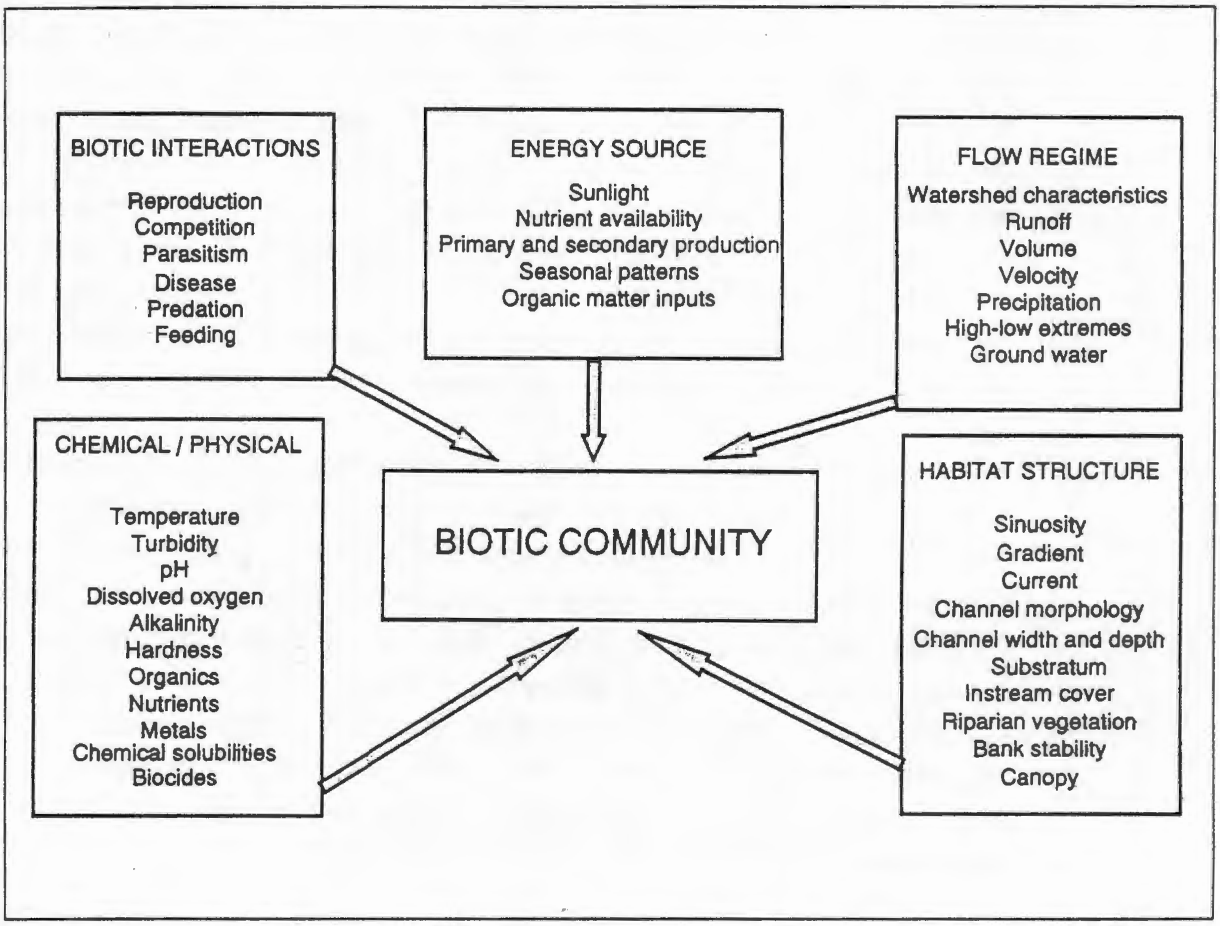
Reice *et al.* (1990) assert that many stream communities exist in a state of perpetual recovery from frequent disturbances. It is this condition that prevents competitive processes from reducing stream species diversity. Similarly, Legendre and Demers (1984 cited in Reynolds, 1988) argued that biotic communities responded first to the physical environment and that the more "traditional" selective chemical and biotic determinants were only secondary. In ephemeral streams, ponds and wetlands a further type of disturbance, namely drying, occurs. Connell's (1975 cited in Davies *et al.*, 1993) "harsh-benign" hypothesis suggests that, as environmental stress declines, biological interactions become more significant in the dynamics of communities.

2.4 FACTORS AFFECTING THE AQUATIC COMMUNITY

Riverine communities are influenced by numerous biotic and abiotic (physical and chemical) factors. These factors (including historical factors) affect the composition of the aquatic community (Figure 2.7).

Biotic factors arise from interactions among living organisms in a community and include competition for light, nutrients and space, territory, or predation (Lewis and Williams, 1984). Little is known about biotic interactions in streams, but even these are influenced by physical factors (Pattee and Bournaud, 1970; Edington and Hildrew, 1973 cited in Ward and Stanford, 1979).

Figure 2.7: Some of the chemical, physical and biological factors that determine the biotic community (after Dallas and Day, 1993)



During the past two decades, a pervasive theme has emerged in stream ecology, namely that biotic dynamics are intimately and inextricably linked to variation in abiotic factors (Power *et al.*, 1988). Abiotic or physical factors include substratum composition, water depth (and velocity), aquatic and riparian vegetation, dissolved substances, light level and water temperature, together with daily and seasonal fluctuations of these variables (Macan, 1961; 1974; Hynes, 1970a,b cited in Ward and Stanford, 1979; Lewis and Williams, 1984). Theoretically, all of these factors affect each other but, in practice, in river ecosystems, three factors are most important in determining the character of the steam community: temperature, flow characteristics and substrate (Ward and Stanford, 1979; Lewis and Williams, 1984). In turn, these three factors are dependent on climate, geology, slope, precipitation and land use and these major controlling factors are also interrelated. For example, current velocity influences substratum particle size, and the type of substratum influences the composition and abundance of aquatic plants, which in turn influences current velocity and therefore substratum particle size.

Additional important factors determining the aquatic community include the area of instream/ hyporheos habitat, the area of riparian/ floodplain habitat and water quality. Components of water quality that may have a strong influence on the aquatic community include turbidity, dissolved oxygen, nutrients and toxic substances (Dallas and Day, 1993). One feature of lotic ecosystems is their chemical homogeneity, which is caused by turbulence throughout the water column

(Winger, 1981 cited in Ryder and Pesendorfer, 1989). Water quality variables may therefore be considered to operate in a homogeneous manner over localized areas of a stream (Rabeni and Minshall, 1977, p 34). However, on a micro-scale, there are likely to be localised effects, especially at and below the substratum.

The relationship between environmental heterogeneity and species diversity has been demonstrated in various forms of animal communities and various types of habitat (Rosenzweig and Winakur, 1969; Karr and Roth, 1971; Allan, 1975 cited in Swales, 1982). According to Dean and Connell (1987a,b cited in O'Connor, 1991), complex physical structure increases species richness by providing a greater number of resources, and/or niches. The scale at which habitat heterogeneity operates varies from species to species. Moreover, different life stages of the same species may require different conditions. However, current velocity, substratum conditions and detritus distribution are varied and represent habitat heterogeneity for a specific stream reach.

A healthy stream typically supports a large variety of organisms with a moderate population of most taxa (Dunne and Leopold, 1978). As health decreases, species richness decreases and a few species may develop very large populations. The general assumption is that high levels of diversity are desirable, and that high diversity equates with high levels of biological integrity (Hart and Campbell, 1991).

Over aeons, species have adapted to certain conditions. The range of conditions within which a species can survive is known as its tolerance range. However, even within the tolerance range, growth, fecundity and other measures of "health" may be negatively impacted (Dallas and Day, 1993). As different species have different tolerance ranges, alterations in environmental conditions will affect the species to a greater or lesser extent. This will gradually alter the constituent species of a biotic community until it is no longer recognisable. Some examples include :

- a shift in the physical position of communities, e.g. the community in the upper reach of a river changes to resemble a middle reach community;
- a change in the direction of earlier stages of succession, and
- a reduction in species diversity.

2.5 SUMMARY

This chapter has presented an overview of the ecological principles and limnological concepts which form the theoretical base of river ecosystem functioning.

Physical, chemical and biological characteristics change along the length of rivers and these changes are reflected in the concept of river zonation. The structure of aquatic communities emphasised the role of producers and consumers, and the complex web of abiotic and biotic interactions which occur within the stream ecosystem.

Stream ecosystems have longitudinal, lateral, vertical and temporal dimensions and the key concepts relating to each dimension were presented. With regard to the longitudinal dimension, it was concluded that downstream organisms depended on the processing of organic matter by upstream organisms; that the food source in the headwater reaches comprised mainly allochonous detritus produced outside of the river channel; that autochthonous food became more important in the middle and lower reaches; that these resource gradients were reflected by the functional feeding groups to which aquatic invertebrates can be assigned and that impacts at any point in the river system had upstream and especially downstream implications.

Concepts applicable to the lateral dimension include that rivers were influenced by activities in the catchment; that the river channel was intimately linked to the floodplain and that the river banks were comprised of diverse ecotones. The vertical dimension included the following key points: that the river channel was linked to the ground water; that there was exchange of water and nutrients between the stream and the hyporheos; that the hyporheos provided an important refuge for aquatic invertebrates during unfavourable conditions, that it can be extensive and can support a large biomass.

With regard to the temporal dimension, it was concluded: that disturbance, mainly in the form of flood events, is a key structuring force in lotic ecosystems; that stream organisms are adapted to the natural magnitude and frequency of disturbance and can recolonise rapidly; that intermediate levels of disturbance lead to the persistence of pioneers and later successional species, thus resulting in maximum species diversity, and that the physical environment influences the outcome of biological interactions.

Another important concept is that environmental heterogeneity leads to a diverse assemblage of species. Furthermore, a large number of species is ecologically more desirable than a few species with large population numbers. Finally, it was concluded that stream communities are largely determined by abiotic, as opposed to biotic factors. The key abiotic factors include flow velocity, substrate composition and water quality. In addition, the area of instream, hyporheic, riparian and floodplain habitat are important determinants of the community.

The assessment of the ecological effects of urbanisation, channelisation and canalisation presented in Chapter Four relies on the ecological concepts of river ecosystem structure and functioning presented in this chapter. Since the key abiotic factors have been shown to have a dominant effect on the stream ecosystem, changes in these factors have been utilised to assess the ecological impacts.

The following chapter provides an overview of conventional stormwater management and the effects of urbanisation on stormwater runoff. It also presents the rationale for river channel engineering works such as clearing obstructions, channelisation and canalisation.

CHAPTER THREE: CONVENTIONAL STORMWATER MANAGEMENT AND RIVER CHANNEL ENGINEERING

CONTENTS

CHAPTER THREE: CONVENTIONAL STORMWATER MANAGEMENT AND RIVER CHANNEL ENGINEERING

3.1 INTRODUCTION AND PHILOSOPHY

> *"The engineer is required to prevent the river from flooding people's houses. To achieve this, many trees would have to be removed, the river deepened and straightened or even lined with cement. The river would cease to be recognizable as the river which the local people enjoyed, but it would become a very efficient drain." (Purseglove, 1989)*

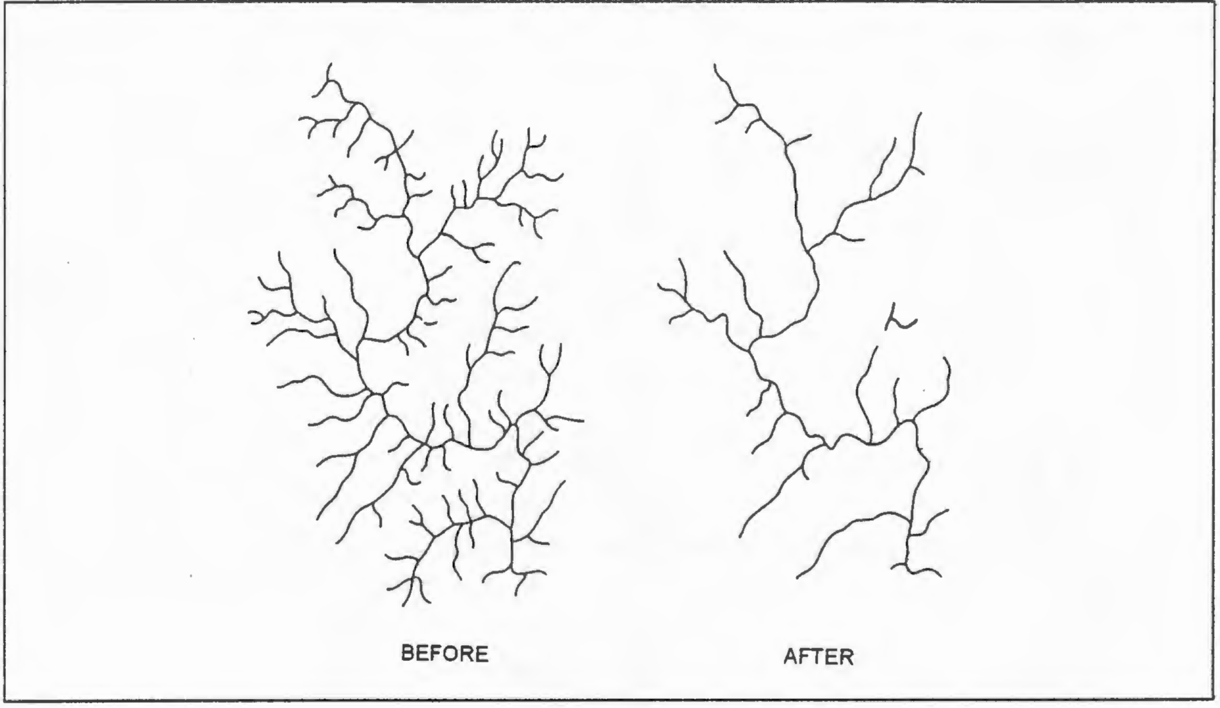
This chapter reviews the philosophy and methods of conventional stormwater management and associated river channel engineering. The motivation for urban stormwater management is to minimise the inconvenience caused by frequent precipitation events, to reduce flood damage and risk to human life during infrequent storm events, as well as to minimise the area of land subject to inundation (Miles, 1984). Conventional stormwater management aims to remove runoff from urban areas and transport it as cheaply and as rapidly as possible to the sea.

In order to achieve rapid transport of flood flows and to prevent inundation of floodplain land, it is necessary to modify or "improve" natural river channels. This chapter describes how urbanisation changes the runoff from a catchment and then discusses some of the conventional river channel engineering works, including river maintenance/ clearing, channelisation (enlarging and straightening) and canalisation (concrete-lining).

3.2 THE EFFECT OF URBANISATION ON THE RUNOFF REGIME

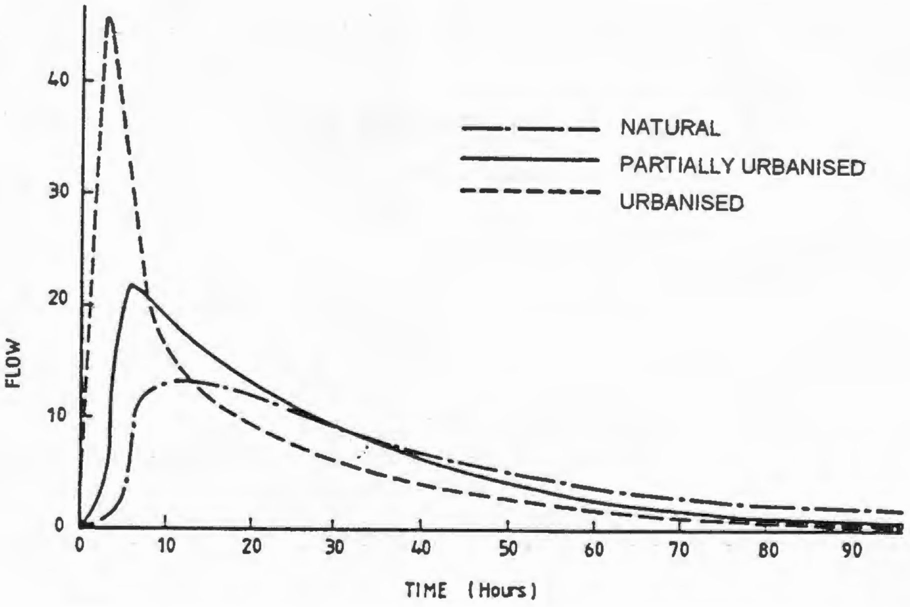
The "hardening" of catchments by the creation of impermeable surfaces, such as roads, car parks, paths and buildings, greatly reduces the infiltration of precipitation into the ground. In addition, urbanisation typically results in the loss of first and second order streams (the smallest tributaries are known as first order, two first order streams form a second order stream, etc.), and their replacement by stormwater pipes and culverts (Figure 3.1). This results in a decrease in the storage of water in these channels, with the result that runoff is delivered to receiving streams more rapidly (Dunne and Leopold, 1978).

Figure 3.1: Theoretical map of the drainage network before and after urbanisation, showing the loss of lower order streams (after Dunne and Leopold, 1978)



The overall effect of these modifications to the catchment is to increase the volume of runoff and to concentrate the flood peak (Miles, 1984). Urbanisation can increase the peak discharge of stream flows by a factor of 3 to 4 (Beaumont, 1988). This is clearly shown in a comparison of a typical urban and pre-urbanisation hydrograph (Figure 3.2).

Figure 3.2: Theoretical hydrograph showing the effect of urbanisation on the flood peak, timing and volume (after Beaumont, 1988)



3.3 CONVENTIONAL RIVER CHANNEL ENGINEERING

3.3.1 Background

To address the increase in stormwater runoff and to make more land available for urbanisation, natural river channels in urban areas, or draining them, are frequently modified. This section describes the methods of increasing the discharge of natural river channels.

Conventional stormwater management and flood alleviation works improve natural stream channels that are hydraulically inefficient, thus reducing the frequency of over bank flooding. They seek to increase either the capacity of the channel or the velocity of water, or both. This is because channel discharge is determined by the product of cross-sectional area of flowing water and its velocity (Dunne and Leopold, 1978).

Figure 3.3: Factors affecting the discharge of a channel

$$Q = A \times U$$
$$= (W \times D) \times U$$

where Q = discharge (m^3/s),
A = area (m^2),
U = velocity (m/s),
W = width (m) and
D = depth (m).

The simplest method of increasing discharge is to enlarge the channel capacity by increasing the cross-sectional area. This can be achieved by increasing the width and/ or the depth of the channel.

The second method of increasing discharge is to increase the velocity of the water. Velocity depends on the depth, the slope, (or the water surface gradient), and inversely on the boundary resistance (Dunne and Leopold, 1978). The relation can be expressed by the well-known Chezy Formula (Figure 3.4).

Figure 3.4: The relationship between water velocity, resistance, hydraulic radius, and energy gradient

$$U = C \sqrt{RS}$$

where U = water velocity,
C = a resistance factor that is large for smooth boundaries and small for rough boundaries
R = hydraulic radius, the ratio of cross-sectional area of flowing water to wetted perimeter
S = the energy gradient, closely approximated by the slope of the water surface

In this way, river channel works may increase flow velocity by steepening the slope of the channel, by producing a channel with an optimal hydraulic radius, and by decreasing the roughness of the channel. These can be achieved by removing instream obstructions, and by widening and deepening natural river channels.

3.3.2 River maintenance/ removing instream obstructions

River maintenance or clearing involves removing obstacles, such as vegetation, tree stumps and rocks, which contribute to the roughness coefficient of the channel. This practice reduces the roughness of the bed and banks and therefore increases the velocity.

A smooth, regular channel can convey up to three times the discharge of a channel of similar section and gradient that has its banks covered with extensive reed and plant growth (Hockin, 1985). However, as there is no effect on the capacity of the channel, additional means of increasing discharge are frequently utilised.

3.3.3 Channelisation

Channelisation involves enlarging and straightening the existing channel.

a) <u>Channel enlargement</u>

The river does not construct its channel large enough to accommodate the highest discharges without overflow (Dunne and Leopold, 1978). Therefore, one of the most common engineering practices is to increase the channel capacity, by increasing the depth and/ or width of the channel.

In order to promote bank stability, a trapezoidal cross section with a flat bottom and banks with a 2:3 gradient is frequently adopted (Newbold, Purseglove and Holmes, 1983). An added advantage of this regular cross section is that the hydraulic calculations are simpler and more accurate.

b) <u>Realignment or straightening</u>

Realignment involves shortening the length of the river channel by eliminating meanders and creating a straighter course. This action increases the velocity by removing the hydraulic resistance of the bends. Moreover, reducing the length of the stream increases the slope and hence further increases the velocity.

3.3.4 Canalisation

Canalisation, or lining of the bed and banks with concrete, is hydraulically the most efficient means of increasing the discharge of a channel. In addition to the advantages of channelisation, the concrete lining has a lower roughness coefficient and can withstand high velocities, thereby reducing the cross-sectional area required to pass the design flow (Shields, 1982a). A further advantage is low maintenance due to limited sediment deposition, especially if the canal is steep enough or designed with a low-flow channel to encourage self-scouring.

A semi-circular cross-section has minimum turbulence and therefore the best conveyance characteristics (Crickmay, 1974). However, as it is more difficult to construct in-situ, large canalisation works usually adopt a U-shaped section (Chow, 1959 cited in Brookes, 1988), although trapezoidal sections are also commonly utilised.

3.4 SUMMARY

This chapter has given an overview of the philosophy and practice of traditional stormwater management. It is essential to management stormwater runoff in order to minimise the inconvenience associated with frequent rain events. It is also necessary to reduce flood damage and risk to human life during infrequent storm events. Traditional stormwater management aimed to remove runoff from urban areas to the sea as cheaply and as rapidly as possible.

Urbanisation results in the "hardening of catchments", which is the proliferation of impermeable surfaces. This reduces the infiltration of precipitation into the ground. Urbanisation also typically eliminates the small streams and tributaries. The combined effect is to increase the volume of stormwater runoff and to increase the peak flows entering the receiving streams.

In order to contain this increased flow and to maximise the amount of floodplain land "available" for urban development, hydraulically inefficient natural river channels are modified. Channelisation involves increasing the width and/or depth of the channel, as well as straightening the alignment. These actions increase the discharge of natural river channels by increasing the cross-sectional area and reducing the roughness of the channel. In addition, straightening increases the slope and therefore increases the flow velocity. If further hydraulic improvements are required, the river channel is canalised. This involves concrete-lining the bed and banks of the river. Canalisation reduces the hydraulic roughness of the channel and therefore results in high flow velocities.

The following chapter describes the ecological and socio-economic impacts associated with urbanisation, channelisation and canalisation.

CHAPTER FOUR: BIOPHYSICAL AND SOCIO-ECONOMIC ASSESSMENT OF URBANISATION, CHANNELISATION AND CANALISATION

CONTENTS

CHAPTER FOUR: BIOPHYSICAL AND SOCIO-ECONOMIC ASSESSMENT OF URBANISATION, CHANNELISATION AND CANALISATION

4.1 INTRODUCTION

This chapter describes the biophysical and socio-economic impacts of urbanisation, channelisation and canalisation on rivers. The ecological implications are described in the first five sub-sections, namely :

- change from natural of flow velocities;
- change from natural substratum;
- reduction in area of instream and hyporheos habitat;
- reduction in area of riparian and floodplain habitat, and
- deterioration in water quality.

The socio-economic impacts are described in the following five sub-sections, namely :

- impairment of aesthetic, recreational and educational opportunities;
- reduction in biological purification of water;
- reduction in corridor conservation value;
- efficiency of stormwater removal, and
- planning, infrastructure and costs.

Each sub-section motivates the importance of that criterion, and provides a qualitative assessment of the effects of urbanisation, channelisation and canalisation.

4.2 BIOPHYSICAL ASSESSMENT

4.2.1 Introduction and methodology

Scientific research on rivers to predict and monitor changes resulting from human activities are hampered by several factors. Firstly, rivers and their aquatic communities change from year to year; secondly, major modifications to river channels may take decades to reach equilibrium; and thirdly, brief pre-project surveys are often of limited value in predictions (Boon, 1992). Methods of assessing impacts on aquatic ecosystems include the use of indicator specie characteristics, community characteristics and ecosystem processes. These three methods are described and their appropriateness evaluated in the following section.

Attributes of individual species that could be assessed include abundance, biomass, survival rate, growth rate and behaviour. Indicator species are typically large, for example, fish, or sessile (attached). In addition to the practical difficulties of undertaking long-term monitoring in the field (as it is extremely unlikely that the host of relevant variables could be simulated in a laboratory), a change merely provides information that the overall conditions are not optimal for that organism. In other words, there is no indication of whether the decline is due to the increased water temperature or the increase in turbidity, or both. Furthermore, extrapolating the likely effects on a particular 'indicator' species to the entire aquatic ecosystem is questionable as each species responds differently to change in the abiotic environment. Each individual species has specific habitat requirements and therefore the response of individual species is not necessarily representative of the response of the ecosystem as a whole.

An assessment of the impact on the aquatic ecosystem based on the community characteristic approach would involve assessing changes in biodiversity, species composition and succession. In contrast, the ecosystem processes approach would describe the changes in the rate of photosynthesis, rate of respiration, rate of nutrient cycling or the rate of decomposition. These approaches integrate the host of abiotic and biotic stresses on the ecosystem. While this integration may be advantageous for water quality studies, it is less problematic when assessing the impacts of urbanisation, channelisation and canalisation as the ecological impacts are not related to the changes in abiotic characteristics. Furthermore, these methods are not easily understood by non-ecologists and do not facilitate linkages to possible mitigation measures. As a result, the biotic assessment method was not deemed to be appropriate for this dissertation.

Assessing the overall impact of a host of interrelated factors, such as changes in flow regime, subtle changes in water quality and direct disturbance to the aquatic ecosystem is extremely difficult. Furthermore, the factors may act synergistic or antagonistically. The poorly developed autecological (the ecological requirements of a single species) knowledge of riverine species in South Africa further hampers this approach. It is apparent that extensive research and long-term monitoring would be required to predict, with any degree of certainty, the ecological impacts of the interrelated effects associated with urbanisation, channelisation and canalisation.

As no suitable method of assessing the ecological impacts of urbanisation, channelisation and canalisation could be found in the literature, a methodology was developed. The approach is based on the fact that there is general agreement that the aquatic community is largely determined by abiotic factors (Macan, 1961; 1974; Hynes, 1970a,b cited in Ward and Stanford, 1979; Lewis and Williams, 1984). The likely ecological effects of changes in the key abiotic variables, namely flow velocity, substrate, area and water quality, were therefore selected and qualitatively described. Significant changes in these abiotic variables compared to the natural variability was assumed to constitute a significant ecological impact.

The assessment is intended to explore the implications of complex and interrelated physical and biological elements and is therefore qualitative. As many of the interrelationships are not fully understood, this section relies on the riverine and general ecological theory. It also relies on principles described in Chapter Two, on personal observation of river systems and the results of case studies published in the literature. Due to the myriad of abiotic and biotic interactions, it was not possible to define the primary, secondary and higher order abiotic and biotic impacts.

The assessment does however provide a holistic attempt at understanding the complexities of anthropogenic impacts on urban riverine systems. In addition, the assessment links ecological impacts to factors such as flow velocity and area, that are easily understood. This is important as the dissertation aims to assist environmentalists, planners and engineers, rather than ecologists. The assessment methodology also facilitates clear linkages to the various mitigation measures described in Chapters Six and Seven. The ecological implications of urbanisation, channelisation and canalisation on the key abiotic determinants, namely flow; substratum; instream and hyporheos area; riparian and floodplain area, and water quality are described in the following five sub-sections.

4.2.2 Change from natural flow velocities

Patterns and characteristics of flow have the greatest control over the occurrence and abundance of species and, therefore, over the whole structure of the aquatic community (Scott, 1958; Ambühl, 1959; Edington, 1968; Chutter, 1969 cited in Rabeni and Minshall, 1977; Gore, 1978; Milner *et al.*, 1981; Jenkins *et al.*, 1984 cited in Brookes, 1988; Hynes, 1970, 1972; Swales, 1982; Statzner and Higler, 1986). In spite of having developed physiological or behavioural adaptations, lotic organisms are limited to particular flow velocities by hydrodynamic factors (Gore, 1993, in Davies *et al.*, 1993). Velocity is a major determinant of detritus retention (Rabeni and Minshall, 1977), and has a significant influence on respiration (Hynes, 1970; Statzner *et al*, 1988), and on the feeding mechanisms of invertebrates (Hynes, 1970). As a result, some stream organisms are found only in swiftly flowing areas, while others occur only in slow flowing areas.

The distribution of macrophytes is also affected by flow velocity. In addition, macrophytes change the hydraulics of the channel, while benthic algae change the shear velocity and micro turbulence close to the bottom (Reiter, 1986; Stevenson, 1983 cited in Statzner, *et al.*, 1988).

In natural channels, flow velocity varies considerably over short distances and temporally over the range from low to high discharge. Flow is characteristically unsteady and non-uniform (Gardiner, 1992). Diversity of flow is particularly important at a micro (that is cm) scale, and this diversity is closely related to the substratum. Furthermore, since sediment particle size is determined by current velocity (Reice *et al*, 1990), different velocity regimes will result in different substratum types.

Discharge itself is of little direct interest in most biological studies because it is more often the velocity which affects the biota through its action on the substratum (Armitage, 1989). The relationship between discharge and velocity is influenced by a number of factors, such as channel width, depth and shape, as well as roughness of the stream bed (Leopold, Wolman and Miller, 1964). Large increases in mean and maximum velocity can be extremely detrimental to aquatic organisms (Swales, 1982; Genetti, 1989).

Riverine organisms are adapted to the natural flood regime by avoiding high velocities (for example, by burrowing into the hyporheos), and through compensatory mechanisms in their population dynamics (Hynes, 1970). However, an increase in the frequency or severity of flooding to above natural levels impacts on the riverine ecosystem. In particular, the more sessile (attached) and longer lived animals and plants may be lost and replaced by more mobile, early colonisers. These "weedy" species are of less conservation importance, and the reduction in species diversity lowers the complexity and stability of the ecosystem (Schaeffer, *et al.*, 1988).

a) Urbanisation

Urbanisation results in an increase in peak flow velocities as well as an increase in the frequency of high flow events (see Chapter Three). However, as the river channel is still relatively natural, the diversity of flow velocities is not affected significantly. Most species are therefore likely to be able to find suitable velocity niches and only those most sensitive to an increase in flow velocity will be eliminated.

An increase in velocity may have indirect effects on the substratum, aquatic and riparian plants, the area of instream/ hyporheos habitat, and the area of riparian/ floodplain habitat. It may also affect water quality.

The hydrograph for an urban stream typically has a depressed "tail", signifying a rapid return to base flows (see Figure 3.2). This reflects the reduced land storage, infiltration, and other factors which retain precipitation for varying periods of time (Simpson *et al.*, 1982). As a result, base flows and summer low flows may be reduced. The abstraction of water directly from the river, or from the ground water by riparian landowners for irrigation or consumption may exacerbate the decreased low flows. As low flow periods are critical and stressful for the riverine flora and fauna, even a slight decrease in flow may have significant biological effects (Southern Waters, 1997). These include reduced instream/ hyporheos area (and therefore greater biological interaction), as well as water quality impacts (reduced oxygen, increased temperature and reduced dilution and flushing of pollutants).

On the other hand, low flows may be artificially increased by urban development as a result of garden irrigation return flows, the washing of vehicles and paved areas, the back-washing of pools, and the discharge of effluent from wastewater treatment works and other industries. A slight elevation of the natural base flow may ameliorate some of the effects of urbanisation (such as poor water quality).

The most significant effect of urban drainage on the ecological state of rivers is usually the change in physical characteristics, due to increased peak discharge rather than the impact of pollutants contained in storm water runoff (Guyer and Krejci, 1987). With the exception of fish, the fauna in these rivers can tolerate fairly high concentrations of pollutants (Guyer and Krejci, 1987). In other words, the physical changes in rivers (increased velocity and associated change in substrate characteristics) are ecologically more significant than the poor water quality of urban runoff.

b) <u>Channelisation</u>

Channelisation removes obstructions to flow such as instream and riparian vegetation, woody debris and local high points. In addition, the elimination of meanders reduces bend friction and the shorter river course results in an increase in gradient. The net effect is an increase in flow velocity under both high and low flow conditions.

However, river meandering, and the associated pool and riffle sequences is one of the most fundamental of fluvial processes and is of major importance in maintaining an energy balance within the river system (Leopold and Lainbein, 1966 cited in Swales, 1982; Petersen, 1992). The elimination of this pattern may result in scour during high flows as energy is not dissipated effectively (Callison, 1971 cited in Simpson *et al.*, 1982; Keller, 1976 cited in Swales, 1982).

Lowering of the river bed may lower the ground water table and reduce over bank flow, thereby eliminating wetlands which are an important source of dry season flow (Hill, 1976; Klopatek, 1978; Gosselink and Turner, 1978 cited in Swales, 1982). Reduced over bank flow causes decreased infiltration to the ground water and further reduces base flow .

Channel modification destroys the diversity of substratum and biotopes and results in more uniform flow patterns and depths. This in turn results in loss of variety of flow velocities at micro-scale. This loss of "velocity refuges" or shelter for the biota would result in species being washed downstream during normal and spate flows.

c) <u>Canalisation</u>

Canalisation typically results in a significant increase in velocity, under both high and low flow conditions. The ability of the vast majority of "natural" organisms to maintain their position is exceeded and the biota is depauparate. In addition, and possibly of more biological significance, the flow on a micro-scale is uniform due to the smooth surface and regular shape. There are therefore few velocity "refuges".

The velocity in a canalised river is typically high enough to prevent sediment from accumulating and therefore no plants exist, other than annual weeds or moss which may grow in cracks or weep holes. This lack of instream vegetation has implications for water temperature, velocity diversity, water quality and instream/ hyporheos habitat area.

The altered flow regime associated with canalisation influences the nutrient dynamics by increasing the throughput of material and reducing the residence time and instream-processing time (Richey 1982 cited in Dallas and Day, 1993). Therefore, less food is available to organisms, and downstream organisms may receive excess nutrients or in the wrong form.

4.2.3 Change from natural substratum characteristics

Many species of plant and animal are confined a particular type of substratum, either because they need a special surface to which to attach, or because they need to shelter under stones, or burrow down into gravel (Hynes, 1970). Substratum type is a critical variable determining macro invertebrate community structure and is undoubtedly a major structuring element in the patchiness of animal distribution in lotic benthos (Cummins and Lauff, 1969 cited by Swales, 1982; Cummins, 1974; Allan, 1975; Minshall and Minshall, 1977; Rabeni and Minshall, 1977; Hart, 1978; Higler, 1975; Wise and Molles, 1979; Shelly, 1977; Reice, 1977; 1980; 1981; 1983 cited in Reice *et al*, 1990; Pennak, 1971; Williams and Mundie, 1978 cited in Simpson *et al.*, 1982), and to a lesser extent, fish distribution (Hynes, 1970).

Current velocity, together with the basic geology and geomorphology of the area exert the greatest influence over the substratum (Hynes, 1970; Keller, 1976 cited in Swales, 1982; Rabeni and Minshall, 1977). Not only is current one of the major factors influencing substratum, but substratum has an influence on current velocity. Boulders and cobble (referred to as 'large substratum') result in a wider range of current conditions than gravel and sand (Rabeni and Minshall, 1977). Thus, if an organism possesses a narrow tolerance range for current, its best opportunity for a suitable habitat would be large substratum. Due to increased microhabitat diversity, there are more possibilities for community diversity in large than in fine substratum (Winget, 1985; Hynes, 1970).

Substratum size affects detritus retention, a factor which Rabeni and Minshall (1977) found was the most important microhabitat factor in determining invertebrate colonisation. As large substratum retains more detritus than fine uniform substratum, it typically supports a higher species diversity. Usually insect abundance is highest in cobble substrate, but some species, such as net-spinning caddisfly, may be more commonly associated with larger more stable substratum, while worms and chironomids are more abundant in fine substratum (Jowett, 1991).

Substratum stability depends on particle size and cohesiveness. Large embedded rocks are less likely to be displaced downstream during high flows, and the displacement of these would result in the dislodging or crushing of organisms. This increased disturbance selects against the sedentary, longer-lived species and therefore promotes early successional stage (colonist/ weedy) species. However, the increased flow velocity also increases the rate of removal of the finer portion of the substratum.

If the increase in velocity is not significant, an armoured layer may be restored. In other words, through a positive feedback loop, the flow regime and substratum may regain an equilibrium. In general, coarse, stable substratum is more productive than sandy, non-cohesive, shifting sediments (Tarzwell, 1936; Pennak and van Gerpen, 1947; Ward, 1975 cited in Wise and Molles, 1979; Shields, 1982a; Winget, 1985; Smith, 1980; Hynes, 1970). However, fine-grained organic muds can be a productive habitat for invertebrates, if the substratum is sufficiently stable (Tarzwell, 1932 and 1936 cited in Shields, 1982a; Hynes, 1970). They can support a greater number of individuals, but at a lower species richness (Wise and Molles, 1979).

The bed of the eroding reach is characterised by pool and riffle sequences which support fine and course sediment respectively. In contrast, the bed of the depositing reaches is relatively homogeneous, consisting of sand, silt and mud. Emergent and aquatic vegetation increase the physical heterogeneity of the substratum and their large surface areas contribute to an abundance of invertebrates by creating additional living spaces in the water column where none exists above unvegetated substratum (Gregg and Rose, 1985).

Channelisation of the lower reaches often results in no change in substratum, and benthic organisms are therefore similar in altered and unaltered segments (Simpson *et al.*, 1982). If permanent alteration of the substrate occurs, a shift in species composition, diversity, density, and biomass can be expected. Removal or alteration of the natural substrate is particularly significant in streams with gravel and boulder substrates (Simpson *et al.*, 1982). Hansen (1971 cited in Simpson *et al.*, 1982) found that the diversity of benthic organisms was drastically reduced when suitable attachment sites were removed by channelisation. After removal of a particular microhabitat to which organisms have adapted, the organisms are no longer protected from high velocities or predators and are swept downstream. As the original organisms are unable to compete as effectively in altered habitats, the population changes. The natural community is either replaced by a species more suitable for the altered habitat or the population is reduced considerably (Simpson *et al.*, 1982).

Rabeni and Minshall (1977) showed that current speed had little effect on species composition in a small stream when substrate particles of appropriate size were available. Interstitial spaces are particularly important to macro invertebrates because they provide retreat from high current velocities and allow organisms to maintain their position in the stream (Simpson *et al.*, 1982). When these spaces have been lost and the resulting substratum is highly unstable, macro invertebrates have no protection against high current velocities and are washed downstream.

a) Urbanisation

In their natural state, rivers are often considered to be in regime - a state of dynamic equilibrium where the channel dimensions are determined by sediment supply and type, and by the magnitude and frequency of occupance of discharge (Reeve, 1988). Urbanisation causes increased runoff and decreased sediment production and therefore urban streams respond by degrading, which increases depths, widths and bed material size (Douglas, 1974; Hammer, 1972 and Wolman, 1967 cited in Nunnally, 1985).

The increase in sediment supply during the initial phase of urbanisation may smother or abrade organisms (see turbidity effects). While many organisms can tolerate isolated high sediment events, sustained amounts are likely to eliminate certain sensitive organisms. The clogging of the spaces between cobbles and even smothering of "hard" substratum during periods of lower flow is likely to have negative impacts on the biota.

The subsequent decrease in sediment availability from the "developed" catchment, combined with the significant increase in runoff, typically initiates excessive erosion of the bed and banks. This accelerated erosion contributes to the turbidity and abrasion effects described above.

Excessive deposition of material from urbanisation and from accelerated erosion of the channel in the eroding zone may reduce the depth of channels and pools and result in aggradation of wetlands and the floodplain. The characteristics of this sediment (in terms of particle size and physio-chemical properties) is likely to be similar to the pre-urbanisation substratum.

The higher rate of deposition may smother some organisms, but the effect is unlikely to be significant as the animals in the lower reaches are predominantly burrowing forms. Similarly, deposition is unlikely to have a negative effect on aquatic and riparian plants which tend to grow rapidly.. However, some benthic plants, such as *Potamogeton pectinus* (pond weed) may be excluded, while some emergent species (for example *Typha capensis*, *Phragmites australis*) may expand their distributions.

b) Channelisation

Channelisation may destroy stable sand and clay beds which may have accumulated over thousands of years to accumulate (Gardiner, 1992). It will further destabilise the banks and bed, and the sediment released during dredging will affect downstream reaches. Adverse effects on invertebrates have been attributed to an accumulation of sediment (Boon, 1988). Channel deepening may have a severe effect on aquatic life if bed erosion takes place and natural substrate characteristics are greatly modified (Swales, 1982).

Since channelisation involves altering one or more of the dependent hydraulic variables of slope, depth, width, and roughness, there must be feedback effects to promote a new state of equilibrium (Brookes and Gregory, 1988; Brookes, 1989). Straightening results in more sediment being transported than is supplied from the natural channel upstream (Parker and Andres, 1976 cited in Brookes, 1989). The difference is obtained from the bed, causing degradation which moves upstream as a nickpoint (Parker and Andres, 1976, in Brookes, 1992). Erosion continues to lower the bed gradient and to increase bed material size, through the process of armouring. Alternatively, the channelised river may accommodate the increased slope by widening its channel, with the new, wider channel being more efficient at dissipating energy (Nunnally, 1978). Straightened channels may attempt to resume their original bed forms and meanders in the absence of measures to stabilise the banks (Noble and Palmquist, 1968; Yearke, 1971; Lewin, 1976; Brice, 1981; Brookes, 1983 cited in Brookes, 1989).

Over-widened channels are out of equilibrium with the normal range of flows and the reduced velocities induce the deposition of sediment. In the absence of maintenance, enlarged channels may resume their original natural widths in less than 30 years (Nixon, 1966; Brookes, 1983 cited in Brookes, 1989). Similarly, reaches that have been deepened may act as sediment traps, so that increased flow depths and channel capacities are progressively reduced (Griggs and Paris, 1982 cited in Brookes, 1989).

Channelisation greatly reduces the abundance and variety of the flora and invertebrate fauna (Engelhardt, 1951; Gaufin, 1959; Hynes, 1960 cited in Hynes, 1972; Clavel *et al.*, 1978; Crisp and Gledhill, 1970; Pearson and Jones, 1975 cited in Swales, 1982). Worms, chironomids and blackfly larvae may dominate the newly dredged bed (Lewis and Williams, 1984; Brookes, 1988). However, if the substratum is not significantly altered, species composition and abundance should be re-established rapidly and the long-term effects may not be severe (Barton and Winger, 1973; White, 1973 cited in Swales, 1982; Simpson *et al.*, 1982).

Macro invertebrates, which specialise in shredding and ingesting coarse particulate organic matter (CPOM), are concentrated in headwater streams. The removal of obstructions, such as rocks, branches and emergent vegetation, results in large amounts of detritus being swept downstream, instead of being trapped in the upper and middle reaches. Channelisation would thus result in a shift toward autotrophy, and in-stream photosynthesis would become the primary organic input rather than leaf fall. Impacts of such shifts in energy bases are difficult to predict (Shields and Nunnally, 1984), but are likely to be severe. In addition, downstream species that rely on the processing of CPOM in the upper reaches would be affected. CPOM deposited in the lower reaches, where shredders cannot survive, (due to the lack of hard silt-free substrata, low oxygen concentrations and high water temperatures) would thus contribute towards further eutrophication and low-oxygen conditions (Bilby and Likens, 1980 cited in Brookes, 1988; Simpson *et al.*, 1982).

Channelisation in upstream rivers removes the pool-riffle sequence, vegetation and in-stream 'cover' which may be of considerable importance to many organisms (Gibson and Power, 1975; Milner *et al.*, 1981; Jenkins *et al.*, 1984 cited in Brooker, 1985). The channelised segment offers severely reduced habitat and species diversity, but is often colonised by a new species assemblage (typically of less conservation value), uniquely adapted to exploit the new, less diverse habitat (Simpson *et al.*, 1982).

Channelisation may reduce the average boulder size by the processes of removing large boulders by the mechanical crushing of rocks and by extending the width of the river channel (terrestrial environments still contain the smaller rock and sand particles which have been eroded from the river channel).

c) Canalisation

Concrete lining results in a uniform substrate which differs from the diverse, flow-sorted substratum which exists in a natural system. This lack of physical diversity, and hence habitat diversity, will limit severely the number of species which can persist.

Concrete lining constitutes an unnatural solid surface in the depositing zone. Its effects are likely to be significant if the flow velocity is enough to limit the deposition of sediment. However, if the gradient is not sufficient to prevent deposition of sediment, a layer of sediment may accumulate. This would allow some annual vegetation and colonising fauna to become established, at least until they are removed by a high flow event. Sediment accumulation would therefore reduce the impact of canalisation to some extent.

4.2.4 Area of instream/ hyporheos habitat

Area refers to the size of the habitat available for organisms to colonise. It includes the volume of water and the surface area of the banks and bed, as well as the area of hyporheos habitat. The surface area of the substratum available for colonisation has a strong influence on the invertebrate population size, as opposed to the species diversity (Henderson and Shields, undated).

a) Urbanisation

Urbanisation may have a direct effect on instream/ hyporheos habitat by the elimination of lower order streams (see Figure 3.1). Where there are many small, typically non-perennial streams, urbanisation may eliminate a large amount of the habitat.

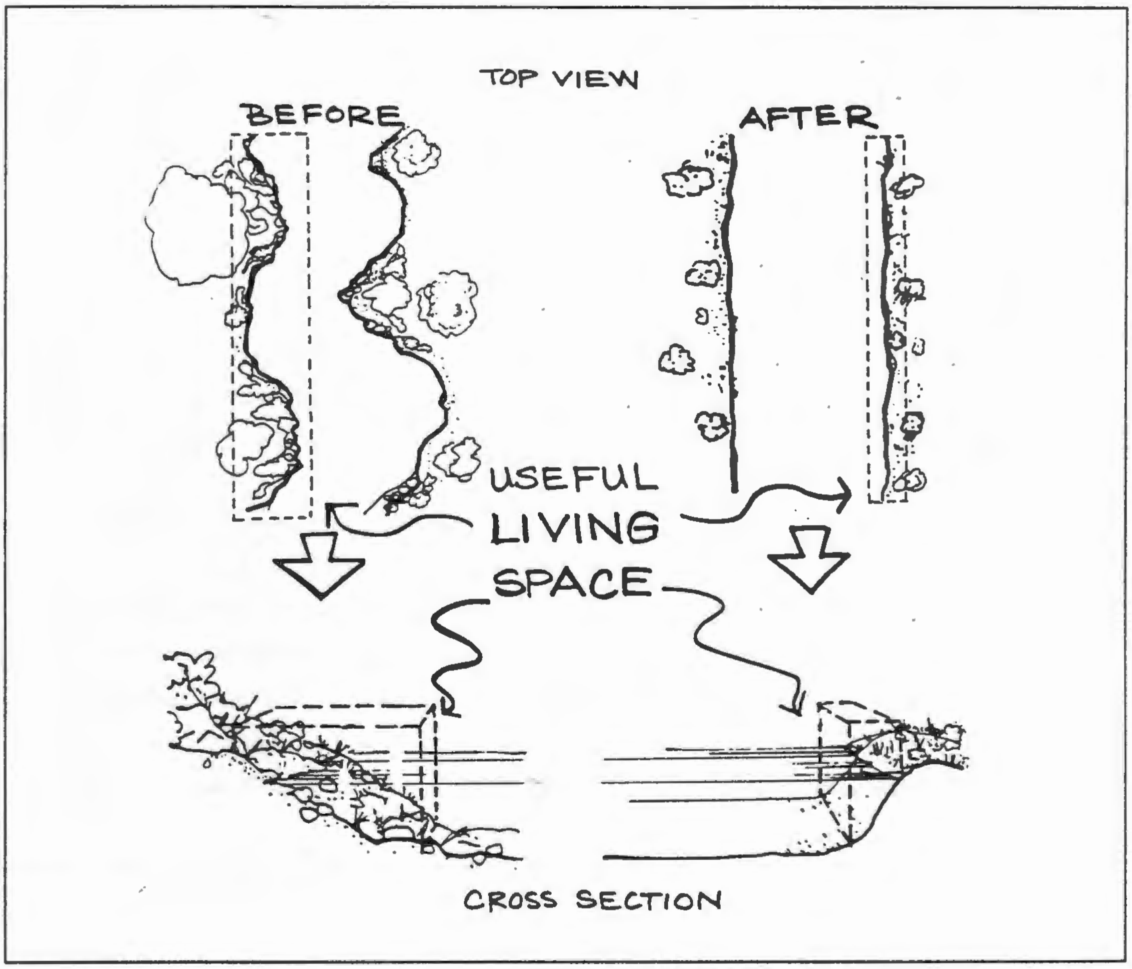
Urbanisation also has indirect effects on the instream/ hyporheos area. These relate to the increased flow peaks and associated erosion which may reduce the instream area if it results in incision, or increase the instream area if it results in channel widening.

b) Channelisation

Channelisation reduces the area of instream habitat due to the elimination of meanders and subsequently a shorter course, and the removal of instream obstacles and vegetation. Channelisation results in a reduction in the quantity of aquatic habitat by 50% to 60% (Genetti, 1989) and many studies have related this factor to reductions in density and biomass of both fish and invertebrate communities (Bulkley *et al.*, 1977; Golden and Twilley, 1976; Hansen and Muncy, 1971; Peters and Alvord, 1964 cited in Swales, 1982) (Figure 4.1).

The increase in area due to the increased channel width may compensate for the reduction in area, but would be poor quality habitat as it would be relatively homogeneous with regard to water depth, water velocity and substrate characteristics. During low flows and drought conditions, the elimination of pools may result in reduced refugia for obligatory aquatic organisms.

Figure: 4.1: Channelisation reduces the length and width of edge habitat (after Simpson, *et al.*, 1982)



The area of the hyporheos is linked to the area of the channel and floodplain, and therefore would be reduced. Furthermore, as channelisation tends to remove the armoured cobble bed, the surface area of the instream habitat may be reduced.

c) <u>Canalisation</u>

For a given discharge, a concrete-lined canal would be significantly smaller than one that was earth-lined, which would be smaller than a natural channel. The area of instream habitat would therefore be reduced significantly.

In addition, the concrete lined canal is effectively a two-dimensional habitat and the hyporheos would be eliminated. Furthermore, the lack of emergent macrophytes would further reduce the surface area available to organisms.

Not only is the habitat area reduced, but the habitat is homogenous and therefore its ability to support a diverse natural aquatic community is severely impaired.

4.2.5 Area of riparian/ floodplain habitat

The riparian and floodplain habitats form an integral part of the riverine system. The loss of riparian and floodplain area reduces the biodiversity of flora and fauna and reduces the self-cleaning capacity of the system (Mitsch and Gosselin, 1986 cited in Petersen, 1992), as well increasing flood peaks. This loss of discharge buffering capacity means that more water enters the channel system more rapidly. This further increases erosion, nutrient transport and sediment load (Petersen, 1992).

a) Urbanisation

Urbanisation frequently has a direct effect on the area of the floodplain habitat by encroaching onto the floodplain. Infilling, urban development, sports fields, crossings for road bridges and pipelines all reduce the extent of the natural floodplain.

Urbanisation also indirectly affects the riparian/ floodplain habitat due to the increased flood peaks and associated erosion. Where the channel becomes incised, the frequency and extent of over bank flow, combined with the lowering of the water table, reduce the area of riparian and floodplain habitat. In other words, urbanisation may cause the riparian and floodplain plant communities to become replaced by more xeric (or terrestrial) species. This is likely to decrease the overall productivity and wildlife habitat value (Barclay, 1980 cited in Shields, 1982a) and impact on the stream ecosystem.

On the other hand, the increased flood peaks associated with urbanisation may cause more frequent inundation of the floodplain.

b) Channelisation

Channelisation lowers water tables and decreases over bank flooding. It also encourages wetland drainage, causes greater variation in discharge and decreases flood storage (Genetti, 1989; Kern, 1992b). The increase in capacity of the channel usually indicates a shallower stream during medium and low flows (Hellawell, 1988). Drier conditions on nearby flood plains and wetlands can result in shifts in floral and faunal communities (Genetti, 1989).

The reduction in stream length results in a direct reduction in area of adjacent riparian areas (Simpson *et al.*, 1982). As the depositing zone is characterised by large areas of floodplain and riparian habitat, channelisation is likely to eliminate substantial areas of habitat.

c) Canalisation

Concrete lining of the bed and banks of the river effectively eliminates all riparian habitat. Instead of a shelving bank grading from dry upper bank through progressively wetter conditions to water margin and open water, with a range of vegetation types reflecting soil moisture content, a concrete-lined channel exhibits a stepwise change from dry land to open water (Brookes and Hanbury, 1990).

All flows (except major floods, typically of a return period in excess of 1 in 20 or 1 in 50 years) are contained within the canal and therefore the floodplain habitat becomes terrestrial and is typically utilised for urban development. In addition, the solid bed and banks cut off the exchange of water between the stream and the ground water. This results in a lowering of the water table and promotes the conversion of the floodplain to terrestrial habitat.

As the depositing zone typically has an extensive floodplain, canalisation may eliminate vast areas of floodplain and riparian habitat. However, compared to the upper reaches, this habitat is relatively homogeneous and there may be fewer organisms that are eliminated, whereas the numbers of each organism may be large.

Lined channels with extremely steep, smooth sides can be impassible for some terrestrial animals. Access to and across the channel may be prevented and animals that fall into the channel may be trapped or drowned.

4.2.6 Water quality

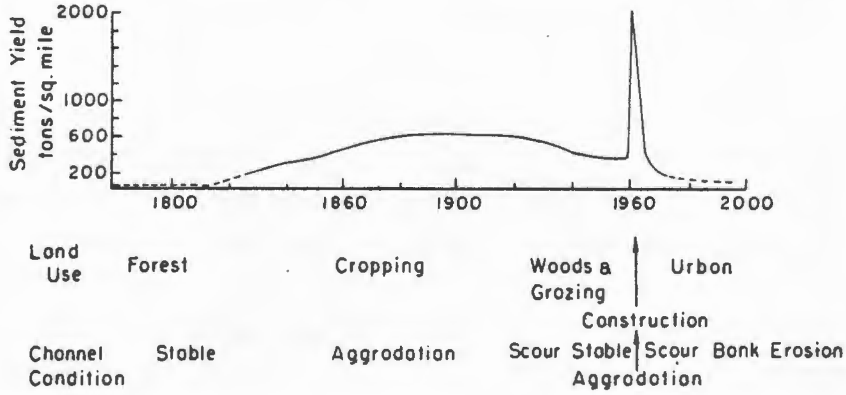
Urbanisation, channelisation and canalisation affect the natural water quality in the receiving streams and therefore impact on the biological diversity of the indigenous aquatic flora and fauna. As discussed, water quality is relatively homogeneous over an area of about 100m, due to the influence of turbulence. Key water quality characteristics affecting the aquatic community include temperature, oxygen, nutrient enrichment, turbidity and toxic substances.

Since each species, and even different life-cycle stages of a particular species, differs in its tolerance of water quality variables, it is difficult to describe the exact effects. However, it is clear that alterations in water quality will affect different species to a greater or lesser extent (Dallas and Day, 1993). Increased changes in water quality will thus gradually alter the constituent species of a biotic community until it is no longer recognisable.

Stormwater runoff from urban and roadway surfaces is a significant contributor of non-point source pollution in many areas. Solids are the largest portion of the pollutant load carried by this runoff (Preul and Ruszkowski, 1987). It has been shown that besides contributing to the oxygen demand in receiving waters, sediments, especially clay particles, adsorb pollutants such as oils, grease and pesticides (Preul and Ruszkowski, 1987) and heavy metals (Douglas, 1985 cited in Thoms, 1987). Therefore sediment removal is an effective step in mitigating the adverse impacts of stormwater runoff on receiving waters.

The accumulation of sediment in urban river channels, as a consequence of construction activities, is short lived as the "artificially" high velocities resulting from urbanisation create a high energy environment which prevents the accumulation of fine material, despite high suspended sedimented concentrations (Woodward, 1983 cited in Thoms, 1987). However, in temperate areas, such as the South Western Cape, urban rivers experience an increased rate of sedimentation during the summer period, followed by an increased rate of scouring during the winter compared with pre-urbanisation conditions.

Figure 4.2: Typical sediment yield before and after urbanisation, showing the elevated yields during the construction phase (after Wolman, 1967)



The following six sub-sections provide an overview of the ecological importance of turbidity, temperature, nutrients, pH, dissolved oxygen and toxins.

- Turbidity

Turbidity is governed by the basic hydrology, geology, geomorphology and land use of the region and it frequently mirrors the seasonal runoff cycle.

Suspended sediment can directly affect aquatic life through damage to organisms and their habitat (Ritchie, 1972; Muncy *et al*, 1979 cited in Walling and Webb, 1992). Suspensoids that settle out may smother riverine plants and animals (Chutter, 1968). This is most severe in riffle areas where the silt interferes with the respiratory and feeding apparatuses of species intolerant of silty surfaces. As a result, the diversity of the benthic community is reduced and those requiring "open" eroded substrata for attachment or feeding (especially filter feeders) are lost (Hellawell, 1986). The replacement fauna consists of burrowing forms, typical of soft, depositing substrates, provided that the deposits are neither excessive in their rates of accumulation or completely sterile and devoid of nutrients (Hellawell, 1986). The dominant organisms are mostly chironomid larvae and oligochaete worms.

The effects on fish include causing abrasive injuries to delicate external organs such as gills, protective mucal coverings and fins (Cordone and Kelly, 1961 cited in Starnes, 1985), or by smothering eggs and nests.

Turbidity can reduce light penetration and therefore reduce primary production (Walling and Webb, 1992). Decreased photosynthesis reduces food availability to organisms higher in the food chain (Hynes, 1974 cited in Starnes, 1985). Thus, overall stream productivity is decreased.

Greater turbidity has been shown to increase macro invertebrate drift (that is the detached organisms that get washed downstream). This in turn leads to a decrease in the density of benthic organisms (Ryder 1989 cited in Dallas and Day, 1993). Predator-prey interactions are affected by the impairment of visually-hunting predators, particularly vertebrates (Bruton, 1986), which may lead to changes in community assemblage (Scholtz *et al.*, 1988 cited in Dallas and Day, 1993).

Nutrients, trace metals, biocides and other toxins adsorb to suspensoids and are transported in this form. This can be beneficial if adsorbed toxins are effectively "lost" to the system. However, dredging may release various pollutants through resuspension and the high concentration of suspended sediments in the water column is detrimental to the aquatic community (Alabaster, 1972; Cordone and Kelly, 1961; Edwards, 1969 cited in Swales, 1982).

The rivers in the South Western Cape are not highly turbid during the rainy season like most southern African rivers. However, Britton *et al.* (1992 cited in Dallas and Day) showed that suspended solid loads increase during storm events. Urban rivers in particular, have elevated suspensoids during high runoff periods, presumably due to the reduced infiltration and increased area of disturbed land.

The recovery of a stream from high sediment deposition depends on the elimination of the sediment source and the ability of the stream to flush out the deposited material (Luedtke *et al.*, 1976 cited in Dallas and Day, 1993) particularly after floods (Hellawell, 1986).

A study by Ractliffe (1991 cited in Dallas and Day, 1993) on the Lourens River in the South Western Cape showed that an increase in suspended solids (from agriculture and land drainage) during the winter period was accompanied by the loss or drastic reduction in macro invertebrate species characteristic of mountain streams and upper river zones.

- Temperature

The thermal characteristics of running waters are dependent on various factors: hydrological (source of water, interaction with ground water and discharge), climatic (air temperature, cloud cover, wind speed, precipitation events and solar radiation) and structural (vegetation cover, river depth and length and turbidity) (Dallas and Day, 1993; Weatherley and Ormerod, 1990 cited in Walling and Webb, 1992).

Rivers undergo seasonal, diurnal and runoff-related fluctuations in temperature, as well as longitudinal changes along a river course. The evolution, distribution and ecology of aquatic organisms is fundamentally affected by river temperature and much research has been undertaken to investigate the thermobiology of fishes and invertebrates (Brett, 1960; Fry, 1964; Langford, 1972; Ward and Stanford, 1982; Crisp, 1982, Crisp, 1988 cited in Walling and Webb, 1992).

Floating vegetation may be the cause of excessive temperatures in rivers due to the restriction of evaporation, absorption of sunlight and the reduction of wind and wave action (Welcomme, 1979; 1985 cited in Ryder and Pesendorfer, 1989). Similarly, suspended silt increases temperatures in turbid rivers (Ellis, 1936; Reid, 1961 cited in Ryder and Pesendorfer, 1989; Reid and Wood, 1976 cited in Ward, 1985). Dallas and Day (1993) however state that turbidity may reduce water temperature as more heat is reflected and less absorbed by the water.

Except for birds and mammals, all organisms associated with fresh water are poikilothermic, that is they are unable to regulate their body temperatures which become similar to the ambient water (Swales, 1982). These animals are very susceptible to changes in water temperature, since a 10°C rise in temperature doubles of the organism's metabolic rate (Hellawell, 1986), thereby increasing its respiration and oxygen demand (McKee and Wolf, 1963 cited in Dallas and Day, 1993).

Vannote and Sweeney (1980) concluded that each species has an optimal temperature regime at which optimal growth, reproduction and general fitness occur, as well as a range in which normal activities can continue. It has been suggested that daily variation in temperature is partly responsible for maximizing species diversity in lotic systems by providing a wide range of thermal optima (Ward, 1976a; Ward and Stanford, 1979b; Vannote *et al.*, 1980 cited in Ward and Stanford, 1983a), although suboptimal conditions occur over a portion of the daily cycle for each species (Patrick, 1970; Ward, 1976b cited in Ward and Stanford, 1983a).

Hart and Allanson (1984) concluded that altered temperature regimes may lead to species elimination as the stenothermal species (organisms adapted to a very narrow range of temperatures) disappear from heated waters and heat-tolerant species increase in number (Reid and Wood, 1976 cited in Dallas and Day, 1993). Moreover, most stream animals have definite breeding seasons, and their life-cycles fit into the annual cycle of temperature change (Hynes, 1970).

The elevation of water temperatures reduces the solubility of oxygen in water, decreasing its concentration and thus its availability to aquatic organisms (Dunne and Leopold, 1978). In addition, the toxicity of many substances (such as cyanide, zinc, phenol, xylene), and the vulnerability of organisms to these toxins, are also intensified as temperature increases (Duffus, 1980 cited in Dallas and Day, 1993). Water temperature also affects many of the physico-chemical properties of water, such as pH, dissolved oxygen, chemical balances of various substances, solubility of substances, nutrient forms, rates of settling of particles and surface tension. All of these affect the aquatic community.

Raising the water temperature lowers the viscosity of water, which causes the solid particles to settle faster (Dunne and Leopold, 1978). In general, the higher the temperature, the less desirable are the types of algae in water: diatoms are replaced by green algae which in turn are replaced by blue-green blooms (Dunne and Leopold, 1978). Many pathogenic bacteria thrive when temperatures are slightly increased, and their abundance can be harmful to fish (Brett, 1956 cited in Dunne and Leopold, 1978). Furthermore, an increase in water temperature causes the release of phosphorus and other nutrients from sediments (Karr *et al.*, 1977 cited in Shields and Nunnally, 1984; Genetti, 1989) and this could exacerbate eutrophic conditions, especially in the lower reaches.

In conclusion, a change in temperature is likely to have an effect on aquatic organisms, but the extent and timing of the change will dictate the significance of the effect. Slight temperature change, if maintained for a period of time, could lead to alteration of community composition, as a result of the differential optimal temperatures of the respective organisms. Acute, radical temperature changes may lead to mortality of organisms by exposing them to their lethal limits. Brown (1991) recommended that a increase of less than 10°C of the original river water temperature is likely to prevent long-term effects (Dallas and Day, 1993). However, Hynes (1970) cautions that even minor changes in temperature may have profound biological effects.

- Nutrients

Organic enrichment almost certainly results in a decrease in species richness and diversity and an alteration in the composition of biotic communities (Dallas and Day, 1993). Clean water is characteristically represented by many species with few individuals of each species, while increasing levels of nutrients typically results in a reduction in species richness and high population numbers of a few species. An interesting effect of organic pollution is that it tends to shift low-altitude animals further upstream (Hynes, 1970).

Severe organic enrichment will result in the development of a greyish growth known as "sewage fungus". This is a community of heterotrophic organisms including bacteria, fungi, algae and protozoans (Dallas and Day, 1993).

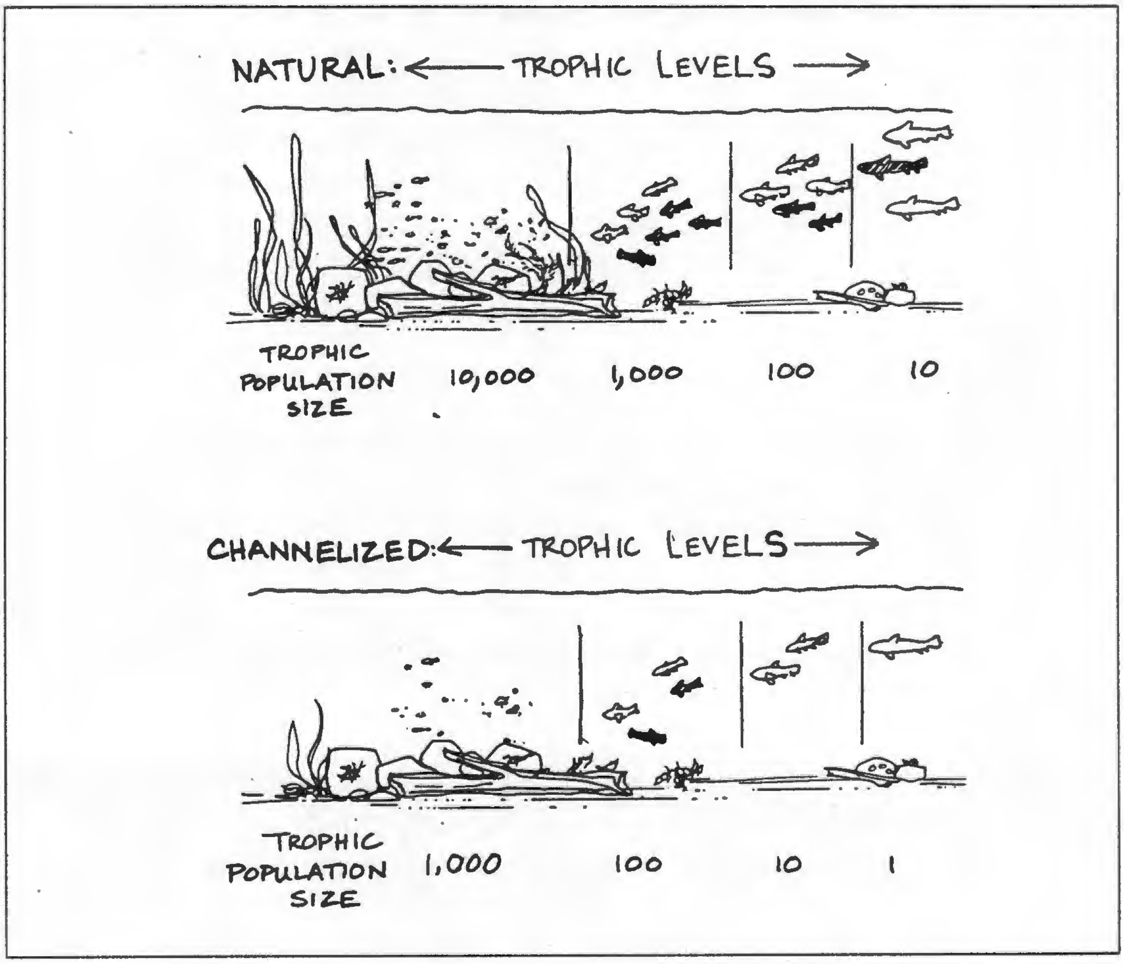
Following channelisation of low-order streams, domination by the macro invertebrate community may shift from detritivores (shredders and collectors) to herbivores (grazers) (Simpson *et al.*, 1982). Diversity will probably be significantly decreased due to the elimination of many microhabitats that support detritivores and associated predators and grazers (Simpson *et al.*, 1982). Total macro invertebrate density may be severely reduced, especially if high velocities prevent the establishment of adequate periphyton communities on which grazers feed.

Colonisation of most headwater areas will be slow as they have low benthic populations dominated by shredders and collectors with few grazers (Hynes, 1970). Therefore, drift from upstream areas will contain low numbers of grazers, and repopulation by this functional group will be slow.

In intermediate-order streams, the loss of allochthonous detritus has less impact than in low-order streams. Natural detrital input into mid-order streams is not large, and neither is detritus is not the major energy resource (Marzolf, 1978 cited in Simpson *et al.*, 1982).

In low-order streams, FPOM from upstream sources is still necessary, and reduction in CPOM upstream will reduce the quantity of FPOM downstream.

Figure 4.3: Schematic influence of the effects of a reduction in allochthonous inputs on aquatic trophic structure (after Simpson *et al.*, 1982)



Additional impacts relate to the introduction of exotic aquatic and terrestrial flora and fauna which may affect ecosystem functioning. For example, replacing indigenous riverine trees, for example *Brabejum stellatifolium* (wild almond) and *Ilex mitis* (Cape holly), with exotic trees, such as *Quercus robur* (oak) or *Populus canescens* (grey poplar), will have a significant impact as the leaves fall at different times of the year. They are not utilised by the indigenous shredder invertebrate community, and therefore impact on the entire food web (King, 1982).

Excessive growth of exotic aquatic weeds such as *Eichhornia crassipes* (water hyacinth) and *Myriophyllum aquaticum* (parrots feather) may choke the channel, reduce light penetration and obstruct flow. It will also impact on the indigenous flora and fauna. Similarly, exotic fish, such as *Salmo trutta* (brown trout) and *Gambusia affinis* (mosquito fish), result in the elimination of indigenous fish species such as *Galaxias zebratus* (Cape galaxias) and *Pseudobarbus* sp. (redfins). In addition, the exotic *Cyprinus carpio* (carp) results in increased turbidity in the lower reaches of rivers due to its benthic foraging habits.

Large quantities of suspended sediments reaching streams will lead to depauperate benthic insect communities (Reed, 1977; Barton, 1977; Chisolm and Downs, 1978 cited in Jones and Clark, 1987). This finding is supported by studies which found that the two genera commonly associated with urbanisation were deposit feeders (Merritt and Cummins, 1984 cited in Jones and Clark, 1987). Thus, the diverse benthic food web found in non-urbanised streams is greatly simplified in highly urbanised watersheds. This is supported by the work of Richey (1982 cited in Dallas and Day, 1993) who found that food quality and temporal availability of POM were significantly lower in an urban stream, and that the altered flow regime increased throughput of material and reduced instream-processing time. It is generally recognised that the overall effect of urbanisation is debilitation of the functioning of the stream ecosystem. Macro invertebrates and fish populations become depleted, algal biomass increases and bacterial decomposition pathways become important (Sloane-Richey *et al.*, 1981 cited in Dallas and Day, 1993).

- pH

Changing the pH of water affects the ionic and osmotic balance of aquatic organisms. Relatively small changes in pH are not normally lethal, although sub-lethal effects, such as slow growth and reduced fecundity may occur due to increased physiological stress.

pH determines the form in which numerous organic and inorganic elements and molecules are found. A decrease in pH may alter the availability and toxicity of such metals as aluminium, cadmium, copper, mercury, manganese, lead and zinc (Dallas and Day, 1993). In addition, at a pH above 8, the ubiquitous non-toxic ammonium ions (NH^{4+}) are converted into highly toxic un-ionised ammonia (NH^{3+}).

The pH of rivers is particularly relevant in the South Western Cape where runoff from fynbos-dominated Table Mountain sandstones has a naturally low pH and in many cases unique species assemblages.

- Oxygen

One of the most important abiotic factors relating to the survival of most aquatic organisms is the concentration of dissolved oxygen in the water. In natural conditions, the concentration of dissolved oxygen fluctuates diurnally, depending on the relative rates of photosynthesis and respiration. It is usually lowest at dawn, increases during the day, peaks in the afternoon and decreases during the night. Factors affecting the concentration of dissolved oxygen in water include the rate of reaeration from the atmosphere (dependent on turbulence, depth, surface area, velocity, and oxygen deficit); temperature (high temperatures decrease oxygen solubility), salinity (less oxygen with increasing salinity), respiration by all organisms and photosynthesis by plants (results in diurnal oxygen fluxes); organic enrichment (biological oxygen demand) and chemical oxygen demand.

In general, the more oxygen there is, the more desirable the aquatic community. However, excessive plant growth results in large diurnal fluctuations and may result in oxygen supersaturation in sluggish or stagnant waters during the afternoon as a result of photosynthesis (Dallas and Day, 1993).

- Toxins

Toxins can be defined as any substance that is detrimental to the health of an organism. Toxins lead to a reduction in faunal density, diversity and richness, and a change in species composition. Each species has different tolerance limits for different toxins. The accumulation of toxic substances leads to a reduction in faunal density, diversity and richness, and a change in species composition (Garie and McIntosh, 1986 cited in Dallas and Day, 1993).

a) <u>Urbanisation</u>

Urban runoff may affect riverine biota more severely than treated sewage effluent (Hellawell, 1986). Comparisons of stormwater/ urban runoff and treated sewage effluent showed that the former contained twenty times the concentration of non-filterable residues, twice the biological oxygen demand (BOD), fifteen times the phosphate and nitrogen concentrations and more suspended solids (Weeks, 1982 cited in Dallas and Day, 1993). The "initial flush" at the start of a rainfall event transports approximately 40% of the pollutants (Weeks, 1982 cited in Dallas and Day, 1993). In seasonal rainfall areas, such as the South Western Cape, the effects of the first flush are likely to be significant.

- Turbidity
  The construction phase of urban development leads to increased sediment availability and transport within the receiving stream. However, once construction is completed and the impervious cover reaches its maximum, sediment load is reduced (Maddock, 1976 cited in Keller and Hoffman, 1977). However, erosion

of the channel and in the catchment may maintain a high sediment load. Both stream erosion and the supply of sediment from the catchment result in the deposition of unnaturally large volumes of sediment in the lower reaches of rivers or downstream of canalised reaches of rivers, where flow velocities decrease.

- Nutrients

  Runoff from urban areas contains elevated levels of plant nutrients, especially phosphorus and nitrogen. This phenomena is known as cultural eutrophication. The increased nutrient levels are a result of the application of organic and inorganic fertilisers, detergents, faecal material, atmospheric fallout, vehicle exhaust emissions and decaying plant matter (Kluesener and Lee, 1974 and Cowan and Lee, 1973 cited in Simpson and Hemens, 1978).

  The effect of organic enrichment on riverine ecosystems will depend, to a certain extent, on the river zone affected. For instance, the upper reach is more susceptible to organic enrichment than is a deposition zone (lower reach) (Hawkes, 1979 cited in Dallas and Day, 1993). Organisms associated with certain habitats, such as riffles, may be more susceptible to the effects of enrichment than are sandy bottom dwellers (Hawkes, 1979 cited in Dallas and Day, 1993). Enrichment results in a decrease in species richness, diversity and an alteration in the composition of biotic communities. Clean water is characterised by many species with few individuals within each species, whilst organically enriched water contains a few species with many individuals of each (Hynes, 1966).

  The most important biotic effect of eutrophication is a stimulation of the growth of aquatic vegetation (Piwoni and Lee, 1976 cited in Swales, 1982). Excessive algal growth in well-lit sections of urban streams may lead to the alteration of aquatic food webs (Jones and Clark, 1987). The enriched stream may also exhibit periods of oxygen deficit. The net result of nutrient enrichment is the elimination of pollution sensitive organisms and the upstream extension of lower riverine conditions (Hynes, 1970b, cited in Ward and Stanford, 1989).

  The increase in nutrients associated with urbanisation (from fertilisers, leaking sewers, human and animal faeces, decomposing leaf material, detergents, etc) frequently results in the excessive growth of aquatic vegetation.

- Temperature

  Floating vegetation may promote the attainment of very high water temperatures (Welcomme, 1979; 1985 cited in Ryder and Pesendorfer, 1989), due to restricted evaporation, absorption of sunlight, and reduced wind and wave action (Ryder and Pesendorfer, 1989). Suspended silt also absorbs heat energy, thus increasing temperatures in turbid rivers (Ellis, 1936; Reid, 1961 cited in Ryder and Pesendorfer, 1989). Urbanisation may reduce the inflow of ground water (Dunne and Leopold, 1978), and its cooling effect in summer.

The effect on the water quality of receiving systems is determined by the type, density and character of urban development, that is industrial, commercial or residential. The main pollutants include sediments, nutrient enrichment and toxic substances.

Biocides, including herbicides, fungicides and insecticides, can reach rivers via direct application (pest control), industrial effluents, sewage, leaching, runoff, and the deposition of aerosols and particulates.

- Toxic substances

During the initial part of a rainfall event, runoff dislodges and dissolves contaminants accumulated on impermeable surfaces. This initial volume of runoff is known as the "first flush" and results in high concentrations of sediments, nutrients and pollutants (Simpson and Hemens, 1978). The longer the period of time since the last rain event, the greater the pollution load carried by the "first flush".

Invertebrate communities that develop in urban areas must be resilient enough to withstand intermittent periods of severe environmental stress such as high flows, unstable substratum and high acute pollution loads (Dallas and Day, 1993). It is generally recognised that the overall effect of urbanization and stormwater runoff is debilitation of the functioning of the stream ecosystem. Macro invertebrate and fish populations become depleted, algal biomass increases (as a result of nutrient enrichment) and bacterial decomposition pathways become important (Sloane-Richey *et al.*, 1981 cited in Dallas and Day, 1993).

Several researchers have studied the impact of watershed urbanisation on the benthic fauna of streams. Jones and Clark (1987) found that there was little effect on the total insect numbers, but a marked shift in the taxonomic composition. Urbanisation is associated with a decline in pollution-sensitive groups such as mayflies, caddisflies and amphipods and a dramatic increase in chiromids and oligochaetes (Pitt and Bozeman, 1982 cited in Jones and Clark, 1987).

b) Channelisation

River channel works may affect water temperatures mainly in ways: through the removal of backside vegetation and through reductions in water depth. The removal of trees and other backside vegetation reduces the extent of river shading and increases insolation, leading to a rise in water temperature (Karr and Schlosser, 1978 cited in Swales, 1982), of between 4°C and 8°C (Burton and Likens, 1973; Crisp and LeCren, 1970; Gray and Edington, 1969; Likens *et al.*, 1970 cited in Swales, 1982). Increases in daily variability of water temperature also result (Likens *et al.*, 1970 cited in Swales, 1980). Reductions in water depth also result in higher temperatures (Hill, 1976).

Channelisation may have varied effects on dissolved oxygen. Huish and Pardue (1978 cited in Simpson *et al.*, 1982) found increased dissolved oxygen concentrations after channelisation, presumably due to the reduction in organic matter and its decomposition were reduced. Widening a stream increases the surface area available for oxygen exchange, while eliminating rapids has the opposite effect. Spring and seepage water tends to be low in dissolved oxygen. In addition, manipulation of streams and the amount of vegetation may change the diurnal or seasonal dissolved oxygen content (O'Rear, 1975 cited in Simpson, *et al*, 1982).

Dredging may release various pollutants through resuspension (Alabaster, 1972; Cordone and Kelly, 1961; Edwards, 1969 cited in Swales, 1982), while the release of anaerobic sediments (Darnell, 1976 cited in Swales, 1982; Darnell *et al.*, 1976 cited in Brookes, 1988) may result in the death of fish and other organisms requiring high concentrations of oxygen.

Channelisation of the upper reaches may increase water temperatures where the riparian canopy is removed or reduced, allowing greater insolation. Channelisation increases silt loads and turbidity.

Silt, manure, fertiliser, pesticides, and herbicides are rapidly washed out of channelised segments due to the high water velocities, but tend to accumulate in downstream regions as the current slows (Simpson *et al.*, 1982).

c) Canalisation

Some lined channels have been observed to experience much higher maximum water temperatures and ranges of diurnal fluctuation of water temperature than nearby natural streams (Genetti, 1989). These effects are often due to the wide, shallow flows, lack of shade, solar heat transfer by the lining material, and to the focusing of solar energy by the vertical walls (Genetti, 1989). While a rectangular section may experience more reflection and heating than a trapezoidal section, the former would benefit from more shade on account of the vertical walls and possibly from adjacent trees or buildings. Furthermore, the impervious nature of lining would prevent the inflow of cool ground water.

The pH is likely to increase due to leaching from the concrete. During construction, in-situ cast canals may lead to substantial increases in pH. Algal growth on unshaded channel bottoms can raise pH levels and increase dissolved oxygen concentrations during the day. The lack of turbulence may result in lower levels of dissolved oxygen.

The stability imposed by channel lining can decrease levels of suspended solids and turbidity.

4.3 SOCIO-ECONOMIC ASSESSMENT

4.3.1 Introduction and methodology

In order to provide a holistic perspective, in addition to the ecological assessment presented above, social and engineering criteria also need to be considered. The theoretical basis for these was, however, not developed in detail and the assessment is less rigorous.

The main purpose of this component of the dissertation is to emphasise the trade-offs between the ecological, and social and engineering aspects. This perspective should promote a more informed and holistic understanding of the management options available for urban rivers.

The socio-economic assessment is divided into four components, namely aesthetic value and recreational/ educational opportunities; biological purification; corridor conservation value and stormwater efficiency.

4.3.2 Aesthetic value and recreational/ educational opportunities

The appearance of rivers and their corridors is important as it influences the level of amenity which they can offer. It can also affect how people treat the river and adjoining space. For example, if the river looks like a drain, it will tend to be treated as an open sewer and there would be little incentive not to litter, dump or discharge effluents directly or indirectly into it. As a result, the "river" enters a spiral of degradation because of its engineered appearance and perception of worthlessness. Even if the river is severely degraded, the consequences of pollution for the ecosystems and humans, who utilise the downstream reaches, estuary and ultimately the ocean, may be severe.

Rivers engineered solely as an element in the stormwater infrastructure are a dis-amenity to the local community and offer little recreational or educational opportunities. The erection of fences and the fact that riverside developments turn their backs on the river, perpetuate the belief that they are hazardous wastelands. Furthermore, swimming, fishing and walking are discouraged by private ownership of the river banks, signage and a lack of maintenance. A self-fulfilling prophesy of neglect, degradation and danger is perpetuated.

Developing the recreational and education potential of riverine corridors is not however a panacea and may in fact create a suite of problems. These include: reduced security for riparian landowners; safety risk for recreational users; vagrancy; littering; dumping; collection of mutti, for example tree bark; increased erosion of paths and banks; and increased management costs. The increased level of human disturbance may negatively affect terrestrial animals and reduce the conservation value. Notwithstanding these potential negative effects, development of the recreation and education potential of the riverine corridor is important in promoting environmentally-sensitive management of urban rivers.

a) Urbanisation

The concentration of people may create a desire or need for the development of recreational and educational opportunities. This could result in more environmentally-sensitive river management.

Urbanisation may, however, have significant indirect impacts on the aesthetics of the riverine system. These effects relate to the impacts of stormwater runoff. They include the increase in flow peaks and the associated accelerated cycle of erosion and deposition. In addition, litter and water pollution may degrade the riverine ecosystem and the amenity value.

Lastly, poorly planned urban development may intrude onto the floodplain and the riverine corridor, thereby directly impacting on the natural aesthetic value of the area and limiting environmentally-sensitive river management.

b) Channelisation

Modified channels frequently result in a monotonous, visually displeasing landscape, characterised by eroding mounds of material excavated from the channel, straight channel alignments, extensive stream bank erosion, uniform flow conditions, turbid water and weedy vegetation (Dale, 1975 cited in Shields, 1982a).

The removal of riverside trees further contributes to the degraded, disturbed character. The artificial appearance may conflict with the surrounding landscape, unique features may be removed or scenic vistas obscured. On the other hand, modified channels with clean lines, graceful bridges, and an overall neat appearance, may be perceived by some people as being more harmonious in the urban context than the severely degraded, eroded, debris-laden stream that preceded it (Shields, 1982a; Genetti, 1989).

Construction may facilitate the development of a riverine path, or sections of the floodplain for active or passive recreation. However, the conservation and thus educational value could be impaired by the unnatural character of the terrestrial and aquatic environment.

c) Canalisation

A concrete-lined canal is generally not regarded as aesthetically pleasing, particularly in highly visible areas and areas of high aesthetic value, such as certain residential and park areas.

Furthermore, the indirect aesthetic impact of litter and degradation typical of canals, contributes to the negative aesthetic value of the area. Conventional reinforced concrete linings present an artificial, unnatural appearance relative to a natural stream channel.

Straight lines and uniformity of form, texture, and colour are less desirable than the visual diversity offered by natural meandering channels with vegetated banks. Aesthetic impacts may be more important than decreased aquatic habitat in dense urban areas.

Typically, the considerable width of the canal in the lower reaches (necessary because of the high discharge and low gradients) increases the magnitude of the aesthetic impact. In addition, the slow current and shallow nature of the channel results in large expanses of concrete bed and frequently the accumulation of unsightly litter and weeds.

4.3.3 Biological purification

The biological community of river systems acts to enhance water quality (Genetti, 1989). Biological purification is proportional to the time that water is retained (dependent on area and flow rate) and the number and diversity of plants and animals present.

Decreasing the amount of self-purification within a reach increases the pollution of downstream reaches, vleis, wetlands, estuaries and oceans. Organic loadings are increased downstream because less detritus and soluble organic material is processed in the altered reach (Simpson *et al.*, 1982).

a) <u>Urbanisation</u>

The deterioration of water quality, combined with the increased flow and disturbance results in a decrease in species richness and consequently a reduction in biological purification. Urbanisation itself is however unlikely to have a direct affect on the amount of biological filtering, although urban development of the floodplain would remove the buffer strip of vegetation that reduces non-point sources of water pollution.

b) <u>Channelisation</u>

Channelisation results in a significant reduction in instream, hyporheos and riparian habitat area and subsequent reduction in species diversity. These two factors reduce the capacity of the stream to assimilate waste products (Simpson *et al.*, 1982; Petersen, 1992).

Furthermore, the increased velocity and reduced retention time in channelised streams results in reduced food processing times (House *et al.*, 1993).

c) <u>Canalisation</u>

Very little biological purification takes place in canalised rivers as they support a very low diversity and number of plant and animal species. Moreover, the retention time of water and detritus is short, and little biological purification occurs. The water is effectively transported through the canal without undergoing any improvement in water quality.

4.3.4 Corridor conservation value

The conservation value of the riverine corridor depends on the area, level of disturbance and ecological integrity of the river and floodplain. Riverine corridors often are the only undeveloped areas in a "sea" of urban development and therefore offer unique conservation opportunities. The conservation value may be further enhanced if the corridor forms a link between terrestrial conservation areas.

The maximum conservation value is likely to be achieved if intact riparian, floodplain and terrestrial habitats are included in the corridor or conservation area.

a) Urbanisation

Urbanisation may impact directly on the conservation value of the corridor by the encroachment of development onto the floodplain.

Indirect impacts include increased disturbance of terrestrial fauna by humans, as well as the introduction of exotic plants and animals.

b) Channelisation

A common motivation for channelising a natural river is to increase the area of floodplain available for urban development. Therefore, channelisation typically reduces the area of floodplain available for conservation.

c) Canalisation

The effective destruction of the riparian and floodplain zones and very narrow corridor, if any, severely limits any conservation potential. Nonetheless, even a narrow corridor of natural or semi-natural habitat could form a link between fragmented portions of natural terrestrial vegetation in the catchment.

4.3.5 Stormwater efficiency

Stormwater efficiency can be assessed according to capital and maintenance costs, reduction of over bank flooding, and maximisation of floodplain area for development.

Traditional stormwater practices, such as channelisation and canalisation usually achieve the primary drainage and flood control goals for the length of the modified reach. They may, however, cause increased flood damage to downstream property by increasing the velocity and discharge beyond that which the downstream channel can convey (Campbell *et al.*, 1972; Little, 1973 cited in Brookes, 1988). Thus whilst solving local flooding problems, canalisation may exacerbate downstream flooding and erosion (Beaumont, 1986).

a) Urbanisation

Traditional urban stormwater systems are likely to reduce the inconvenience associated with runoff events. At the same time, they typically increase the flow entering the receiving stream, as described in Chapter Three. Urbanisation may therefore increase downstream flooding. For example, urban development upstream from existing riparian urban development, which under natural runoff conditions was only subject to inundation by occasional storms (say every 50 years), could become subject to more frequent flooding (say every 5 years) as a result of increased runoff from recently urbanised areas upstream (Beaumont, 1988).

The faster runoff may compound flooding by reducing the concentration time of runoff from the furthest parts of the catchment, thereby making downstream areas of the catchment susceptible to storms of shorter period and greater intensity of rainfall (Beaumont, 1986).

b) Channelisation

Channelisation results in considerable hydraulic improvements and the discharge capacity of the natural channel is enhanced. The majority of flows are contained within the channel.

However, the overall effectiveness of channel works used in flood alleviation schemes has increasingly been questioned in recent years (Swales, 1982). In a study of flood control in the United States, Costa (1978 cited in Swales, 1982) suggested that the engineering approach has not been successful in reducing flood damage as flood control measures encouraged further development in flood-prone areas. Thus, costly flood alleviation schemes may increase damage caused by large flood events.

c) Canalisation

Lined channels reduce the hydraulic roughness dramatically, thereby increasing the flow velocity (Brookes, 1988). For example, a reduction in Manning's n-coefficient from 0.025 to 0.015 would increase a channel's carrying capacity by about 80% (Brookes, 1988). The required cross-sectional area of a lined channel for a given flow is therefore smaller. As the design flood is contained within the canal, the floodplain is not required for conveying stormwater.

However, the lining of channels to increase the velocity of flow and rate of discharge is contrary to the concept of retarding flow to reduce flood peaks. It may compound drainage problems downstream (Dunne and Leopold, 1978; Miles, 1984) and often necessitates further extension of the canal.

Most benefits of canalisation are derived in the eroding zone as high velocities can be tolerated due to the erosion-resistant nature of the lining. In the depositing zone, the hydraulic benefits are less evident due to the reduced gradients and therefore lower flow velocities.

4.3.6 Planning, infrastructure and cost

Streams and rivers impose various constraints on floodplain land use and form barriers to movement. It is often for these reasons that rivers are engineered and it therefore follows that increasing levels of development or engineering of rivers are associated with reducing such constraints and limitations.

In order to determine the costs and benefits of urbanisation, channelisation and canalisation, the engineering, ecological and social implications would have to be assigned financial values. These financial values would then have to consider the costs over a period of time. Even if this huge environmental economics task could be completed to the satisfaction of all stakeholders, it would not necessarily identify the parties that would benefit and those that would be disadvantaged.

As the above exercise is clearly beyond the scope of this dissertation, this section merely provides an indication of the direct financial engineering costs.

a) Urbanisation

To retain a river in its natural state, the floodplain must be accepted as part of the river. This may sterilise large areas of land from urban development. In addition, the river system would be one of the primary informants of town, regional and infrastructural planning, and crossing the natural river and floodplain system would involve considerable expense.

Utilising the existing water course as a stormwater conduit would not entail any financial cost.

b) Channelisation

Channelisation results in large areas of the floodplain becoming available for urbanisation. In addition, as the river is confined to a narrow defined channel, crossing the river is easier. It allows the river course to be moved to an alignment that is more convenient for urban development.

Channelisation is likely to incur a relatively high capital cost. There would also be maintenance costs associated with regular dredging or draglining to remove sediment and vegetation.

c) Canalisation

Canalisation has the same benefits as channelisation, but even more floodplain land can be utilised for urban development and crossing the canal is less expensive due to its restricted width.

Frequently a riverine corridor is not required, as maintenance, if required, can take place from within the canal and therefore the amount of land which can be developed is maximised.

Canalisation would incur very high capital costs and subsequently minimal maintenance costs, especially if the canal is self-scouring.

4.4 SUMMARY

Urbanisation results in an imbalance in sediment and flow regimes in the receiving stream system and this in turn leads to biophysical and socio-economic degradation of the stream system. Channelisation exacerbates the imbalance and causes in further degradation. This degradation, and especially the accelerated cycle of erosion and deposition, may result in canalisation being required to redress the problem of channel degradation. However, while canalisation may, in certain circumstances, "solve" the channel degradation efficiently, as well as flooding problems, it does so at the expense of most of the other functions that rivers perform.

From an ecological perspective, this chapter has shown that the abiotic effects of urbanisation, channelisation and canalisation impact on the key abiotic determinants of the aquatic ecosystem. These include the increase in the magnitude and frequency of high flow velocities, the reduction in substrate heterogeneity, the decrease in the aquatic, riparian and floodplain area and a deterioration in water quality. These changes in the key abiotic determinants may affect each floral and faunal species in different ways, and are likely to have a greater effect on species in the upper reaches and rare or specialised species. Increasing changes from the natural range of abiotic factors will affect all species and result in the loss of some. The species diversity of the system will therefore be reduced. The altered conditions may, however, be suitable for other less desirable, "unnatural" or even exotic species. Over time, the aquatic community will bear less resemblance to the original stream community. Eventually, basic ecological functioning may be impaired and the system will only support a limited number of extremely "hardy" species.

It can be concluded from this chapter and Chapter Two that river ecosystems are complex and have a myriad of abiotic and biotic interactions. These interactions involve temporal components with stochastic events or disturbance playing a major role. Consequently, in predicting the impacts on riverine systems, it is not always possible to separate the primary, secondary and higher order abiotic and biotic impacts. Moreover, these impacts will vary from system to system and from reach to reach within the same river. Nonetheless, by focusing on changes to the key abiotic determinants, the ecological assessment in this chapter should be understood by non-ecologists. An added advantage is that it provides clear links to potential mitigation measures as the abiotic determinants can be manipulated.

From a socio-economic perspective, the main effects of urbanisation, channelisation and canalisation include:

- aesthetic degradation of the river and corridor;
- impairment of recreational and educational opportunities;
- reduced biological filtering of the water;
- reduction in the conservation value of both the river and corridor and the impairment of linkages between fragmented natural habitats, and
- an increase in stormwater efficiency resulting from channelisation and canalisation.

It is concluded that the increase in stormwater discharge and deterioration in water quality have indirect impacts on the receiving river system. On the other hand, channel engineering works, such as clearing obstructions, channelisation and canalisation, result in increasingly severe direct and indirect impacts on river systems. However, it is possible to reduce the negative impacts and realise potential functions or values through appropriate mitigation measures.

Chapter Five provides some background to environmentally-sensitive river engineering, while Chapters Six and Seven describe measures to mitigate the impacts at the catchment and floodplain. Chapter Seven derives mitigation measures at the level of the river channel.

CHAPTER FIVE: MITIGATION THROUGH ENVIRONMENTALLY-SENSITIVE RIVER MANAGEMENT

CONTENTS

CHAPTER FIVE: MITIGATION THROUGH ENVIRONMENTALLY-SENSITIVE RIVER MANAGEMENT

5.1 TOWARDS A DEFINITION

5.1.1 Introduction

> *"A prudent technology should alter the natural order as little as possible" (Leopold, 1941 cited in Likens and Bormann, 1974, p 454).*

Urban stream channels are often neglected, abused, or modified without knowledge of the consequences. As a result, many urban streams represent a sad testimony to our civilization (Keller and Hoffman, 1977). They tend to be straightened, deepened, or lined with concrete and filled with every imaginable type of urban rubbish. Urban streams need not be a sensual blight if the concepts and practice of environmentally-sensitive river engineering are adopted.

Historically, throughout the world a structural or interventionist philosophy of engineering has been followed, whereby rivers have been straightened, widened, deepened, or lined to achieve engineering objections. A more holistic approach is needed in order to achieve sustainable development of rivers and their associated flood plains. This new, less harsh philosophy emerged during the 1970's in North America and the majority of European countries and is based on the emulation of the natural forms and processes of meandering channels (Brookes and Gregory, 1988). The understanding of fluvial processes and natural stream geometry is a vital ingredient to all successful environmental designs (Gardiner, 1992). The approach that "technology can fix it" is changing towards a softer, more sympathetic approach which is exemplified by the "design with nature" school of thought proposed by McHarg (1969), characterised by Winkley (1972) and others as "working with the river rather than against it" (Brookes and Gregory, 1988).

The emerging philosophy of dealing with urban flood management involves utilising a mixture of structural and non-structural approaches. Non-structural approaches include catchment management (on-site stormwater retention) and floodplain management, (land use zoning), and are described in further detail in Chapter Six. Structural approaches relate to river channel works (such as retaining meanders and riverine vegetation) and are the subject of Chapter Seven.

To many people a river represents something more than simply a drain which carries water off the land. It is therefore reasonable - and has proved possible - to build flood prevention schemes worth cherishing, which afford beauty and pleasure to humans as well as providing a refuge for wildlife (Newbold, Purseglove, Holmes, 1983). Sympathetic river engineering in the urban context benefits from the large number of people who could gain from the aesthetic, amenity, recreation and educational opportunities. Even the unseen reaches of a river deserve sympathetic treatment as they form part of the longitudinal ecosystem. Thus, from an ecological viewpoint, Beaumont's (1988) suggestion that concrete canals are appropriate in industrial areas is questionable, as there are likely to be both upstream and downstream impacts. Nonetheless, more sympathetic treatment of rivers usually begins in up market residential areas.

Past designs of stormwater channels have largely focused on technical aspects with little or no regard for social or ecological aspects. The new approach to channel design considers flood-hazard reduction as one component of a multi-objective riparian corridor management strategy (Williams, 1990). This strategy may give equal weight to the protection and enhancement of the riparian environment and the improvement of aesthetics (Williams, 1990). The new emphasis is on continual long-term management of a river corridor.

Rivers will always flood and, where they threaten humans, steps need to be taken to minimise or prevent damage. Most rivers therefore will require a relatively high level of management (Newbold, Purseglove, Holmes, 1983). However, it is critical that the requirements of wildlife, and the contribution wildlife can make to the scheme as a whole, are established at the outset rather than included as a last-minute 'cosmetic' (Newbold, Purseglove, Holmes, 1983). Good river management aims to maintain, and in many places to extend, a buffer for wildlife between the watercourse and the adjacent land. Playing fields and over-mown parklands sloping to the water's edge, are preferable to buildings and roads, but provide a sterile habitat for wildlife.

5.1.2 The history of sensitive river engineering

Initially, concern for the environment involved 'bolt-on extras' or mitigation, such as tree-planting and timber hand railing. It is now accepted increasingly that care for the environment is "an essential ingredient of thinking and planning" (Gardiner, 1988) and should be integrated into all stages of the project (Department of Environment Affairs, 1992).

Progress toward environmentally-sound engineering in Britain is illustrated in Table 5.1. It would appear that Cape Town is some five to ten years behind Britain.

Table 5.1: Progress towards environmentally-sound engineering in Britain (modified after Gardiner, 1988)

PERIOD	CHARACTERISTICS
pre 1970	Hard engineering
1970-1980	Hiding local impact of hard engineering (by improved architectural designs, planting trees, shrubs, etc.)
1980-1985	Reducing local impact by 'soft', biotechnical engineering involving the use of natural materials and fibres in place of steel and concrete

1985-1990	Mitigation of local impact by preinvestment studies: - holistic review of the catchment drainage system - engineering/environmental partnership to assess and refine the best practical environmental option Mitigation of adverse impact through post-investment review: - restoration of river habitats damaged by insensitive works Acceptance of environmental enhancement
1990-	Establishment of a sustainable dynamic equilibrium in river corridors by development of catchment management. The concept involves: - production of urban catchment management plans - special (re-) designation of planned areas (floodplain, storage areas)

The professionals who control a more balanced management are the engineers, with the responsibility to control flooding and to protect the environment (Purseglove, 1989). In 1984, the Royal Society for the Protection of Birds, in conjunction with the Royal Society for Nature Conservation, published a handbook which, through examples, showed that while eco-engineering was compatible with the effective and necessary control of flooding, the cost of the ecological approach was not prohibitively expensive.

5.1.3 Public demand for environmentally-sensitive schemes

In urban areas, rivers may be one of the few natural features remaining. It is illogical to treat the rivers flowing through the places where people live and work as drains, and for those people to claim to be "environmentally aware". It should not be necessary to travel to the country or wilderness areas to enjoy river landscapes or to find environmental education opportunities.

The degree of benefit to that the environment will receive depends upon the level of public interest and pressure. If the public actively demand high environmental standards for river management, then it may well achieve them (Purseglove, 1989). The call for natural solutions to river engineering problems has become constant in many European countries (Binder *et al.*, 1983). This concern has been support by research papers on the morphological, hydrological and biological impacts of humans on rivers (Hynes, 1960, 1970; Moore and Morgan, 1969; Whitton, 1975; Gregory, 1977a and Hollis, 1979 cited in Brookes, 1988).

During the past two decades in the United Kingdom, a series of handbooks advocating the adoption of environmentally-sensitive designs for flood alleviation and land-drainage schemes have been produced by organisations such as the Nature Conservancy Council (Newbold *et al.*, 1983), the Water Space Amenity Commission (1980a,b cited in Brookes, 1988), the Royal Society for the Protection of Birds together with the Royal Society for Nature Conservation (Lewis and Williams, 1984), and by individual water authorities (Purseglove, 1989).

Table 5.2: Some of the early articles describing the controversy surrounding river channelisation (after Brookes, 1988)

TITLE OF ARTICLE	AUTHOR
Ravage the river	Posewits, 1967
A river fights back	Spence, 1968
Our ruined rivers	Bagby, 1969
A vanishing part of Louisiana: its streams	Davidson, 1969
Twilight for two rivers	Robertson, 1969
The gravediggers	Bauer and East, 1970
The vanishing stream	Gebhards, 1970
Crisis on our rivers	Miller and Simmons, 1970
The stream that used to be	Seaburg, 1971
How to kill a river by "improving" it	Whistleblower, 1974
Channelization: short cut to nowhere	Coming, 1975
Wildlife down the drain	Davies, 1982

The process of public participation and iteration of project proposals is the distinguishing mark of the engineering and environmental partnership approach (Gardiner, 1992). There has been increasing progress towards environmentally-sound river management in the United Kingdom and elsewhere (Gore and Petts, 1989), in response to improved scientific knowledge, wider public awareness of environmental issues and the implementation of Environmental Impact Assessments. For example, in a particular case in the United States, the courts prohibited channelisation under the National Environmental Protection Act (NEPA), because of inadequate discussion of project alternatives such as floodplain planning and zoning, floodplain insurance or upstream retention (Brookes, 1988). Similarly, in South Africa, according to Regulation number 1182 of 5 September 1997 of the Environment Conservation Act of 1989, river channel engineering works will be subject to Environmental Impact Assessment, and this should include consideration of alternatives. In this way, the concept of environmentally-sensitive river engineering, including catchment and floodplain management, should be promoted.

Throughout the world, governments, international organisations and major corporations, as well as ordinary citizens, are now insisting that planning decisions take cognizance of the impact of human actions on the environment (Fuggle and Rabie, 1992). This is the result of an undoubted rise in environmental awareness throughout the world and in South Africa during the last three decades (Fuggle and Rabie, 1992).

The conservation of rivers in Southern Africa has been the subject in the last ten years of much attention (O'Keeffe,1986b, O'Keeffe *et al.*, 1987, Ferrar *et al.*, 1988, Ferrar, 1989, O'Keeffe *et al.*, 1989a,b, Allanson *et al.*, 1990, O'Keeffe and Davies, 1991, and King *et al.*, 1992 cited in Davies *et al.*, 1993). It has increasingly been recognised that rivers are significant features of the landscape, and form part of an interrelated network of biotic and abiotic factors (Hynes, 1972; Vannote *et al.*, 1980; Binder *et al.*, 1983). Rivers contain a diverse biological flora and fauna and may thus be considered as ecosystems in their own right. They are not simply conduits merely for conveying fluids (Likens and Bormann, 1974).

Recently, in South Africa there has been a growing awareness of the neglect of urban river systems and the importance of riparian corridors for nature conservation (Cape Town City Engineer, 1982; 1985; Polyton and Roberts, 1985; Davies and Day, 1986; Roberts, 1987; McDowell *et al.*, 1991; Low, 1991), education (Wallace, 1991) and recreation (Cape Town City Engineer, 1982; Luger and Davies, 1993; Luger, 1994).

In the past, conservation in South Africa has focused almost exclusively on terrestrial ecosystems, especially large mammals (epitomised by the "big five"), individual "high profile" species, and rare plants (Davies and Day, 1986). During the last 20 years, however, there has been a greater awareness of the impacts of water and land resource development on riverine ecosystems (Ward and Stanford, 1979; Welcomme, 1979; Petts, 1984; Whitton, 1984; Davies and Walker, 1986 cited in Petts *et al.*, 1989). Problems in conserving and managing rivers are due to:

- lack of societal concern for river ecosystems (compared with terrestrial ecosystems) - this is related to the "need for water" to sustain economic growth and to dispose of wastes;
- the inability to predict precisely the ecological impacts of river engineering works using current scientific knowledge;
- the longitudinal nature of rivers which make it necessary to conserve and management a long strip and to limit downstream impacts, and
- the necessity to manage the quantity and quality of runoff from the entire catchment area.

In Cape Town, there has been significant growth in the awareness of urban rivers and elements of environmentally-sensitive river engineering. This is evidenced by studies on the Kuils, Constantia Valley, Hout Bay, Lotus, Silvermine, Liesbeek and Lourens Rivers (Ninham Shand, 1979, 1990, 1993, 1994; Day, 1995; Oberholzer, 1996; Tharme, Ractliffe and Day, 1997). There was a module of lectures on environmentally-sensitive river engineering to final year civil engineering students at the University of Cape Town, and a Committee on Urban River Management was formed. A one day Symposium on Urban Rivers was hosted by the South African Institute of Civil Engineers (SAICE), the University of the Western Cape and the Wildlife and Environment Society of Southern Africa.

In addition, "friends" groups of the Liesbeek, Silvermine and Diep Rivers have been established under the auspices of the Wildlife and Environment Society of Southern African and a number of academic theses relating to various aspects of river engineering and river history (Villet, 1974; Saggeson, 1992; Bottaro, 1996) have been written. Issues related to rivers and urban water bodies have also received growing coverage in the press. Popular articles (Davies and Luger, 1993; Luger and Davies, 1993, 1994; Van Niekerk, 1993a,b,c) have been published and primary research (Davies and Behrens, 1995) undertaken.

With this increased interest in urban rivers and their management, the development of a theoretical framework for assessing and justifying environmentally-sensitive engineering has become increasingly important.

5.1.4 Economic aspects

> *"... economics and ecology must be completely integrated in decision-making and law making processes. Economy is not just about the production of wealth, and ecology is not just about the protection of nature; they are both equally relevant for improving the lot of mankind" (Brundtland, 1987, Our Common Future).*

In the past, it was possible to implement flood schemes using calculations of estimated economic benefit and risk. Professional standing, together with a lack of public interest in environmental, and even economic considerations, facilitated schemes which would not be tolerated today (Gardiner, 1992). The traditional approach to projects was that they should be justified economically, then designed in accordance with engineering criteria.

In designing channelisation projects, economic and environmental objectives are frequently in conflict (Keller, 1975). Economic benefits resulting from channel modification, such as flood control, are often achieved at the expense of environmental considerations (Keller, 1975). It is generally agreed that converting urban rivers from an attractive source of wildlife, regarded by many people as a local amenity, into concrete-lined drains is a poor investment (Gardiner, 1992). The concept of "best practical environmental option" is proposed as an alternative to the traditional cost-benefit analysis.

5.2 OBJECTIVES FOR ENVIRONMENTALLY-SENSITIVE RIVER ENGINEERING AND MANAGEMENT

Environmental objectives for river engineering projects should aim to minimise the impact on, and where possible enhance, the ecological integrity of the stream and associated riparian areas. They should also aim to maximise the cultural, archaeological, recreational, water quality and aesthetic potential. These objectives should be attainable and measurable and be selected early in the planning process. They should also consider public issues and concerns. Moreover, all projects should be technically feasible and economically justifiable. They should aim to be equitable (in terms of costs and benefits to various groups) and sustainable.

In terms of the ecological rehabilitation of urban rivers, there is no point trying to recreate the ecosystem of a century or more ago. However, the past may be used as a reference for the habitat elements that should form part of the ecosystem (De Jong and de Wit, 1994). Because rehabilitation will be a process of trial and error, river managers will need to experiment with these developments.

It has been shown that for environmentally-sensitive river engineering to be successful, it requires actions at the catchment, floodplain and channel levels. Objectives at each of these spatial levels are summarised as follows and are described in detail in Chapters Six and Seven.

5.2.1 Catchment management objectives

In order to achieve environmentally-sensitive floodplain and channel management, it is necessary to limit the increase in stormwater runoff as much as possible - preferably to pre-urbanisation levels. In addition, the quality of water discharged or seeping into receiving stream systems should not be detrimental to aquatic organisms. Potential measures to achieve these objectives are contained in Chapter Six.

5.2.3 Floodplain management objectives

Land use control should ensure that lower-order streams are not infilled or lost and that urban development does not occur within the floodplain of the main rivers and their tributaries. Flood lines should be based on the maximum future development scenario. The floodplain should be reserved or developed for amenity and conservation purposes. Measures to assist in the realisation of these objectives are contained in Chapter Six.

5.2.4 River channel management objectives

River channel management should aim to maximise the physical diversity of the channel in order to maximise the biodiversity and conservation value of the river. These objectives should, however take cognisance of the stormwater drainage function of urban rivers. Chapter Seven outlines the means to assist in the achievement of these objectives.

5.3 CASE STUDIES OF RIVER RESTORATION

5.3.1 Introduction

River restoration or rehabilitation is becoming more common in certain developed countries. The following section contains a summary of various studies in the United States of America, the United Kingdom and Europe. This section concludes with some local examples of environmentally-sensitive river engineering.

5.3.2 Overseas examples

Overseas, numerous rivers have been restored or rehabilitated. A short description of some of the better known examples follows.

- In 1976, the Florida legislature passed the Kissimmee Restoration Act which allowed for measures to alleviate the impacts of channelisation and restore the environmental values of the Kissimmee River system (Toth, 1989). Restoration involves backfilling 47km of channel, recreating fluctuating water levels in pools and the flooding of over 11 500ha of wetlands. The project was scheduled to be implemented over a 15-year period and to cost $422 million (Woody, 1993). Significant improvements in river invertebrate and fish communities have already been noted (Toth, 1989).

- In 1992, the National Research Council in the United States recommended the restoration of 400 000 miles of river over the next 20 years; this was partly to offset damage due to river engineering works (Williams, 1994). Part of this programme involves whole system rehabilitation of the extensively altered and regulated Columbia and Missouri Rivers (Sedell *et al.*, 1990).

- The relatively small River Roding scheme in England involved the construction of a two-stage channel cross-section; the retention of the natural river as the lower channel and the formation of an upper channel by excavating the floodplain (Sellin, 1990). The reduced sinuosity of the artificial upper channel optimized the discharge capacity without destroying the appearance of a natural river (Sellin, 1990).

- Other United Kingdom examples include the River Cole in Oxfordshire and the River Skerne in Darlington

- The Rhine Action Plan has improved the water quality of the Rhine River in Germany and the Netherlands considerably. Ecological recovery of the river, however, is hampered by the deficiency of food and suitable habitat such as shallow banks, snags and water plants (Barneveld *et al.*, 1994).

- Danish stream restoration began with the River Voer Å and its tributaries in 1980 (Cueto, 1981 cited in Iversen *et al.*, 1993). Other well-known examples include the Brede Å and the De Blauwe schemes. Between 1984 and 1990, some 118 projects were undertaken. These involved both large scale once-off restoration and repeated, ecologically appropriate maintenance practices.

5.3.3 Selected examples in the Cape Town Metropolitan Area

Within the Cape Town Metropolitan Area, no large scale environmentally-sensitive river engineering has been undertaken. However, various aspects or features that can be regarded as displaying elements of environmental sensitivity have been implemented on numerous river systems as the following examples illustrate.

- At a catchment level, the construction of detention ponds, such as those on the Diep River in Constantia and on the Kuils River upstream of Khayelitsha, although constructed for engineering purposes, are environmentally-sensitive.

- An urban catchment management research project on the Lotus River is attempting to incorporate a host of environmentally-sensitive features (A. Grobicki, pers comm.). The plans include managing water quality, and constructing off-channel wetlands.

- At the floodplain and river channel levels, on a section of the upper Liesbeek River downstream of Kirstenbosch, the banks have been regraded and revegetated with indigenous plants.

- Construction of the Liesbeek Walkway has served to increase the profile of the river and provides an amenity.

- Similarly, the development of the Constantia riverine open-space system has proved to be an educational resource and popular amenity.

- Few projects to increase the ecological value of the river channel have been undertaken. The series of cores and weirs incorporated into the Liesbeek River canal as part of the Albion Springs development is probably the best local example. Monitoring of the aquatic macroinvertebrate fauna has shown that these minor modifications can have significant benefits (K Snaddon, pers comm).

- Another local example is the creation of 'bays' in the Black River through the Mowbray golf course to provide some ecological benefits.

- Lastly, management of the rivers in the Constantia valley takes into consideration some environmental aspects.

5.4 SUMMARY

This chapter has provided background information on environmentally-sensitive river management. There has been a gradual shift from a structuralist or interventionist philosophy of stormwater management and river channel engineering to a more integrated, sustainable approach which evolved during the 1970's in the United States and Europe. Environmentally-sensitive river management promotes the aesthetic, recreational, amenity, education and conservation value of urban rivers and corridors. In the United States, public demand, and the consideration of a wide range of alternatives to river channel engineering by environmental impact studies, has promoted the environmentally-sensitive management of urban rivers. Public participation was also found to be an important component of successful management.

In South Africa, there has been an increase in general environmental awareness, particularly in urban rivers. In the Cape Town Metropolitan Area, this awareness is manifested in the increase in studies on urban rivers, the incorporation of environmental aspects into civil engineering courses, and the hosting of two symposia on urban rivers. There is, too, an increase in the number of dissertations and press and popular articles and a number of public involvement groups have been formed.

It is suggested that traditional cost-benefit analysis is inadequate as it does not cover the cost of and benefits to the natural and social environments, so that the alternative approach of 'best practical environmental alternative' is promoted. It is also stressed that urban rivers cannot be pristine and that it is essential for them to be managed. The case studies of environmentally-sensitive river management have highlighted the range and scale of projects that have been or are being undertaken in various countries. Some recent stormwater management and river channel works in the Cape Town Metropolitan Area have incorporated elements of environmentally- sensitive design.

Environmentally-sensitive river management involves utilising both structural and non-structural approaches. Non-structural approaches include catchment management measures to limit the increase in stormwater runoff and to minimise the deterioration in water quality. It also includes management of the floodplain and control over land use zoning. It is argued that to implement these non-structural measures is essential in order to minimise the impacts on, and potential to engineer, the river channel in a sensitive manner. These measures are described in further detail in Chapter Six.

Structural approaches to environmentally-sensitive river management relate to the engineering and management of the river channel itself. The objective of river channel management is to maximise the physical diversity of the channel. This will in turn maximise the biological diversity and thus the conservation value of the river. Specific river channel mitigation measures are described in Chapter Seven.

CHAPTER SIX: MITIGATION THROUGH NON-STRUCTURAL SOLUTIONS: CATCHMENT AND FLOODPLAIN MANAGEMENT

CONTENTS

CHAPTER SIX: MITIGATION THROUGH NON-STRUCTURAL SOLUTIONS: CATCHMENT AND FLOODPLAIN MANAGEMENT

6.1 BACKGROUND

> *"Since structural control measures often have little effect in alleviating flooding, instead of continuing a losing battle to control nature, efforts should be made to control man" (Costa, 1978 cited in Swales, 1982, p 121).*

The fundamental aim of catchment and floodplain management is to conserve, enhance and where appropriate, restore the total river environment through effective land and resource planning and management. Catchment management can be regarded as the taproot of sustainable development and should be fully integrated with traditional planning concerns, such as transportation and housing (Gardiner and Cole, 1992). Retrospective catchment management, while both possible and desirable, is frequently more costly and less effective.

In order to be effective and sustainable, environmental protection of rivers implies management of the catchment (Petts *et al.*, 1989). The first component of this chapter stresses that catchment management needs to contain the volume and quality of stormwater runoff supplied to receiving river systems, while the second component covers the floodplain. It discusses the necessity of limiting urban development in flood-prone areas and promotes the multiple use of river corridors for aesthetic, cultural, amenity and recreational values, and conservation of the aquatic and terrestrial environment.

6.2 CATCHMENT MANAGEMENT

6.2.1 Introduction

That flood defence can be best achieved through planning and development control, rather than through traditional engineering means, is difficult for engineers to accept due to the near universal use of structural measures (Gardiner and Cole, 1992). Not only does this method have environmental benefits, but it may also be more cost-effective in terms of public investment in both capital works and subsequent channel maintenance (Countryside Commission, 1987 cited in Gardiner and Cole, 1992). In particular, steps to limit the increase in stormwater runoff and control water quality need to be implemented in order to ensure the integrity of the riverine system.

6.2.2 Reducing the volume of stormwater runoff

Reducing the volume of post-development stormwater runoff by means of catchment controls (such as detention dams and land use controls) has been increasingly implemented during the since the 1970's in the United States (Brookes, 1988). There, many local government authorities require that a development that involves the clearing of vegetation and the grading and paving of land should be accompanied by measures to detain stormwater runoff. This ensures that the peak discharge rate into stream channels does not exceed that from a similar storm before construction (Dunne and Leopold, 1978).

In South Africa, guidelines to minimize the increase in stormwater runoff from new townships, by the establishment of major and minor stormwater systems and attenuation areas, have been promoted (Department of Community Development, 1983; Miles, 1984). Although there has been some support for stormwater attenuation, it has tended to be large schemes (such as Driftsands Detention Dam on the Kuils River, the ponds in the vicinity of Edith Stevens Nature Reserve on the Big Lotus River and the series of ponds on the Diep River in Constantia) rather than numerous on-site measures. While these schemes have considerable downstream benefits, there has been little support for the detention of stormwater at or near its source.

The goals of stormwater management are (modified after Miles, 1984):

- to protect life and property from the hazards of major storm runoff;
- to reduce the inconvenience of runoff from minor storms that disrupt normal urban activities, and
- to reduce the degradation of receiving waters by polluted runoff, to reduce soil erosion and protect the environment.

Catchment stormwater management requires a shift from the narrow concept of serving individual areas to considering the entire catchment. Miles (1984) motivates that urban stormwater systems should have two components, namely a minor system and a major system. The minor system resembles a conventional urban drainage system and is designed to handle frequent storms. The major system on the other hand will only operate on rare occasions (once every two years on average). At such times, due to the severity of the storm, many normal activities will be disrupted. Solutions to urban flooding using "natural" methods are in many cases less expensive than conventional systems (Miles, 1984). In a 2000-acre residential development in Texas, for example, it cost $4.2 million to develop the natural drainage system, whereas the equivalent conventional methods would have cost $18.7 million (Dunne and Leopold, 1978).

Urban runoff should be regarded as a resource, with potential for use, rather than an inconvenience (Maskell, 1992). Advantages of the storage of runoff water are that this practice (modified after Miles, 1984):

- reduces excessively high flood peaks, thus reducing downstream flooding, erosion and sedimentation of water courses and protects the ecosystem;
- enables smaller downstream pipe work to be used;
- improves the quality of stormwater runoff by settling and retaining natural channels;

- incorporates recreational and social facilities in the storage area, which reduces the construction and maintenance costs of both facilities;
- enables ground water to be recharged through increased retention of stormwater;
- helps maintain soil moisture and therefore "greening" of the area, and
- enhances the value of property in the vicinity of storage facilities such as "permanent" or "wet" retention ponds.

Measures to reduce the volume of stormwater runoff include internal flood attenuation and detention ponds. These measures are briefly described in the following sections.

a) Internal stormwater attenuation

Internal stormwater attenuation is fast becoming accepted in several countries, including the United Kingdom and the United States, and it is compulsory in Japan (Ninham Shand Incorporated, 1979). Internal flood attenuation measures aim to minimise the generation of stormwater runoff, and include on-site stormwater storage and measures to enhance infiltration. They also aim to avoid the generation and concentration of stormwater runoff, while detention ponds (described in the following section), aim to ameliorate the effects once stormwater has been concentrated.

Because most of the stormwater runoff generated in urban areas originates on impervious surfaces such as rooftops and parking lots, one method of reducing runoff is the storage of water in these areas. For example, many flat-roofed buildings in the United States are designed to hold up to 75mm of water on their roofs (Dunne and Leopold, 1978). In addition, extensive use is made of small detention ponds in parks, while car parks and malls can also be designed to hold a few centimetres of water.

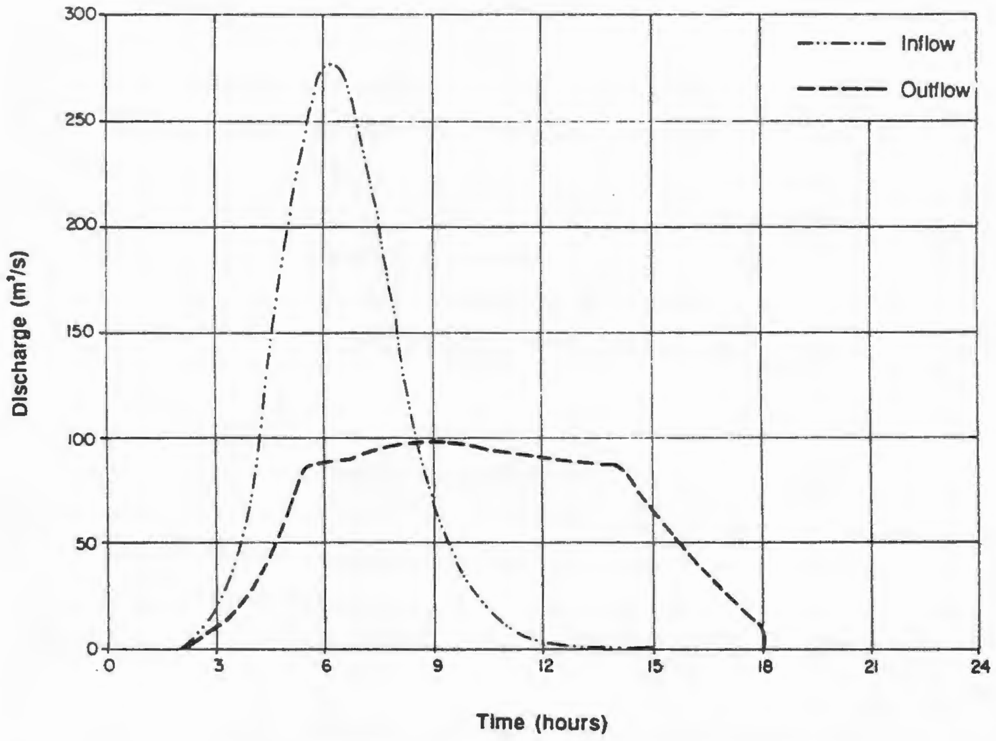
Measures to increase infiltration include stone-filled trenches to encourage rapid infiltration (often surrounded by filter fabrics to prevent clogging the voids), porous pavements and vegetated open channels (or swales).

Porous pavements to increase infiltration are used extensively in Europe and are beginning to gain acceptance in the United States (Dunne and Leopold, 1978). These pavements include permeable asphalt, various interlocking concrete blocks and brick paving. All footpath and low traffic areas in Tokyo, for example, have been changed to permeable asphalt (Fujita, 1994). Even when clogged, permeable asphalt allows a minimum of 10mm/hour of stormwater infiltration (Fujita, 1994). Porous asphalt and permeable concrete blocks allow rainwater to percolate and effectively reduce traffic-generated pollution (Marsalek *et al*, 1993). As fewer puddles form, the surface does not become slippery (Fujita, 1994).

b) <u>Detention basins</u>

Detention basins can be used in an attempt to replicate the natural infiltration, storage, and attenuation of flow that is lost through urbanisation (Sloat and Hwand, 1989). By providing storage, detention basins can reduce the peak flow after urbanisation to below the pre-urbanisation peak for a given storm.

Figure 6.1: Hydrograph for the Driftsands Detention Dam on the Kuils River, showing how detention storage reduces the flood peak (after Ninham Shand, 1990)



"Flood storage is the option everybody likes" (Lewis and Williams, 1984, p 76). Detention or retention dams have been used successfully in many areas of the world as well as in South Africa. Some areas served by detention or retention dams in the Cape Metropolitan Area include Kleinvlei, Scottsdene, Bellville South, Constantia and Brackenfell.

Barnard (1978) reports that a new development planned to control stormwater runoff by using on-site storage can be designed and implemented at costs of 10% to 15% less than conventionally planned urban developments with conventional storm sewer layouts. The state, regional or local authority may also share the costs of additional retention facilities where downstream areas are protected or where the facilities negate the need for downstream channel improvements. As channel improvements are expensive, detention dams are often financially favourable.

However, detention dams may not be appropriate for certain areas. For example, towards the lower end of a catchment, detention may act to increase the peak discharges as the detained flows may correspond with the upstream peak. Moreover, it must be properly designed and maintained. To be completely effective, detention options need to be incorporated into the design and planning of townships (Ninham Shand, 1979).

Detention has significant downstream ecological benefits. The reduction in peak flows reduces or may eliminate the need for downstream channel improvements. In addition, storage of flood water minimises damage to downstream riverine habitats which would otherwise be caused by increased discharge (Lewis and Williams, 1984; Gardiner, 1992). However, because the same volume of water is discharged over a longer period, higher flows are produced for an extended period, and this may result in increased channel erosion (Lewis and Williams, 1984).

It is well known that rivers and water features, including wet detention basins, can create a sense of identity, distinguishing one development from another (Bookout *et al.*, 1994; Clinger, 1991; Larson, 1992 cited in Emmerling-Dinovo, 1995). Studies have also shown that property values are increased by about 22% adjacent to detention basins designed to enhance wildlife (Emmerling-Dinovo, 1995). Consideration of these factors add to the economic viability of detention dams.

It can be concluded that both internal stormwater attenuation and detention dams have considerable stormwater and environmental benefits, and in many cases are economically favourable.

6.2.3 Improving the quality of stormwater runoff

Chapter Four discussed the sources of pollutants that affect aquatic ecosystems. Point sources of pollution should be limited and strict measures taken to ensure compliance with water quality objectives. As point source pollution is cheaper to control than diffuse sources, these sources should be effectively managed as a matter of urgency. However, the control of point source pollution is largely a technical and administrative issue and is not considered further in this dissertation.

Non-point sources of pollution are of particular concern, especially in urban areas. Winget (1985) states that it is generally less expensive to improve physical habitat than to improve water quality significantly, especially with regard to non-point sources. Although the focus of this dissertation is on improving the physical habitat for aquatic organisms, these benefits could be jeopardised by water pollution. It is therefore vital to implement measures that reduce the water quality impacts on receiving water systems. Possible measures to reduce non-point source pollution include street sweeping, controlled use of fertilizers and pesticides, use of lead-free petrol, effective waste management and the use of low input or indigenous plants. However, these measures will never be entirely effective and therefore measures to reduce the pollution of stormwater runoff should be implemented.

All the stormwater attenuation measures already described in this chapter to reduce the volume of stormwater runoff, also act to improve the quality of runoff entering the river system. However, a large amount of the total stormwater pollution load is carried by the small volume of runoff produced during the initial stages of the rainfall event - known as the "first flush". Consequently, managing stormwater quality differs from stormwater attenuation in that it focuses on runoff from minor or frequent rain events rather than major events. During high flow events, pollutants are more diluted and they tend to be flushed rapidly through the receiving river system. Measures to reduce pollution from stormwater runoff include grassed waterways, vegetative filter strips; infiltration by the use of wells, ponds, trenches, seepage areas, overland flow, check dams, rock-lined channels, sediment traps, retention and detention ponds; diversion of the first flush into the sewage system, and the use of wetland areas to filter and settle out pollutants.

The efficiency of many of these "Best Management Practices" in improving water quality have been tested in the United States as part of the Nationwide Urban Runoff Program (National Transportation Research Board, 1993). The studies demonstrated that wet detention basins exhibit some of the highest pollutant removal efficiencies, especially with regard to solids and associated pollutants (40% to 95%), and dissolved pollutants (particularly nutrients, 20% to 70%) (Environmental Protection Agency, 1983 cited in Marsalek *et al.*, 1993). Detention basin and other control measures, such as grass swales, were found to be more effective than street sweeping (National Transportation Research Board, 1993).

Riparian vegetation, or stream buffer strips, reduce the potential for water quality degradation (Herricks and Osborne, 1985). The ability of narrow strips of riparian land (that is 10m) to retain and reduce nutrient concentrations has been well documented (Petersen *et al.*, 1992). Dissolved and particulate nutrients are precipitated, flocculated, adsorbed abiotically or consumed or converted biologically by the plant and microbial communities of the strip.

6.3 FLOODPLAIN MANAGEMENT

6.3.1 Introduction

> Little (1983, p 146) defines (town) planning as "*a continuing process which aims at co-ordinating human activities according to a unifying policy through which human and natural resources are used effectively to promote health, safety, order and general welfare while retaining the integrity of the natural resources*".

If the ultimate procedure for conserving rivers is the proper planning and control of the catchment, then the management of riparian zones constitutes the first step (Peterson *et al.*, 1987 cited in Boon, 1992). A river corridor has value for recreation, amenity and nature conservation, amongst other things.

In engineering terms, a river corridor should perhaps be defined by the 1:100 year floodplain. In urban areas, the basic minimum river corridor should be the area of land required for the river to achieve a natural meandering course with associated riparian habitats (Gardiner and Cole, 1992). This minimum corridor should be designated even it is now completely developed, on the basis that future re-development would be compelled to recognize restoration of the river corridor as a planning principle (Gardiner and Cole, 1992). If riparian property is sold, sub-divided or redeveloped, the portion of land within the riverine corridor should be ceded to the local authority as public open space. Where the river has been canalised, the minimum corridor should be determined by a morphological assessment of the likely meandering pattern of the river, unconstrained by concrete (Gardiner and Cole, 1992). This regulation would remove the incentive of private landowners and local authorities to channelise or canalise rivers, as there would be no increase in the availability of developable land.

The objectives of river corridor management include:

- protecting floodplains by zoning or other designations;
- conserving aquatic and terrestrial flora and fauna;
- providing for flood storage;
- restoring and enhancing the natural elements of the river environment;
- promoting, where appropriate, public access and recreation, and
- preventing any development will detrimentally affect the character of the river, banks, or floodplain.

Land-use policies and management have not usually considered low-order channels and their associated riparian habitats, and thus low-order (especially non-perennial) streams have frequently suffered the most abuse - from channelisation, canalisation to being culverted or filled in.

"It is both impossible and undesirable to entirely tame the flood" (Purseglove, 1989, p 23). Flooding is a natural process, as well as a natural hazard (Keller and Hoffman, 1977). This is an important philosophical concession that governments, landowners, and the public must make, if they are to minimise negative impacts on river systems.

6.3.2 Limiting urban development on floodplains

> *"River management works are no substitute for effective land use controls for a catchment and for a flood plain" (Anderson, 1989, p 351).*

There will always be pressure for development in flood-prone areas. Urban development on the floodplain is incompatible with environmentally-sensitive river engineering and inevitably leads to demands for flood protection and associated degradation. This is exacerbated by the increase in stormwater runoff from upstream urbanisation.

The anticipation of flood protection is lowest when a natural hazard has not occurred for many years and there has been little damage over a small area. However, immediately after a flood, there is typically intense pressure for increased flood protection from those negatively affected.

In addition, if there is some reason to suggest that the flood frequency or magnitude has increased - such as development in the catchment - then the expectancy of protection rises rapidly, and those affected demand immediate action.

In the United States, in spite of billions of dollars having been invested in flood alleviation projects, particularly levees, flood losses in the United States have continued to rise (Brookes, 1988). Alleviation schemes reduce flood frequency, but the enormity of floods, when they do occur, and flood damage is actually increased due to increased development (Hollis, 1974; Brookes, 1988; NHRAIC, 1992 cited in Tobin, 1995).

The flood hazard is appreciated and even exaggerated immediately after a flood event (Kates, 1962; White and Haas, 1975; Smith and Tobin, 1979; Smith *et al.*, 1981 cited in du T de Villiers and Maharaj, 1994). However, shortly afterwards the risk is "forgotten", or information may be suppressed by unscrupulous land developers (Dunne and Leopold, 1978). Alternatively, the occupation of flood-prone areas occurs because of ignorance of the hazard. Poor people are often forced to occupy high-risk areas such as floodplains and therefore become the victims of environmental disasters.

The public acceptance of risk varies considerably between "natural" risks and risks caused by humans. For example, while protection against a flood of 1 in 50 years is frequently regarded to be reasonable, such odds would not be tolerated in terms of a large dam, let alone a nuclear power plant! It is not merely the scale of damages. That individuals build on the floodplain implies acceptance of the natural risk, yet the more the floodplain is developed, the greater is the potential for flood damage.

Flood insurance and relief aid, such as special voluntary funds or government grants, tend to encourage continued occupation of hazardous zones and therefore are not beneficial to society in the long term (Hollis, 1974). In their studies, Ward (1978), White (1974) and Sewell (1969 cited in de Villiers and Maharaj, 1994) concluded that flood relief beyond humanitarian grounds is therefore not desirable.

Floodplains are inherently unsuitable for urban development and in the most cases the benefits for a particular land use on the floodplain are smaller than the costs of flood alleviation works (Linsley and Franzini, 1964 cited in Hollis, 1974). A local example of this is the Sonstraal Villas development adjacent to the Kuils River in Durbanville, where expensive engineering works were required to relocate a tributary to around a new residential development. The costs of flood alleviation are also frequently borne by the local authorities (ratepayers) and not by the landowner or developer who benefits financially by this form of subsidisation of his/ her poorly planned development.

The owners of riverside property must accept and respect the inherent limitations for urban development on the floodplain. The management of human activities forms an important pre-condition for sensitive engineering of the river channel itself. Floodplain areas, where little or no urban development has taken place, should automatically be reserved for conservation, recreation and flood attenuation. Whilst this could pose difficulties in legal terms, with possible compensation claims, it is likely to be efficient, equitable and sustainable in the long term.

6.3.3 Promoting the multiple use of river corridors

In the past the design of stormwater channels was based solely on engineering criteria and took little or no account of social or ecological aspects. An interesting observation is that during the life of a stormwater channel (say 50 years, or 438 200 hours) the total time in which flood-flows occur is unlikely to exceed a few hundred hours (Beaumont, 1988). The proportion of time when the channel is operating under design (flood) conditions is therefore 0.091% (Beaumont, 1988). Thus whilst the need to cater for flood flows cannot be ignored, it should be noted that flood channels are not "in use" for some 99.9% of their life.

Technical designs, which may be cost-effective when evaluated purely on technical grounds (that is for the 0.1% time condition), could, however, have major adverse impacts on adjacent land, recreation and nature conservation values for the remaining 99.9% of the time. The design of future flood alleviation schemes is therefore likely to require greater consideration of the overall value and use of the river environment than has happened in the past (Beaumont, 1988).

Open space greatly enhances the quality of city life by moderating the extremes of the urban environment, for example by the reduction of air and noise pollution, the decrease in runoff, the aesthetic and psychological benefits, recreational and educational opportunities. Open space could, with correct planning and management, ensure the preservation of diverse communities of aquatic and terrestrial indigenous flora and fauna (Roberts, 1987).

The next four sub-sections describe potential values: aesthetic; cultural; amenity and recreational, and conservation of river systems.

a) <u>Aesthetic value</u>

> *"What river engineers sometimes forget, is the paradox that, while rivers are potentially death-dealing, they are also supremely life-enhancing" (Purseglove, 1989, p 148).*

Landscape assessment is sometimes dismissed as subjective and of little relevance. However, it is the perceived impact on the environment, and particularly any changes in visual quality by which the majority of schemes will be judged (Gardiner, 1992). It is important that the sense of place, the unique qualities and elements of a site, is retained and reinforced.

It has become increasingly clear that people are sufficiently concerned about the non-monetary values of the environment that they are willing to forgo some opportunities for gain or are even willing to pay directly for the maintenance of the amenities of the landscape (Dunne and Leopold, 1978). The aesthetic value of a landscape is subjective and may vary considerably from one individual to another. Natural streams are frequently regarded as valuable resources which can provide variety and spatial definition to the surrounding landscape (Risser and Harris, 1989). Visual diversity is provided by riparian vegetation of varying sizes, shades, and hues; a variety of stream bank slopes; a sinuous channel alignment; a variety of cross-sectional sizes and shapes; clear water and water movement (Shields, 1982a).

If the existing stream is visually degraded, the flood-control channel project can offer to improve existing conditions. High-visibility areas should be designed by landscape architects to harmonize with surrounding views and provide a pleasant visual experience.

b) Cultural value

Traditional river engineering, in addition to threatening the natural environment, may impact upon cultural and historical resources. Society has accepted a responsibility to protect and preserve buildings, structures, works, and natural areas and habitats so that they may be handed on to future generations as part of our natural heritage and cultural achievement (Gardiner, 1992).

Most towns and cities in South Africa are located near to rivers. Some water courses may not meet nature conservation criteria, but may be of significance from a cultural, religious or historical perspective (Boon, 1992). For example, the Josephine Mill in Newlands is intimately related to the Liesbeek River, and the presence of the mill increases the conservation importance of the river environment.

c) Amenity and recreational value

Riparian areas are favoured by recreational users because of the availability of water, aesthetics and microclimate (increased humidity, decreased wind, shade and decreased noise). The modification of channels for flood control offers many opportunities for recreational development and these features are easier to include in an urban project because of the higher levels of project usage (Shields, 1982a). A wide river corridor can be used for a golf course, a fishing lake, play parks, minibike courses and playing fields. Cycling trails, equestrian trails and walkways can be developed in a relatively narrow river corridor. They can provide many possibilities for recreation and can connect distant units of the metropolitan open space system (MOSS). Lighting, parking, water supply, picnic tables, fireplaces, sanitation facilities, and other amenities may enhance the value and usage of the corridor, or nodes along the corridor.

Natural areas increase the amenity value and visual quality of the townscape and take pressure off the countryside by providing opportunities for education and recreation (Kelcey, 1985). Urban corridors are vital parts of the urban fabric. As such, they are important elements in the urban open space system and likely to be used by local communities (Low, 1991).

The development of extensive hiking trails in countries like Germany, Switzerland and the United States of America has demonstrated the success of, and the rapidly growing public demand for, a variety of hiking, biking, jogging and equestrian trails along natural corridors such as rivers (Rabie, 1991). Objections to trails include the cost of land acquisition (although other options include agreement with landowners, right of way servitude, and conservancy); maintenance costs which could be reduced by the involvement of volunteers and school clubs; and vagrants and safety issues which could be improved by increased usage and policing.

Some well-known riverine trails include the Braamfonteinspruit trail in Johannesburg, the Moreletaspruit trail in Pretoria, the Lourens River in Somerset West, the Elsieskraal in Pinelands, the Eerste River trail in Stellenbosch, the Liesbeeck trail in Newlands and the Constantia riverine trails in the southern suburbs of Cape Town.

Private land ownership, lack of funding (private and state) and difficulties in co-ordinating and controlling maintenance and repair work often hinder the sensitive management of river environments in South Africa (Beaumont, 1989). It is highly desirable for sections of river to be maintained by community organizations such as local schools, interest groups or wildlife clubs. The idea of "adopting a river" as advocated by certain conservation groups has been taken up by quite a few South African action groups (McVeigh, 1981b). The Friends of the Liesbeeck and the Lourens River Conservation Society represent community groups who contribute to the management of their local rivers.

d) Conservation value

> *"Ecological considerations should be part and parcel of the planning process in our cities, not something distinct" (Roberts, 1987, p 1).*

The case for global ecosystem conservation has been forcefully made, and in many countries largely accepted - at least in principle (Boon, 1992). The reasons generally given for the importance of biological conservation are embodied in the aims of the World Conservation Strategy (International Union for Conservation of Nature and Natural Resources, 1980 cited in Boon, 1992), namely:

- to maintain essential ecological processes and life-support systems;
- to preserve genetic diversity, and
- to ensure sustainable utilization of species and ecosystems.

The paucity of published information concerning the ecology and conservation of riverine ecosystems in urban areas can be attributed to the historical lack of interest by researchers, funding agencies and government in the management of urban green space. Why most ecologists, naturalists and conservationists dislike the urban environment with its complex diversity of habitats and structures remains a mystery

(Kelcey, 1985). With increasing pressure on the rural and natural environment and growing awareness of, and interest in, wildlife, it is probable that urban areas will play a major role in conservation in the future (Kelcey, 1985).

Riverine corridors provide both terrestrial and aquatic habitat. The conservation value of the aquatic component is dealt with elsewhere in this dissertation. This section therefore focuses on the direct conservation value of the riverine corridor/ floodplain system and its role in linking isolated patches of terrestrial habitat.

Natural communities require less maintenance than formal park landscapes, and are therefore more cost effective (McDowell *et al.*, 1991). However, a survey of the major cities in South Africa by Roberts and Poynton (1985) showed that there is a tendency to favour exotic planting in highly manicured, parkland landscapes managed as traditional or European parks. Ecological fragmentation results and the conservation potential of open spaces is diminished. This emphasis on traditional parks is contrary to the aims of the Metropolitan Open Space System (MOSS), which are to establish and maintain the most meaningful open space system which will endeavour to link established, proposed and potential nature conservation areas, natural and modified open space areas and/ or parks.

Although Cape Town is located within the Cape Floral Kingdom, this does not appear to be taken into account in urban planning. Rebelo (1991, cited in McDowell, 1991) states that the only viable option for additional conservation of the some 74 lowland fynbos Red Data species which occur in the greater Cape Town Metropolitan Area comprises road and railway verges and powerline and riverine corridors. Furthermore, drainage, canalisation and pollution have made seasonal wetlands the scarcest natural feature on the Cape Flats (McDowell *et al.*, 1991).

The Cape Town Metropolitan Area guide plan (Department of Development Planning, 1988), identified large peripheral open spaces (mountains, vleis, rivers and coastal areas) as conservation resources. However, little cognisance was taken of the ecological potential of the smaller, more central, formally and informally managed areas. Roberts and Poynton (1985) suggest that the use of indigenous planting both in more formal and in more derelict open areas, would be less costly in meeting aesthetic and amenity requirements. It would improve educational and scientific potential, and facilitate the dispersal of indigenous species throughout the urban environment. These features should therefore be incorporated into the conservation areas and linked via river corridors.

The spatial continuity of open spaces is central to the effectiveness of conservation in urban areas (Roberts and Poynton, 1985). Urban river corridors offer unique opportunities for linking isolated patches of natural terrestrial habitat (Murphy, 1988). The "Greening the City" report (City Engineers Department, 1982) was the first of its kind to address the concept of a city-wide open-space network in South Africa. Although the use of corridors is advocated, their largely artificial character severely limits any biogeographical potential as conduits for genetic transfer between indigenous habitat remnants (Polyton and Roberts, 1985). Corridors also facilitate the migration of fauna, such as insects, birds and rodents, several of which are essential pollinators of indigenous Fynbos vegetation.

There is still considerable potential for at least partial restoration of road verges as well as the edges of water bodies to natural vegetation (McDowell *et al.*, 1991). In most cases, however, the areas are mowed, fertilized, lawned, irrigated and planted with ubiquitous exotic tree species. Today, rivers (and the verges of major roads and powerline servitudes) represent ribbons of semi-natural habitat which can serve as corridors linking habitats and species which have become isolated through intensification of land-use (Cross *et al.*, 1991).

6.4 SUMMARY

> "*In the past 'improving' rivers often meant increasing their flow capacity. In future it should refer to multi-purpose schemes designed to improve the capacity of each river valley to function as a visual amenity, a recreation area, a fishery, a nature reserve, a water supply, a storm-detention area, a drainage network and a movement corridor for boats, walkers, cyclists and equestrians*" (Tom Turner, Landscape Planning, 1987 cited in Gardiner, 1992).

This chapter has put forward the argument that mitigation through non-structural means, such as catchment and floodplain management, is not only essential to achieving environmentally-sensitive river channel management, but is also efficient, equitable and sustainable. While structural measures, such as river channel works, treat the symptoms of increased runoff from urban areas, non-structural measures treat the cause of the problems.

Environmentally-sensitive catchment management aims to reduce the volume of stormwater runoff, preferably to pre-development levels. This has a number of advantages, including:

- a reduction in downstream flooding;
- reducing the need for downstream channel upgrading;
- protection of the riverine ecosystem, and
- improving the quality of stormwater runoff.

Reducing the stormwater runoff can be achieved by internal stormwater attenuation measures which aim to reduce the generation and concentration of runoff. These include the storage of rainfall on flat-topped roofs or in car parks, the use of stone-filled trenches, porous pavements (asphalt, brick paving or concrete blocks) and grass-lined channels. Furthermore, detention dams can be constructed to reduce the peak flood flows. This is common practice and can provide considerable environmental and economic benefits.

Environmentally-sensitive catchment management also aims to minimise the deterioration in water quality supplied to receiving river systems. Although water pollution is expensive to mitigate, compared with maintaining or recreating physical habitat - hence the focus of this dissertation - it is important that water quality does not become the limiting factor determining the diversity and integrity of the aquatic ecosystem. Point source pollution, for example the discharge from industries or waste water treatment works, is cheaper to control than non-point sources of pollution. Non-point sources of water pollution arise throughout the catchment and are transported via runoff to the receiving river system. The first runoff from a rainfall event, the "first flush", especially after a long period without rain, contains high concentrations of pollution. The management of water pollution therefore concentrates on this "first flush".

Measures to improve the water quality include the education of people within the catchment regarding the use of fertilisers, pesticides and toxic substances; the use of wells, ponds, trenches, vegetated channels and wetlands; and the diversion of the "first flush" to waste water treatment works.

The concept of removing the minimum amount of stormwater required for the safety and hygiene of the urban area, at the slowest possible rate, would result in reduced peak discharge, increased infiltration, reduced pollution, and less degradation of receiving waters. The impact on aquatic organisms would therefore be reduced. Despite the successful implementation of such stormwater attenuation schemes in many overseas countries, and guidelines for their use in South Africa, conventional stormwater philosophy and practise is still entrenched amongst planners and stormwater engineers in the Cape Town Metropolitan Area today.

Environmentally-sensitive management of the floodplain requires limiting urban development. Flood insurance and disaster relief, beyond humanitarian grounds, encourage further development of flood-prone areas. Reserving inadequate corridor widths forecloses river channel management options and it is therefore essential for the authorities to acquire a corridor. This chapter has also argued that flood alleviation reduces the frequency of inundation and therefore flood damage. However, the magnitude of damage which occurs due to major floods is likely to be significant.

Stormwater channels are only fully utilised for 0,1% of the time. They should therefore be designed and managed as multi-purpose facilities. Rivers and their riparian corridors have the potential to fulfil a variety of functions, including stormwater removal, amenity, aesthetics and education. Corridors also frequently constitute areas of natural or semi-natural habitat within an urban area and therefore have considerable conservation potential. Furthermore, their linear nature can play an important role in linking isolated patches of terrestrial habitat.

If the mitigation measures suggested in this chapter are implemented, environmentally-sensitive river channel engineering and management should be feasible. The next chapter provides details of measures to enhance the ecological value of the aquatic environment.

CHAPTER SEVEN: OBJECTIVES OF ENVIRONMENTALLY-SENSITIVE RIVER CHANNEL ENGINEERING AND MANAGEMENT

CONTENTS

CHAPTER SEVEN: OBJECTIVES OF ENVIRONMENTALLY-SENSITIVE RIVER CHANNEL ENGINEERING AND MANAGEMENT

7.1 INTRODUCTION

The aim of environmentally-sensitive river channel engineering and management is to maintain or restore the ecological value of the river system. Urban rivers are resilient in the sense that, following the recreation of the physical environment, the biotic community should assume the structure and function of a community in a similar unperturbed stream (Margalef, 1969; Holling, 1973; Hill, 1975 cited in Winget, 1985). In addition, rivers have an inherent ability to cleanse themselves (Hynes, 1970) and therefore to improve the water quality. As they exhibit strong, natural recovery processes (Cairns *et al.* 1977 cited in Gore, 1985), even minor improvements in the abiotic environment may result in significant ecological benefits. Rehabilitation of river channels aims to increase the rate of recovery of the ecosystem by improving in-stream and riparian habitat (Gore, 1985).

Restoration requires the re-establishment of numerous biological, chemical and physical processes, dynamics of intricate food webs, and an array of river and floodplain habitat characteristics. These complex interrelationships preclude the establishment of specific restoration criteria for each component of the river ecosystem and require that restoration be based on an ecosystem perspective (Toth, 1989). The primary goal of restoration is "ecological integrity". This involves the "reestablishment of an ecosystem that is capable of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region" (Karr and Dudley, 1981 cited in Toth, 1989). Because structural and functional aspects of biological communities are shaped primarily by the environmental forces and characteristics to which they are exposed, criteria for accomplishing this goal focus on key environmental variables (Toth, 1989).

The previous chapters have concluded that non-structural measures are a necessity if environmentally-sensitive river channel works are to be successful. However, it is acknowledged that it is unlikely that the increase in stormwater and the decrease in water quality can be totally mitigated. Urban rivers therefore need be engineered and managed in order to minimise degradation.

Degraded urban rivers have the potential to be rehabilitated. A number of studies have explored ways of restoring or enhancing the ecological value of river channels (Keller, 1975, 1978; Nunnally and Keller, 1979; Nelson and Weaver, 1981; Lewis and Williams, 1984; Nunnally and Shields, 1985; Brookes, 1987a, 1988; Brookes and Gregory, 1988 cited in Brookes, 1990). This chapter discusses the objectives of sensitive river channel engineering. It then provides a comprehensive list of potential river channel mitigation measures. These mitigation measures are grouped into river maintenance practises, stream bank protection options, mitigation measures for channelised reaches and mitigation measures applicable to lined sections. The ecological benefits of these mitigation measures are described in terms of their effects on the key abiotic variables utilised in the assessment of impacts in Chapter Four. In addition, the socio-economic benefits are briefed discussed. Table 9.2 provides a summary of the potential mitigation measures, the situations where they may be applicable and their potential benefits. The case study presented in Chapter Eight illustrates how some of the mitigation measures could be applied to enhance the ecological and amenity potential of the Liesbeek River.

7.2 OBJECTIVES OF SENSITIVE RIVER CHANNEL ENGINEERING AND MANAGEMENT

The objectives of environmentally-sensitive river channel engineering and management are described in the following five sub-sections.

7.2.1 Retain rather than recreate habitats

As with any complex, established natural habitat, the retention of existing features is preferable to disturbance followed by reinstatement (Lewis and Williams, 1984). The first question to be posed therefore, is whether the river channel or banks could, or should, be left entirely untouched. If human interference is necessary or desirable, a variety of options which minimise negative impacts and enhance the positive effects can be utilised.

Refugia are critical components of natural river ecosystems and play an important role in maintaining biodiversity (Sedell *et al.*, 1990). Recovery of aquatic biota on a macro scale (kilometres) is dependent on the presence of unimpacted reaches of stream (Sedell *et al.*, 1990, so that modifying long sections of river channel is not desirable due to impaired colonisation by the aquatic biota.

7.2.2 Maximise physical diversity

The most fundamental objective of sensitive river channel engineering and management is that physical diversity must be preserved where it exists, or newly created where it is no longer found. Physical diversity will provide the necessary preconditions for a varied flora and fauna, and thereby promote the development of a biologically intact, healthy, stable aquatic community (Binder *et al.*, 1983; Lewis and Williams, 1984; Purseglove, 1989).

Restoration to pre-disturbance condition may not often be possible and therefore restoration aims to achieve naturalistic, rather than natural assemblages of organisms and their pre-disturbance environments (Cairns, 1991).

"The basis of habitat conservation is the assumption that species richness follows from habitat richness, subject to limits imposed by chemical water quality, and that biological diversity is the prime conservation objective" (Harper *et al.*, 1992, p 318). This assumption underlies the habitat survey approach used by the Nature Conservancy Council, namely that by safeguarding or increasing the range of habitats along a section of river, the richness of the invertebrate and vertebrate fauna can be maintained (Marshall and Westlake, 1978 cited in Wright *et al.*, 1992). The Danish stream restoration philosophy is simple: "if it is harmful to wildlife to destroy stream biotopes, re-establishing them should be expected to be beneficial" (Iversen *et al.*, 1993, p 89). Stream restoration efforts must be focused on those environmental factors that have the greatest influence on natural biological communities, and that can realistically be altered through management or physical alteration (Richards *et al.*, 1993).

7.2.3 Work with the natural river system

Environmentally-sensitive river channel designs aim to complement natural processes rather than controlling them absolutely (Keller, 1978). Since the biological recovery of rivers depends on their morphological recovery, natural river features such as pools and riffles must become established before complete recovery of the aquatic community can occur (Simpson *et al.*, 1982; Swales, 1982). These features must make use of flow dynamics, that is, work with nature, if they are to be self-maintaining.

7.2.4 Site specific designs

Environmental objectives are best attained when channel design is accomplished with attention to the details of the site (Shields, 1982a). There are no detailed design criteria for most environmental features, due to the limited base of experience and the complexity of environmental effects. Considerable creativity and professional judgement are therefore required (Genetti, 1989).

The biggest impediment to rehabilitation is the uncertainty of success (Petts *et al.*, 1989). This uncertainty reflects the lack of knowledge about the flow, water quality and physical habitat requirements of aquatic organisms throughout their life cycle.

7.3 ENVIRONMENTALLY-SENSITIVE ENGINEERING AND REHABILITATION MEASURES

> *"We may reduce the dredging of rivers, but if we stop it altogether, floods will return to overwhelm us. We are committed to managing rivers. It is the way we do so which counts" (Purseglove, 1989).*

This section contains a comprehensive list of potential features which could be incorporated into the design of new channels or utilised to improve the ecological and socio-economic value of degraded channels. These mitigation measures are grouped into river maintenance activities, stream bank protection options, and measures to mitigate the effects of channelisation and canalisation.

7.3.1 River maintenance activities

Significant improvements in the ecological integrity of urban rivers can be achieved by changed maintenance practices (Iversen *et al.*, 1993). There are also measures that can improve the ecological condition of river systems. These include reducing the modifying: maintenance activities, spoil disposal, working from only one bank, mowing of the river banks and floodplain, terrestrial and aquatic vegetation and the use of sediment traps.

a) Reducing the frequency of maintenance activities

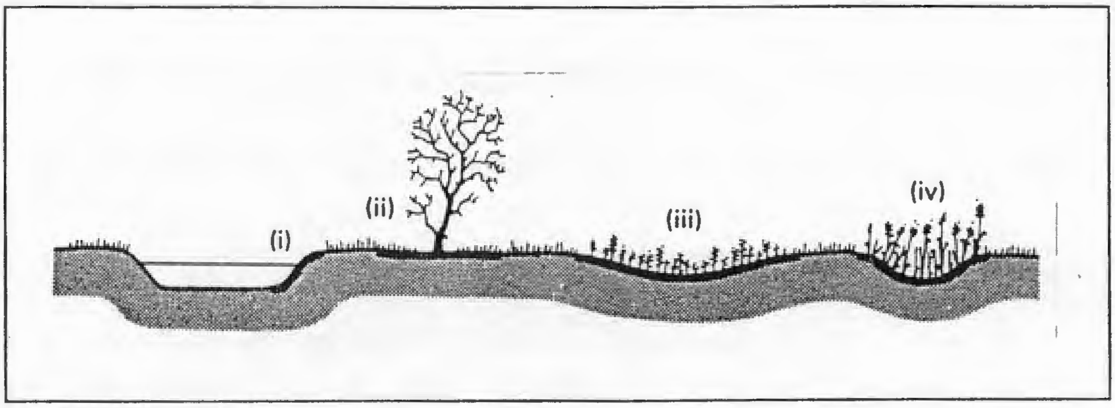
All river maintenance offsets stream recovery, while a lack of if permits gradual recovery (Brookes, 1992). A study of 42 sites of channelisation in North America revealed how maintenance destroys the habitats of various organisms by removing the bank side vegetation, encouraging bank instability and preventing the development of a stable substrate (Little, 1973 cited in Brookes, 1988; Brookes, 1989). Regular maintenance will encourage "weedy" species at the expense of more permanent shrub vegetation.

The types of equipment used for various construction and maintenance tasks should be selected to minimise disruption to the banks and beds. Manual labour is often preferable to machinery, and could provide additional employment opportunities.

b) Disposing of spoil material

Excavated material should not be placed on the river banks, from where it erodes back into the channel. Nutrients leach back and it is aesthetically unpleasing. Spoil should not be dumped on marginal or bank habitats, spread around trees, or used to fill in hollows and other irregularities in the floodplain (Holmes and Newbold, 1989).

Figure 7.1: Areas where spoil material should not be disposed (after Holmes and Newbold, 1989)

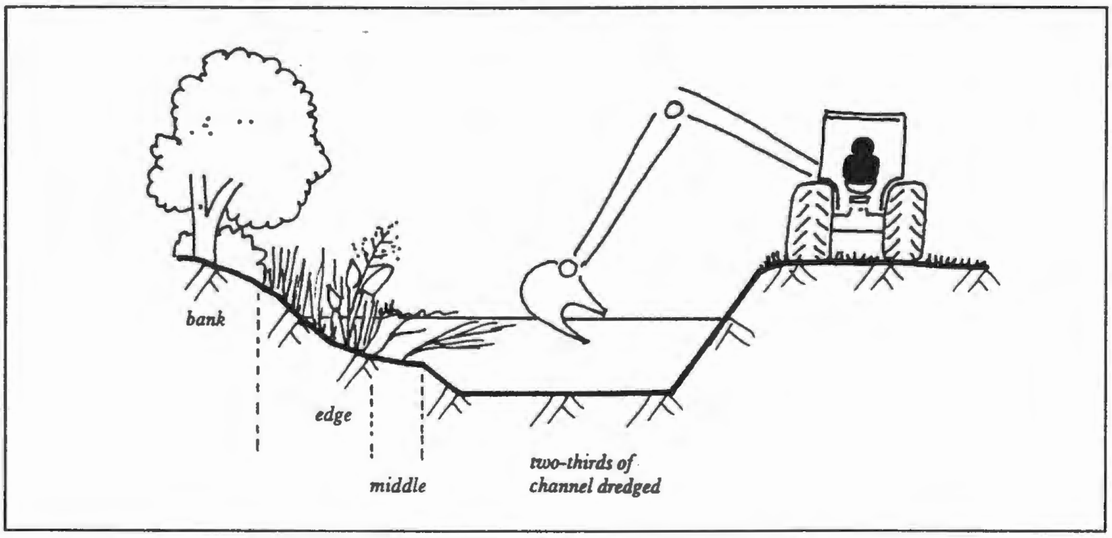


In urban areas, excavated material may be used to develop a park-like atmosphere around the channel by constructing noise and visual barriers to screen out views of unrelated activities (Shields, 1982a).

c) Modifying only one bank

Single bank modification involves following the existing channel alignment and enlarging the channel from one side only. The most valuable areas for wildlife or aesthetics should be maintained by alternating between sides (Shields, 1982b; Brookes, 1988). Hydraulic considerations should also determine the side to be modified. For example, it may be desirable to modify the insides of bends and preserve vegetation on the outsides for bank stability (Shields, 1982a; Shields, 1982b). The unmodified area therefore provides a reserve from which plants and animals can recolonize.

Figure 7.2: Modifying only one bank and working from one side of the channel (after Lewis and Williams, 1984)



If site conditions permit, single-bank modification is the preferred construction method for channel enlargement (Genetti, 1989; Newbold, Purseglove and Holmes, 1983) and is now commonly used in many countries (Shields, 1982a, b; Brookes, 1989).

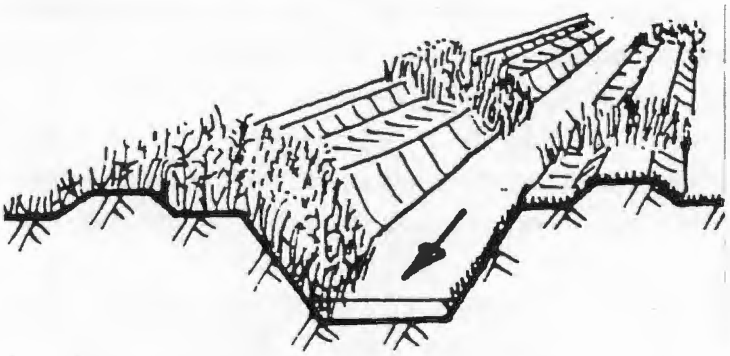
Single bank modification is cheaper than conventional channel work. However, if the contractor is forced to make frequent channel crossings or travel greater distances due to restricted access, the cost may increase (Shields, 1982a, b).

d) Reducing the frequency and intensity of bank and floodplain mowing

Reducing bank mowing to once a year, after plants have set seed, will maximize plant diversity, and thus animal diversity, as well as being financially beneficial (Holmes and Newbold, 1989). Long grass attracts small mammals and thus predatory birds, so that the greatest variety of vegetation and physical structure should be aimed for.

Leaving patches of vegetation uncut in narrow strips from the top to the bottom of the bank is the method favoured by the Welsh Water Authority. Discharge efficiency is only affected slightly since the uncut areas are effectively flattened by floods (Holmes and Newbold, 1989).

Figure 7.3: Leaving strips of vegetation uncut across the width of the channel (after Lewis and Williams, 1984)



In contrast, Wessex Water Authority cut only one bank in any one year (Holmes and Newbold, 1989). The following year the opposite bank is cut. This retains plant richness and prevents invasive plants from dominating the community. It also provides nesting cover for birds and animals as well as a wide range of foods. Moreover, no operator skill is required in identifying patches of rare or important species that should be left and the timing of the mowing is less critical (Holmes and Newbold, 1989).

e) <u>Maintaining or establishing terrestrial vegetation</u>

The roots of riverside trees increase the tensional strength of the bank and protect it against erosion (Zimmerman *et al.*, 1967 cited in Brookes, 1987a). Riparian vegetation and large woody debris stabilize stream channels and flood plains by binding sediments and reducing erosion (Swanson, 1980; Harmon *et al.*, 1986 cited in Risser and Harris, 1989). Bank sediment with a root volume of 16% to 18% and a five centimetre root mat provided 20 000 times more protection from erosion than comparable sediment with no vegetation (Smith, 1976 cited in Brookes and Hanbury, 1990).

The establishment of trees on river banks, in order to increase the extent of water shading, has been proposed as a more appropriate means of controlling the growth of aquatic vegetation than conventional cutting methods (Dawson, 1978; Krause, 1977 cited in Swales, 1982) and has been practised in the Netherlands and Germany for over a decade (Purseglove, 1989). Shading the channel by half was found to reduce the biomass of macrophytes by half (Dawson, 1978).

The ideal vegetation, from a maintenance standpoint, is a stand of large trees and shrubs a short distance from the top of the bank and no significant vegetation in the channel (Shields, 1982a). The trees should be large and close enough to the channel to shade out invader vegetation, yet sufficiently far back from the top of the bank to be stable and not easily undercut.

Trees in the floodplain increase the roughness factor during floods and allowance should therefore be made for the increased roughness. Where a two-stage channel is used, trees can be accommodated in the area designed to take floods, provided they are planted in straight lines or narrow hydrofoil shapes (Newbold, Purseglove, Holmes, 1983). A small group of trees and associated shrubs is better for wildlife than an isolated tree and also facilitate access for machinery.

Trees perform many valuable roles for nature conservation as well as enhancing river landscapes (Holmes and Newbold, 1989). Although important in their own right, and as food sources for a vast range of small and large animals, trees should be considered for the habitats they create for fish fry, birds, bats, mosses and lichens. Dead wood is an important habitat for invertebrates such as woodlice and numerous families of flies and beetles (Lewis and Williams, 1984). Felled trees and branches should therefore be left to decompose naturally in areas away from the river. Collectively, trees are also important in creating microclimates for plants and animals which require shade combined with a damp environment (Holmes and Newbold, 1989).

Allochthonously derived organic matter, often tree leaves, may be the major energy source in a stream (Cummins, 1974, 1979), and losses of bank-side vegetation may substantially reduce energy flow in the aquatic system.

Because organisms are regulated by their food source, detritus is also a major controller of micro distribution (Egglishaw, 1964 cited in Simpson *et al.*, 1982). However, the quantity of detritus is not necessarily as important as the quality (Rabeni and Minshall, 1977). If the proper association of micro-organisms is not present to initiate breakdown, detritus is of limited use to benthic detritivores (Cummins, 1974).

Riparian vegetation controls water quality in streams by contributing nutrients and by retaining nutrients in plant biomass and sediments (Swanson *et al.*, 1982 cited in Risser and Harris, 1989). Erman (1984 cited in Risser and Harris, 1989) indicated that nearly all aquatic insects spend some portion of their lives in the riparian zone for feeding, pupation, emergence, mating or egg laying.

Loss of riparian vegetation may cause algal blooms due to elevated water temperatures, increased light and increased nutrient availability (Risser and Harris, 1989) and these changes can cause shifts in the entire structure of aquatic communities. Spatial patterns of suspended solids, turbidity, erosion, sedimentation, and nutrient cycling can be affected by losses of riparian vegetation (Richards, 1982; Schlosser and Karr, 1980 cited in Risser and Harris, 1989; Dunne and Leopold, 1978).

Increased light levels may have a detrimental effect on animals in channelised reaches where shading is reduced (Tarplee *et al.*, 1971 cited in Simpson *et al.*, 1982). Meanwhile, the diversity of wildlife is affected by the diversity of food-producing plant species (Shields, 1982a).

f) Maintaining or establishing aquatic vegetation

Many of the adverse impacts of channel work may be avoided or reduced by preservation of the existing vegetation and prompt revegetation of disturbed areas with appropriate species (Shields, 1982a, b). Species for revegetation should be carefully selected to meet the following criteria: aesthetics, habitat value, hardiness, adaption to site conditions, growth rates, and self-propagation (Shields, 1982a). The vegetation should neither hinder nor negate the flood-control effort.

"The importance of plants within a river cannot be over-stressed" (Holmes and Newbold, 1989, p 294). They not only oxygenate and purify the water, but also offer shelter, food and egg-laying habitats for fish and invertebrates.

Plants modify the physical characteristics of the site: its flow velocity, silt accumulation, temperature regime, light availability and dissolved oxygen concentration (Lewis and Williams, 1984). From source to mouth, and in any natural cross section, the variation of water depth, flow velocity, substrate size, bank height, slope, aspect, period of inundation and soil type, forms an intricate pattern of zones which different types of plants may inhabit. In addition, as succession progresses, different types of plants can occupy the same patch.

Aquatic plants form valuable spawning substrate for many fish species (Braum, 1978 cited in Swales, 1982) and are an important habitat for invertebrates (Hynes, 1970). Emergent plants meanwhile, form a vital link between air and water for aquatic insects, such as caddisflies, damselfies and dragonflies, as the mature nymphs or larvae crawl up out of the water to emerge as adults clinging to stems and leaves (Lewis and Williams, 1984). Macrophytes provide a substrate and habitat for denitrifying bacteria (Howard-Williams, 1983).

At the microhabitat level, most taxa and individuals occur in stands of aquatic vegetation (Boulton and Lloyd, 1991). Current velocity apparently determines assemblage composition at the macrohabitat scale whereas the structural complexity of submerged vegetation operates at the microhabitat level (Boulton and Lloyd, 1991).

From an engineering viewpoint, the prolific regrowth of plants may be undesirable because vegetation increases the channel roughness with a consequent loss of flow capacity (Brookes, 1987b; Haslam, 1978; Marzolf, 1978 cited in Swales, 1982). Plant removal temporarily reduces the risk of flooding, but, subsequently, plant regrowth is both vigorous and synchronized (Dawson, 1978). If left undisturbed, natural fragmentation may be high after flowering, and late summer growth is often low (Dawson, 1978).

Well-anchored, submerged plants stabilize channel beds and flatten against the bed as velocity increases, thereby minimising hydraulic resistance. Aquatic plants are favoured by slow flows, shallow water, stable substrates, nutrient rich waters, and an absence of shade.

Few invertebrates eat living aquatic plants, although many utilise epiphytic algae (Lewis and Williams, 1984). Aquatic plants remain the foundation of life in streams - they are the primary source in all food chains, and their structure adds to the physical diversity of the environment . The more varied the structure and composition of the plant community, the greater the diversity of other wildlife it can support (Lewis and Williams, 1984). By providing substrate for attachment, instream vegetation is one of the most productive elements of a stream. Numerous studies, as summarized by Hynes (1970), have shown that density, diversity and biomass of macroinvertebrates are greater in vegetation than in bare substratum.

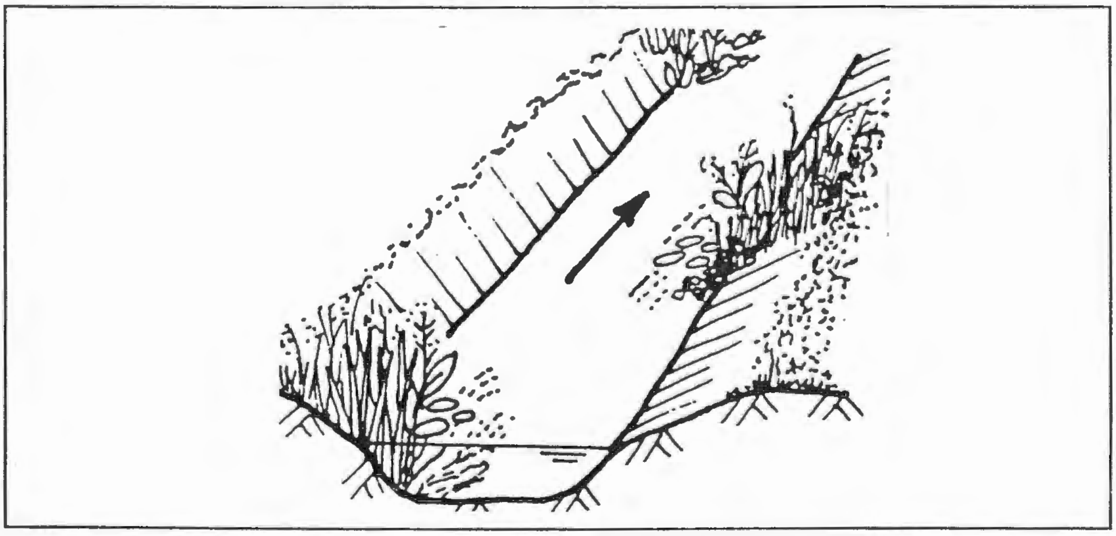
It is preferable to establish plants from the same river catchment as some populations, even in an adjacent catchment, may be genetically different (Newbold, *et al.*, 1983). Most marginal aquatic plants are extremely easy to transplant and will grow quickly from the smallest fragment (Newbold, *et al.*, 1983). Riverside plants can be reestablished, when dredging, by replacing scooped out clumps on narrow shelves on the inside of bends.

Besides forming the basic source of food in the aquatic food chain, macrophytes provide the most suitable breeding, nesting and sheltering places for varied macrofauna, including fish and waterfowl. They also support huge quantities of periphyton which is, to some extent, the life environment of most aquatic animals (Pandit, 1984).

g) Aquatic weed cutting/ dredging

Cutting weed in short sections of river (less then 100m) at different times ensures that uncut vegetation is always available (Holmes and Newbold, 1989). Leaving patches undisturbed as refuges during regular maintenance work aids rapid recovery of the community (Lewis and Williams, 1984).

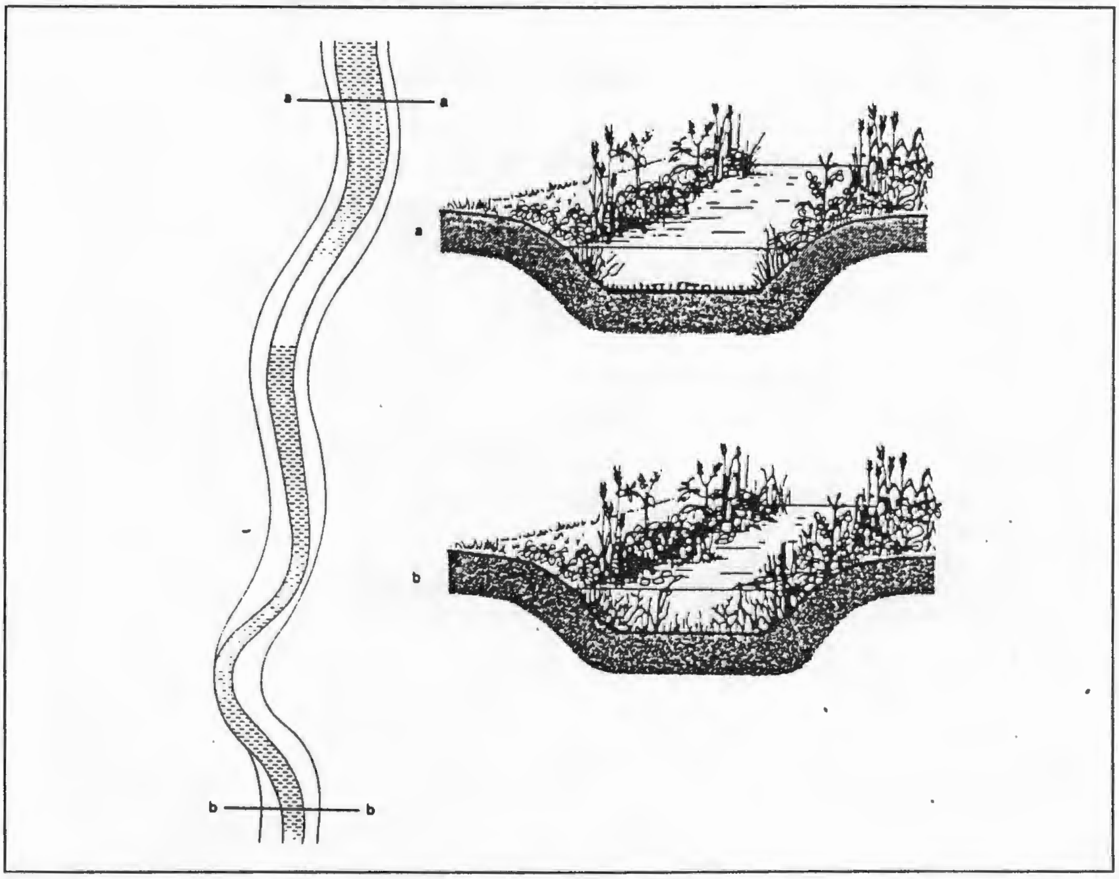
Figure 7.4: Retaining clumps of vegetation (after Lewis and Williams, 1984)



Cut weed should be removed to prevent eutrophication and oxygen depletion (Holmes and Newbold, 1989), and not dumped on the banks, as the nutrients which leach out will enrich the river, thus encouraging further weed growth (Lewis and Williams, 1984). High nutrient loads are the major cause of excessive weed growth in the first place and reducing the nutrient loading could reduce growth rates (Mitchell, 1974 cited in Brookes, 1988).

The hydraulic roughness is greatest when vegetation is centrally positioned and therefore retention of marginal vegetation may be more desirable from an hydraulic perspective (Brookes, 1988). The retention of marginal vegetation is also ecologically more desirable due to the increase in structural diversity. In straight channels, a meandering path should be cut through the weeds to recreate a thalweg (that is the deepest part of the river channel) (Holmes and Newbold, 1989).

Figure 7.5: Cutting a meandering swathe in a vegetation-choked channel (after Holmes and Newbold, 1989)

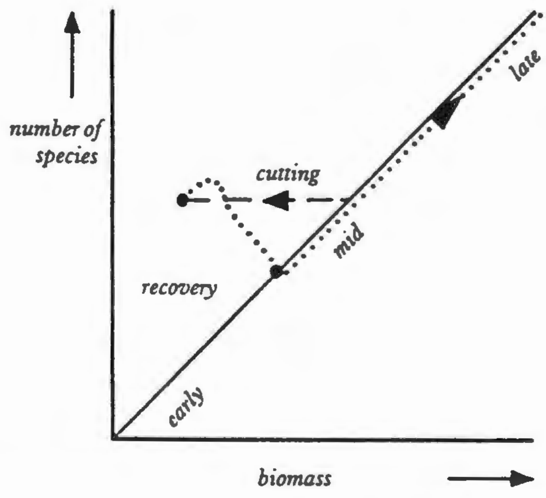


The weed-cutting regime should be adapted so that the cutting is done at a different time of year each year to avoid losing susceptible species (Purseglove, 1989). The timing is important, not only to the regrowth of plants from roots and rhizomes, but also because of its effects on wildlife breeding (Lewis and Williams, 1984). Frequent cutting results in certain species becoming dominant whilst those less able to withstand cutting become rarer, or are replaced completely (Holmes and Newbold, 1989).

Recovery is promoted if cutting or dredging is carried out working upstream so that plant fragments and invertebrates drift down to recolonise the already worked section (Lewis and Williams, 1984).

Alternatively, since the majority of bulky aquatic plants grow in shallow water of less than a metre deep, their growth may be inhibited by the excavation of a deeper channel - providing that the water-level is maintained (Lewis and Williams, 1984).

Figure 7.6: Graph showing how the relationship between biomass and species diversity is affected by weed cutting (after Lewis and Williams, 1984)



h) <u>Shading of aquatic weeds</u>

The reduction of light by planting trees is recommended as an ecological control of aquatic weeds (Lohmeyer and Krause, 1974; Dawson, 1978; Hermens, 1978; Leentvaar, 1978; Mitchell, 1974; Seymour, 1978 cited in Brookes, 1988), and has been practised for several decades throughout Europe. Research suggests that a 70% reduction in light will inhibit nearly all growth; while a 50% reduction will exclude all shade-intolerant plants and reduce the vigour of other plants (Lewis and Williams, 1984).

The tree line should be incomplete to allow for bars of aquatic vegetation. Dawson and Kern-Hansen (1979 cited in Brookes, 1989) recommend shading a channel by half, thereby halving the maximum biomass of aquatic plants. The orientation of the watercourse will affect where (which bank, or both) to plant. Alternation of sides will improve aesthetics, and clumps of trees are desirable for both aesthetics and wildlife.

i) <u>Sediment traps</u>

Urbanisation, construction and channel excavation elevate silt loads above naturally occurring levels. This leads to aggradation or raising of the level bed of channels

(Genetti, 1989). Trapping sediment reduces downstream deposition and associated maintenance costs. It also usually has positive effects on downstream aesthetics, recreation, water quality and aquatic habitat (Genetti, 1989).

The design of sediment traps is dependent on local conditions. They should be located at a point where easy access by a machine is possible to remove the sediment. Iversen *et al.* (1993) recommend that silt traps should be 50m to 100m long, and one metre deeper and two metres wider than the rest of the river channel. However, the courser fraction of the sediment load can be captured in shorter traps (approximately 10m in length).

Temporary silt traps are recommended to reduce the excessive increase in sediment loads resulting from channel work. Sedimentation can be minimized by limiting disruption to the bed and banks, reducing the excavation and the length of works, and avoiding such maintenance during periods of high flow.

7.3.2 Stream bank protection

a) Indirect methods or deflecting flow

Indirect methods of bank protection involve deflecting erosive flows from the bank by means of dykes, jetties or gabions, projecting perpendicular or slightly downstream from the stream bank. The placement of non-continuous structures projecting into the stream minimizes disturbance to bank vegetation (Henderson, 1986), creates protected slack water habitat on the downstream sides of the structure and encourages deposition of stable substrate (Genetti, 1989).

Indirect stream bank protection is generally not practised in South Africa, although it is inexpensive and environmentally-sensitive. There is enormous potential for this type of treatment in the middle and lower reaches of larger rivers (Henderson and Shields, 1984 cited in Henderson, 1986). The use of steel jetty fields (jacks), as a means of bank protection, has proved to be highly successful in the United States (Alexander, 1976). The use of perpendicular gabions has also proved successful in the middle reaches of the Kuils River near Cape Town. However, extremely variable water levels may preclude this option for certain urban rivers.

b) Bioengineering or the use of vegetation

> "*In the rush to capitalise on the products of the last 50 years' technology in machinery and materials, the water industry has abandoned its roots*" (Lewis and Williams, 1984, p 9).

Traditional methods of river management frequently used the attributes of local plants to stabilise banks and deflect flows. In several countries there has been extensive research into the use of living vegetation as a means of bank protection (Miers, 1977 and 1979 cited in Brookes, 1989). In West Germany and Austria, the application of such "biotechnical engineering" methods has been apparent for the last 40 years (Bittmann, 1957; Olschowy, 1957; Hautum, 1957; Miers, 1977, 1979; Pfeffer, 1978; Binder *et al.*, 1983; Wentz, 1983; Januszewski and Range, 1983 cited in Brookes, 1988). In South Africa meanwhile, the use of plants is generally not utilised.

The strength, resilience and large surface area of plants allow them to absorb more erosive energy then artificial materials such as concrete (Holmes and Newbold, 1989). The use of vegetation can reduce the cost of construction, but maintenance and repair should be considered (Henderson, 1986). Additional benefits of bioengineering include the provision of food and cover for animals both above and below the water (Holmes and Newbold, 1989). Furthermore, when the material is washed out, eroded or deteriorates in the short or long term, it will not cause degradation of the environment (Lewis and Williams, 1984). A further advantage is that bioengineering methods are labour-intensive.

Herbaceous or woody vegetation may be used to protect channel side slopes (depending on the frequency of inundation, velocity, and geotechnical constraints) where velocities do not exceed 1,8 to 2,4 metres per second (Genetti, 1989). During floods, high stream velocities force vegetation into mats that effectively protect the bank (Beschta and Platts, 1986). Smith (1976) found that a bank with a 50mm thick root mat of 16% to 18% root volume afforded 20 000 times more protection from erosion than a similar bank without vegetation.

Bonham (1980 cited in Lewis and Williams, 1984) suggested that reed planting for bank protection has several advantages such as:

- absorbing erosive energy, rather than reflecting it;
- preventing scour of the substrate;
- promoting sediment accumulation;
- regenerating and maintaining their own stability, and
- increasing productivity of the reach both through its own leaf production and by providing a habitat for other wildlife.

In parts of Southern Africa, *Phragmites australis* is planted to form dense reedbeds in eroded watercourses and erosion dongas (Greyvenstein and De Villiers, 1975). Most reeds and softwood trees (willows, poplars and alders) are deeply and strongly rooted and resist erosion (Brookes, 1988). Although vegetation forms a valuable means of protecting alluvial river banks, however, uncontrolled plant growth can result in increased flooding (Brookes, 1988).

Grassed channels have the benefits of low velocity, sociological and aesthetic benefits and low construction cost (Miles, 1984). Sod-forming grasses should adequately protect the banks of low-gradient streams or ephemeral channels (Beschta and Platts, 1986). To ensure that the flow velocity remains low, the channel should be shallow and have sides which slope at not more than 1 in 4 (Miles, 1984).

The application of biotechnical engineering techniques may be restricted by the need for large amounts of land (Miers, 1977 cited in Brookes, 1988). Furthermore, even vigorous stands of trees cannot prevent bank erosion and collapse following deep channel incision (Shields *et al.*, 1995).

c) Combinations of vegetation and man-made materials

The use of vegetation for bank protection is most effective when combined with structural components (Henderson, 1986). These composite designs have many of the same environmental benefits as vegetative designs (Genetti, 1989).

There are a number of interlocking concrete block systems available in South Africa, including "Terraforce", "Terrafix", "Loffelstein", "Waterloffel" and "Armorflex". The most objectionable aspect, from the wildlife and aesthetic viewpoints, is that cellular blocks tend to be used to stabilise and protect uniform, evenly graded slopes (Lewis and Williams, 1984). However, these interlocking systems are all flexible and can be utilised to stabilise gentle horizontal and vertical curves. Where the interlocking systems are utilised for bank stabilisation, they usually require a gabion or reno matrass foundation and/or concrete grouting of the lowest layer.

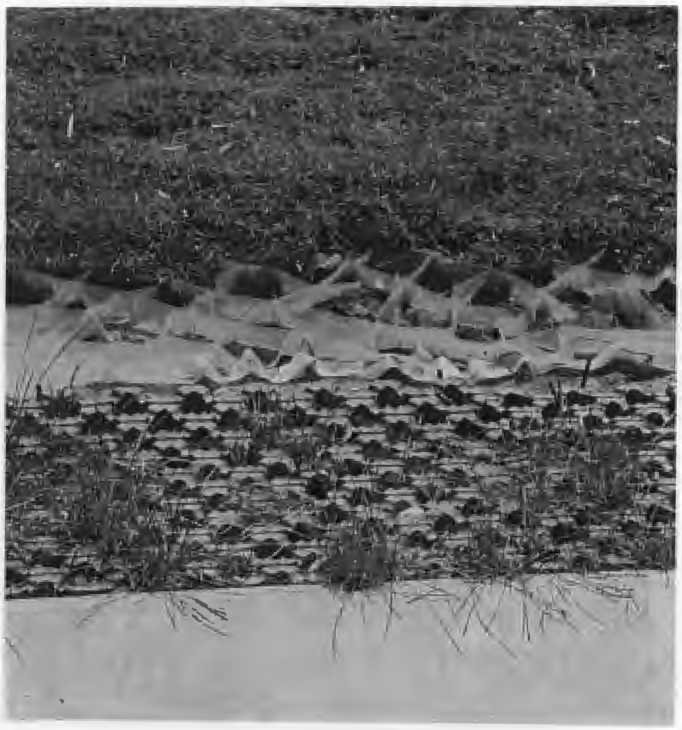
Figure 7.7: "Armorflex" interlocking blocks being used to stabilise a the bed and banks of a channel

In order to achieve a good plant cover, it is important that the depth of soil, both within and below the blocks, is adequate. The closed cell design of the "Waterloffel" for example, restricts the plant roots to a shallow (less than 250mm) pot. In addition, the lack of drainage holes prevents the drainage of water. Furthermore, in order to prevent fine material from being washed out, the interlocking block systems are frequently laid on a filter layer which may be a geotextile or graded layers of granular material. Both alternative filter layers however may restrict root penetration.

Figure 7.8: There are numeous types of cellular concrete revetments available: the "Waterloffel" shown here has limited soil space and no drainage holes

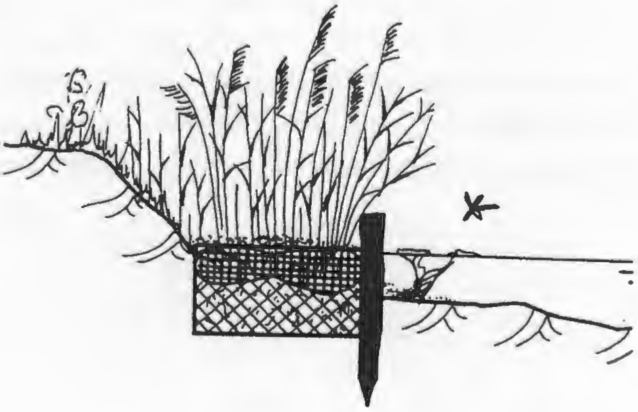
As an alternative to the preformed cellular blocks, "Grasscrete", "Dymex", "Gobimat" and "Hyson cells" are formed by pouring concrete in situ into plastic formers. The result is a high percentage area of concrete in relation to space. In addition, the smoothness of the concrete reduces friction at the surface, which may increase scour of soil from the spaces, thus inhibiting plant growth (Lewis and Williams, 1984). These systems offer relatively few environmental benefits, but are preferable to solid concrete. Furthermore, many of these plastic formers can be filled with topsoil and then planted with vegetation.

Figure 7.9: Preformed "Hyson" cells can be filled with concrete, or with topsoil prior to seeding the banks with grass



Another technique used widely in southern Germany is to take clumps of reed rhizomes and use them as the top layer in otherwise stone-filled gabion baskets (Burkle, 1978 cited in Lewis and Williams, 1984).

Figure 7.10: Reed planting in the upper parts of a gabion (after Lewis and Williams, 1984)



d) Combination of vegetation with fabric and mesh products (temporary or permanent)

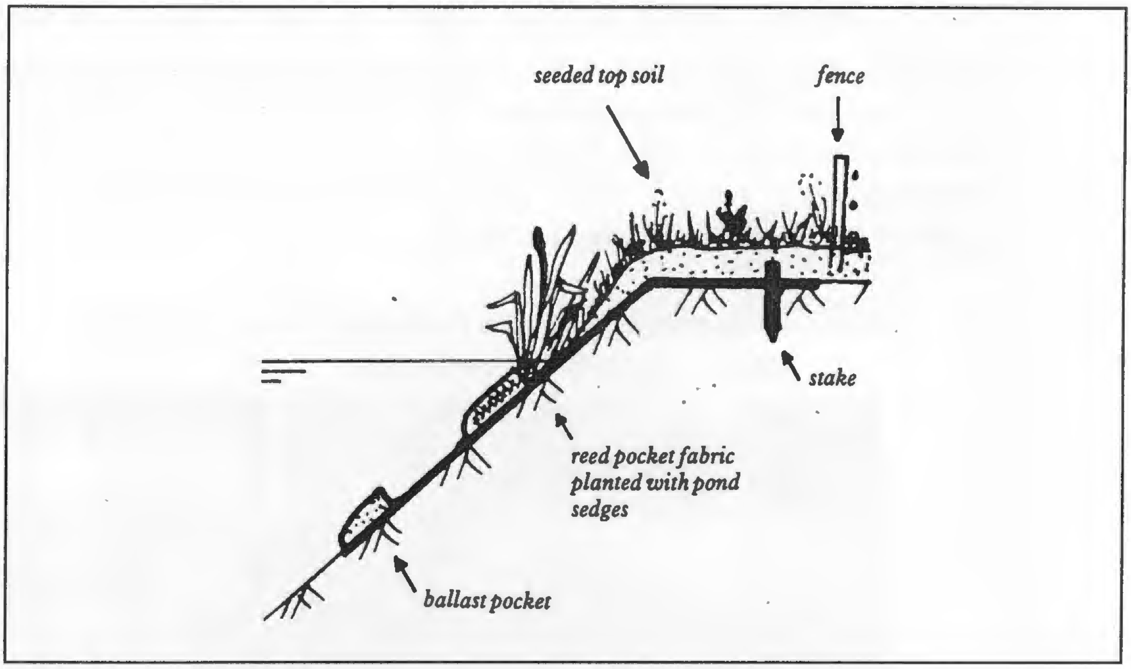
Fabric and mesh products are increasingly being used for bank protection (Lewis and Williams, 1984). Biodegradable fibre rolls and carpets of coconut fibres have been used throughout Europe, North America and Asia to protect plants until they are established (Lewis and Williams, 1984; Russell, 1992). In the interests of nature conservation, biodegradable geofabrics are preferable as decaying products, such as nylon, may pose a threat to waterbirds if it gets washed out.

Figure 7.11: Biodegradable geotextile mesh assists the establishment of vegettion and allows the plants to grow through

Utilising a fine or tight weave reduces colonisation of bank side plants. Use of a wide mesh, combined with deliberate planting of aquatic plants in the pockets and spreading of the original topsoil, is on the other hand, likely to promote the rapid establishment of a natural diverse and abundant plant community (Lewis and Williams, 1984). The material should (after Lewis and Williams, 1984, p 184):

- permit rhizomes to grow through it;
- not inhibit the growth of grasses and other herbaceous vegetation;
- either be stable, to function effectively as long-term bank protection, or be biodegradable, functioning as short-term bank protection until dense vegetative cover has developed (which is preferable), and
- have non-toxic, physically unobtrusive and unobstructive breakdown products which should not pose a physical hazard to wildlife.

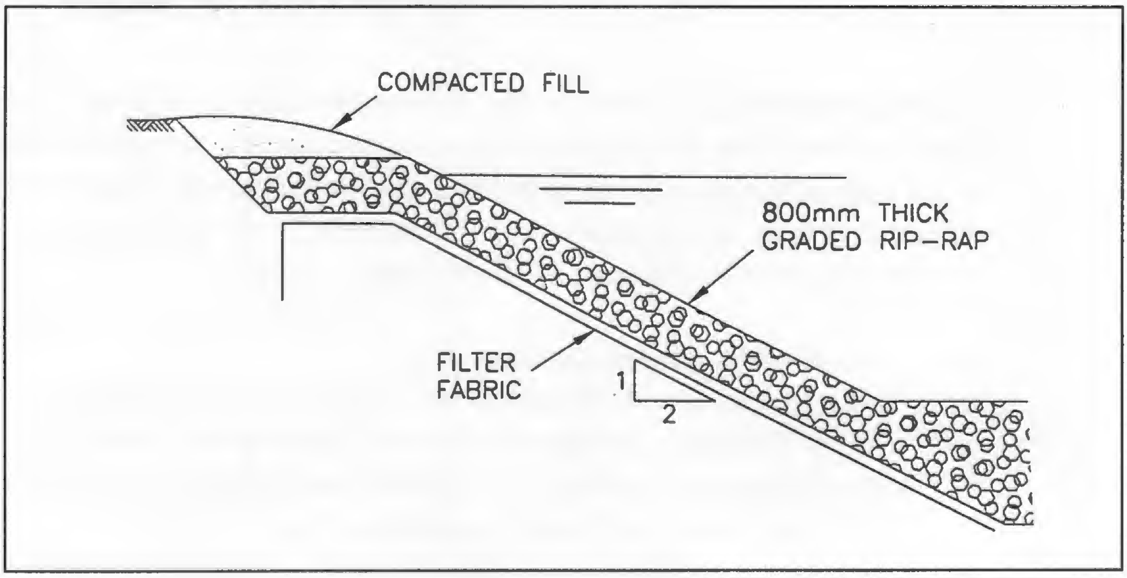
Figure 7.12: Geotextiles which planting pockets are suitable for establishing vegetation on steep slopes (after Lewis and Williams, 1984)



e) Riprap or natural stone

Direct protection of the channel bank by means of riprap or natural rock can, providing a range of stone sizes are used, increase substratum diversity. In contrast, concrete mats or interconnecting blocks, although controlling erosion, provide little habitat diversity (Petts *et al.*, 1989).

Figure 7.13: Riprap or graded stone



Experience, particularly in North America, has shown the advantages of riprap, as opposed to more conventional stabilization methods (Keown *et al.*, 1977; Fernholz, 1978; Nunnally and Keller, 1979; Keown, 1981 cited in Brookes, 1988). These advantages include increased primary productivity and abundance of invertebrates (Hansen, 1971a,b cited in Brookes, 1988).

Natural stone has an advantage over concrete in that it has many crevices, spaces and rough surfaces - places where invertebrates can shelter, soil can develop and plants grow. Where substrates are sand, silt or gravel, the use of stone provides new habitats for wildlife, and species diversity will probably increase (Lewis and Williams, 1984). Natural stone is also aesthetically pleasing. The main disadvantages are high transport and handling costs.

f) Gabion baskets

Gabions are wire mesh baskets filled with rocks. They provide flexible structures for bank protection, and allow smaller sizes of stone to be used where otherwise they might be unstable. Gabions can be used for bank and bed protection, and to construct weirs and groynes. Newly constructed gabions are unattractive and, if plant growth is prevented by scouring, they remain so. The habitat offered to wildlife improves as silt collects in the spaces between the stones and plants grow over the wire mesh (Lewis and Williams, 1984). Underwater, algae and invertebrates may colonise the gabions, sheltered from the force of the current.

Figure 7.14: Once damaged, gabions lose their effectiveness and can become a hazard to people and animals

A disadvantage of gabions is that sooner or later the wire cage will corrode or fail through metal fatigue, and the cage will break open. This is a major problem in the naturally corrosive waters of many of the streams in the Cape Metropolitan Area (Rust, pers comm.). In addition, in high velocity boulder streams, the gabion wire mesh is damaged by rolling rocks during spates. Damage such as this occurs for example in the Liesbeek River above Paradise Motors (R. Arnold, pers comm.). The gabion then loses its effectiveness against scour and a mass of broken, tangled, rusty wire is left in the river.

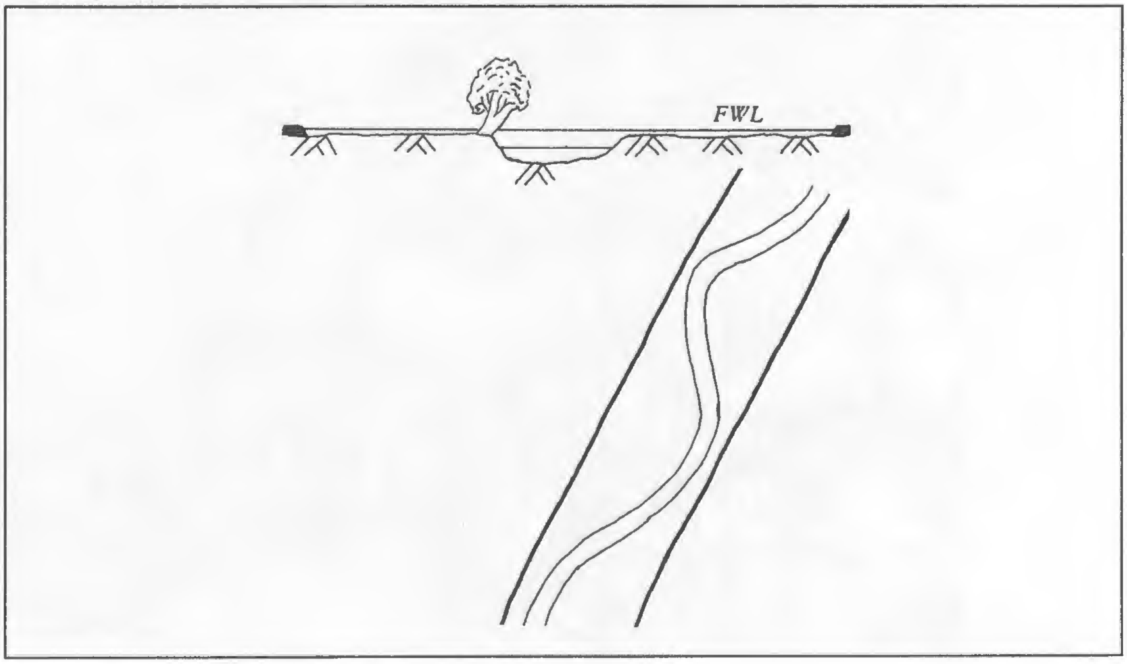
7.3.3 Mitigation measures for channelised reaches

The following 14 sub-sections describe possible mitigation measures for channelised reaches. The mitigation measures include the construction of levees away from the river channel; flood bypass, and flood relief or two-stage channels, new pools adjacent to the river; off-channel wetlands; preservation of severed meanders; adopting a meandering alignment; modifying the cross section; creating pools and riffles; grade control structures; regrading of the banks; over-widening the channel; recreation of the substrate, and installing instream habitat devices.

a) <u>Levees created away from the river channel</u>

Levees and flood walls are earth embankments that provide flood protection from infrequent high water. They artificially increase the capacity of the channel so that high flows which would normally have spread onto the adjacent floodplain are confined. In urban areas, where land costs are high, concrete walls may be used instead of levees since they require less space (Genetti, 1989). Levees, in general, may create drainage problems in the area behind the embankment, and could result in significant flooding and danger to life if the levee is overtopped or fails.

Figure 7.15: Levees set back from the river channel



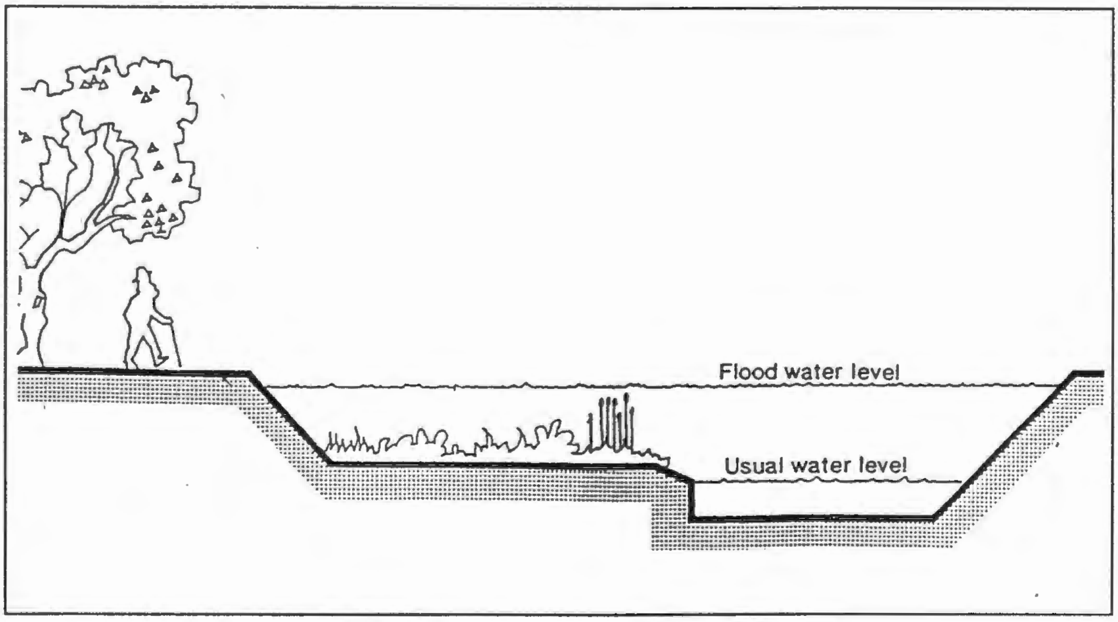
Levees that hug the top of the river bank have further disadvantages. They are more expensive to construct and maintain, as the meanders increase their length; they are prone to be undermined; and they lead to considerable loss of floodplain storage, so that flood attenuation is reduced (Holmes and Newbold, 1989). Moreover, they result in deep, narrow channels with high flow velocities which may be damaging to the flora and fauna (Lewis and Williams, 1984).

There are a number of environmental benefits in setting back levees by several channel widths. It allows space for the river to change course (Welcomme, 1989) and allows the retention of riverside trees and vegetation (Purseglove, 1989). It also allows the natural channel and riparian vegetation to remain unaltered (Genetti, 1989). Levees may have either negative aesthetic impacts (such as a uniform profile, straight lines, or blocking views of the stream) or positive effects, in that they add topographic relief to flat areas or create scenic views of the river. Levees can also be used for walking, equestrian or cycling trails. Spoil for constructing levees can be obtained from dredging. Ideally, the material should be imported or obtained from the construction of wetlands or ponds.

b) Two-stage channels

A natural channel contains flows with a recurrence interval of one to two years, whereas a flood-control channel may be required to carry the 25- or even 100-year flood (Keller, 1975). In the case of a two-stage channel, the normal range of flows are confined to the original channel, whilst the capacity of the immediate floodplain is increased to contain flood-flows. In addition to maintaining the channel habitats, the banks are stabilized through dissipation of erosive energy over a wider area, and there is opportunity for habitat creation in the secondary channel (Holmes and Newbold, 1989).

Figure 7.16: A two-stage channel - the floodplain on one or both sides may be lowered to form the flood channel



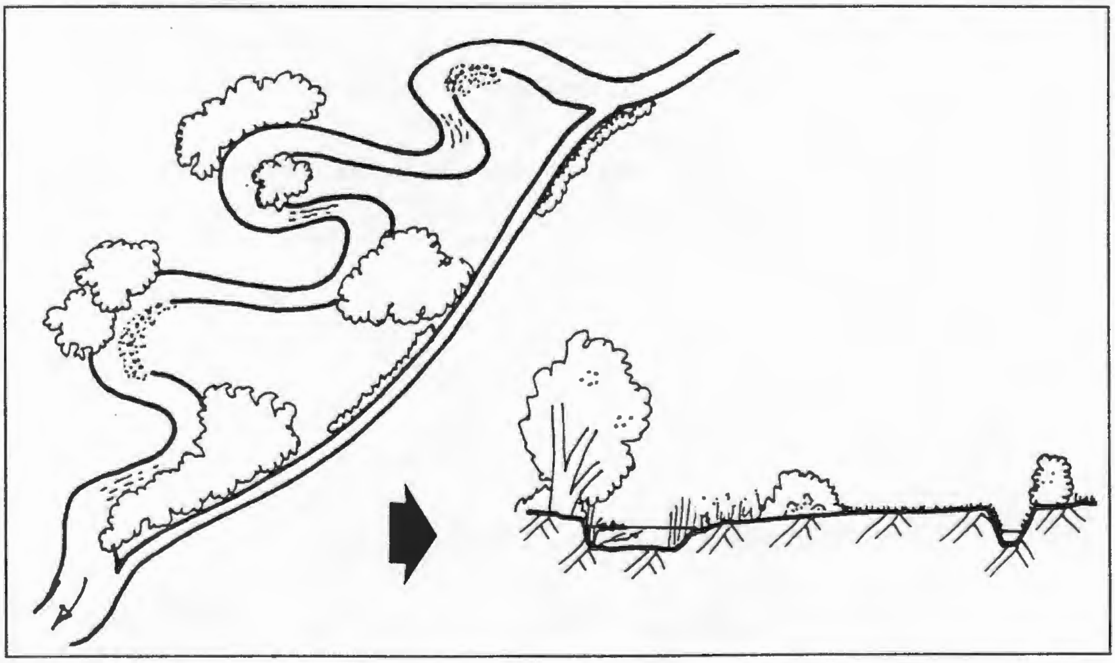
It is even more desirable from an ecological perspective to create a second-stage channel on one bank only. The side of the two-stage channel could even be alternated from bank to bank (Paynting, 1982; Weeks, 1983 cited in Brookes, 1989).

c) Flood bypass or flood-relief channel

The construction of flood bypass or flood-relief channel has been recommended by several investigators as environmentally-sensitive (Hey, 1986; Brookes, 1988; Keller and Brookes, 1984 cited in Shields and Hoover, 1991). An alternative to enlarging the existing channel is to create a flood bypass channel, which involves diverting flood flows along an entirely new route. The existing channel is left untouched and conveys the low and normal flows. As a result, the ecological value of the existing channel is maintained or even enhanced due to the reduction in high flows.

The bypass channel may be comprised of a pipe, culvert, grass-lined or concrete-lined canal. It is typically dry when not in use and could be utilised for recreation purposes. Alternatively, it may be possible to design and manage the bypass as ecological habitat with a steady trickle of water, or at least a standing pool or wetland (Newbold *et al.*, 1983). Flood bypass channels are particularly suitable in urban areas where it is not possible to widen the existing channel due to development (Brookes, 1988). A flood bypass channel is proposed for a section of the Lourens River through the centre of Somerset West.

Figure 7.17: A flood bypass or flood-relief channel (after Lewis and Williams, 1984)



d) New pools adjacent to the river

The creation of new pools can be a valuable refuge for threatened aquatic plants and animals. One method is to reestablishment connections from the river channel to the floodplain.

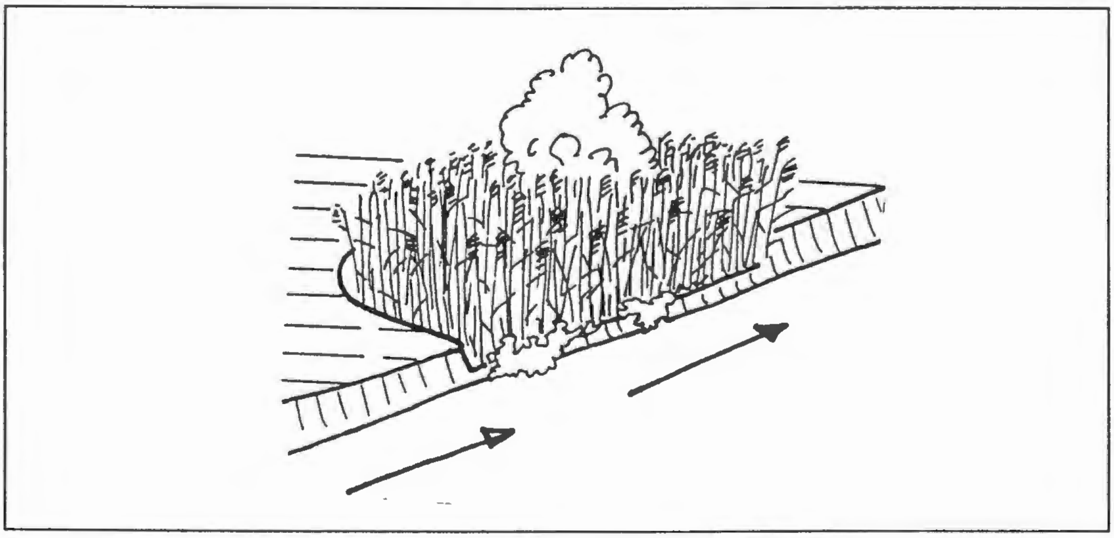
Along the River Rhine, channels and floodplain pools isolated by channelisation, have been reconnected to improve habitat. New ponds have been excavated along the Danube, while dredged sand has been used to create islands in areas of inundated flood plains along the Missouri and Mississippi Rivers (Petts *et al.*, 1989).

e) Off-channel wetlands

The values of wetlands are well established, and opportunities for including wetland features in flood control channel projects are numerous (Genetti, 1989). Desirable site criteria for wetland construction include flat topography, relatively impermeable soils and a high ground-water table. Wetlands may be constructed by excavation, or the placement of excavated material.

Wetlands connected to a riparian system function as a natural purification system for the stream (Simpson *et al.*, 1982). They also minimise the rapid transport of nutrients downstream where they accumulate, causing eutrophication (Simpson *et al.*, 1982). Constructing small wetlands on all inflows of water to the river system reduces the nutrient load (Petersen *et al.*, 1992).

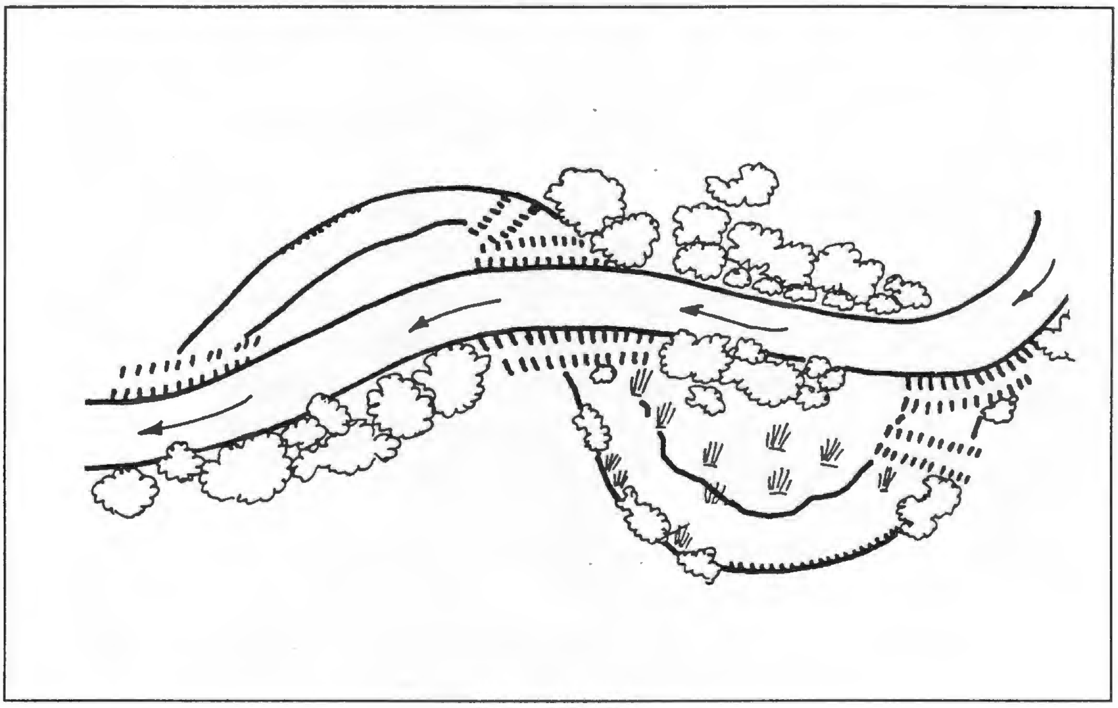
Figure 7.18: An off-channel wetland created by excavating a section out of the river bank (after Lewis and Williams, 1984)



f) Preservation of severed meanders as pools

Channelisation of meandering streams results in the severing of meander loops. The net result is a loss of aquatic habitat and a reduction in overall habitat diversity and quality (Shields, 1982a, b).

Figure 7.19: Preserving a severed meander (modified after Lewis and Williams, 1984)



Severed meanders can be retained as isolated pools. The backwater habitat, as well as the land enclosed by the severed meanders, can be managed to provide aquatic, riparian and terrestrial habitat. The whole oxbow area could also provide an aesthetic and recreational resource.

Severed meanders, or oxbows, can also act as retention dams during floods. The retention function would be optimised if culverts were constructed between the river and the oxbow, and one-way flaps are fitted to allow flood flows to enter the oxbow area (US Army Engineer District, Memphis, 1979 cited in Shields, 1982a).

g) Adopting a meandering alignment

A meandering channel by definition is one that has a channel length at least one-and-a-half times the length of the down-valley distance, where an absolutely straight channel has a channel length of one (Leopold *et al.*, 1964 cited in Petersen *et al.*, 1992). Where a channel has to be moved, the size, shape, meander geometry, slope and bed roughness should be similar to the old channel (Brookes, 1988). Reinstating meanders in a straightened channel can result in a number of benefits.

In a meandering channel, flow patterns alternately transport sediment from the concave bank and deposit it near the convex bank (Petersen *et al.*, 1992). This erosional and depositional process allows the stream to dissipate its energy and induces the formation of a series of pools and riffles (Seibert, 1960 cited in Brookes and Gregory, 1988).

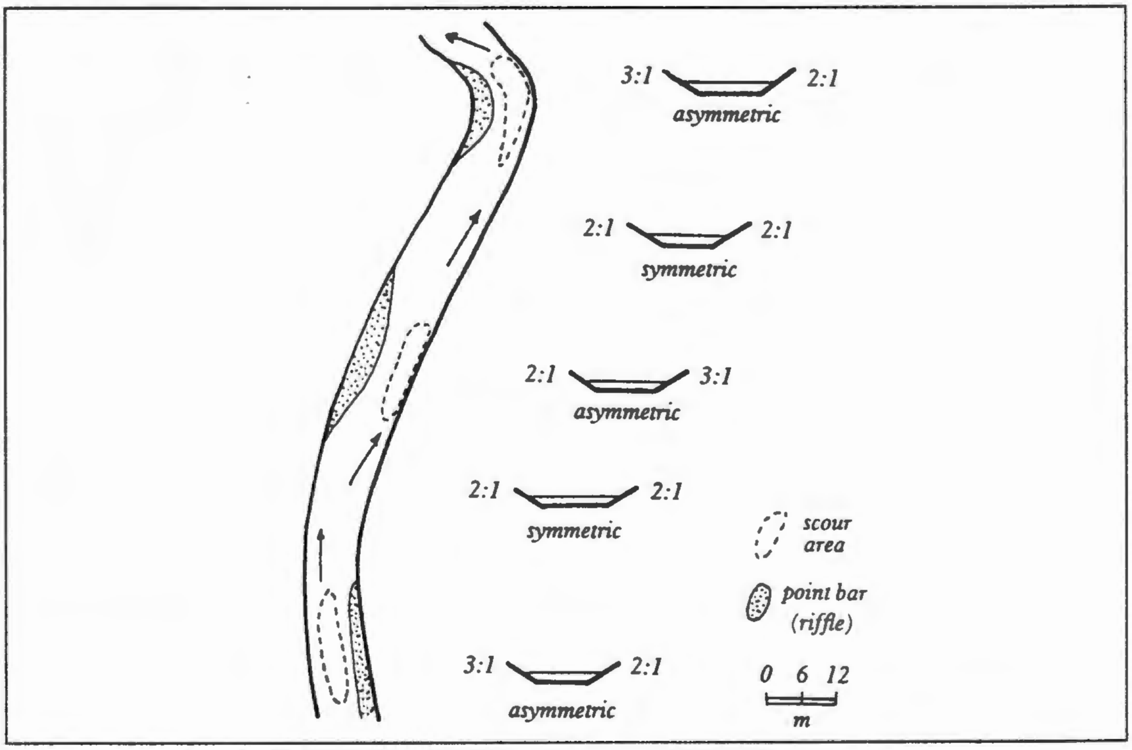
Meandering alignments may be more expensive to construct than straight channels because of increased excavation costs. However, the environmental benefits and reduced maintenance may offset increased construction costs over the life of the project (Brookes, 1988, 1989). Well-designed meandering channels are more stable (Genetti, 1989), provide a greater variety of flow conditions and aquatic habitat diversity and are aesthetically more pleasing (Keller and Brookes, 1984 cited in Brookes, 1988).

Reinstatement of meanders is now common practice along straightened lowland watercourses in Denmark, Germany and Austria (Petersen *et al.*, 1992; Brookes, 1992). Realignment of the River Roding, for example, demonstrated the success of recreating meanders and was loss costly than adopting a straight alignment, as extensive bank stabilisation was not required (Lewis and Williams, 1984).

h) Asymmetrical cross-sections

Channel works usually seek to produce a uniform trapezoidal cross-section with banks having 2:1 slopes. However, these channels tend towards a state of disequilibrium (Nunnally, 1978). There is little reason why cross-sectional variation cannot be retained or created in any river (Holmes and Newbold, 1989).

Figure 7.20: Use of asymmetrical cross-sections to create a pool-riffle sequence



Riffles are symmetrical, while bends and pools have asymmetrical cross-sections (Leopold *et al.*, 1964 cited in Swales, 1982; Keller, 1975; Keller, 1978). Asymmetrical cross-sections may be used to induce, or preserve meanders by directing the flow and inducing the development of pools and riffles (Seibert, 1960; Binder and Grobmaier, 1978; Keller, 1978 cited in Brookes, 1989; Lewis and Williams, 1984).

i) Pools and riffles

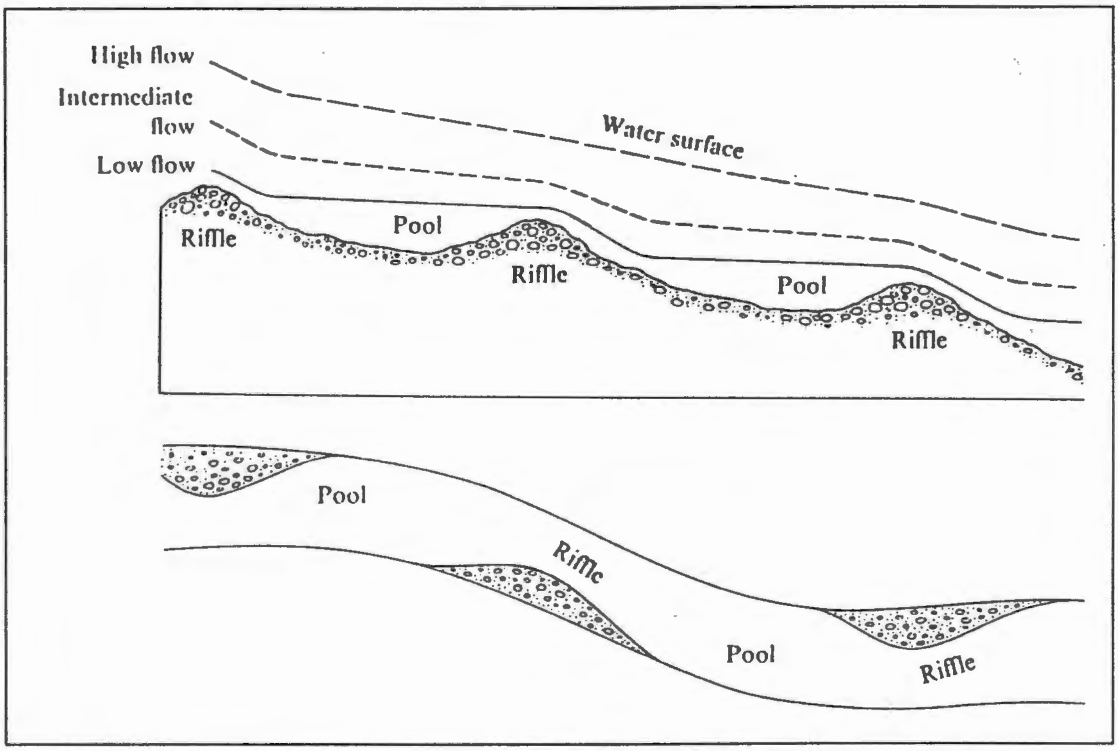
The upper and middle reaches of many rivers consist of an alternating sequence of pools and riffles. The combined effects of channel straightening, widening and deepening invariably eliminate the pool-riffle pattern and therefore the natural energy balance of the fluvial system (Keller, 1978).

The pool-riffle pattern produces a variety of environmental characteristics which are important in maintaining a balanced aquatic community (Hynes, 1970; Coming, 1975 cited in Keller and Hoffman, 1977; Keller, 1975). Pools not only provide shelter in depth, but also protection from the main force of the current (Swales, 1982). Shallow, fast-flowing riffles are areas of highly oxygenated, turbulent flow with high substrate diversity where invertebrate production is highest (Hynes, 1970).

It is desirable to retain or create pools within a channel in places where the river naturally deepens, for example at bends, where there is a steeper gradient, or where a tributary joins the main river (Newbold *et al.*, 1983). A reversal of bed and shear stresses occur between riffles and pools over a range of discharges (Richards, 1982 cited in Brussock *et al.*, 1985) so that pools are depositional areas during low flows and erosional at high flows (Keller, 1978). A net loss of material downstream occurs even though distinct depositional areas (riffles) are formed at high flow (Brussock *et al.*, 1985). This pattern of scour and fill maintains the pool-riffle sequence and sorts the bed material so that the coarser material is deposited on riffles and point bars (Keller, 1978). This sorting provides a quality environment for bottom-dwelling organisms. The bed of pools is composed of fine sediment and during low flow periods the water is relatively deep and slow moving. Pools provide habitat for a variety of insect larvae, fish and decomposer organisms as well as storage areas for organic material that is slowly released into the stream (Petersen *et al.*, 1992).

The pool-riffle pattern is sensitive to channel width (Keller, 1978). Riffles and pools should be used in sections that have a steep gradient and coarse sediment (Petersen *et al.*, 1992). Artificial pools and riffles may not be self-maintaining in ephemeral streams, channels with a steep gradient, where there is a high sediment transport, where the bed is armoured, or where the banks are unstable (Brookes, 1989). Pools and riffles may occur in sand channels when the slope is between 0.002 and 0.015 (Schumm and Khan, 1972 cited in Keller, 1975). For gravel-bed rivers, pools and riffles should not be constructed when slopes exceed 0.005 (5m/km) (Keller, 1975).

Figure 7.21: Diagram showing a longitudinal and plan view of pool- riffle sequences (after Dunne and Leopold, 1978)



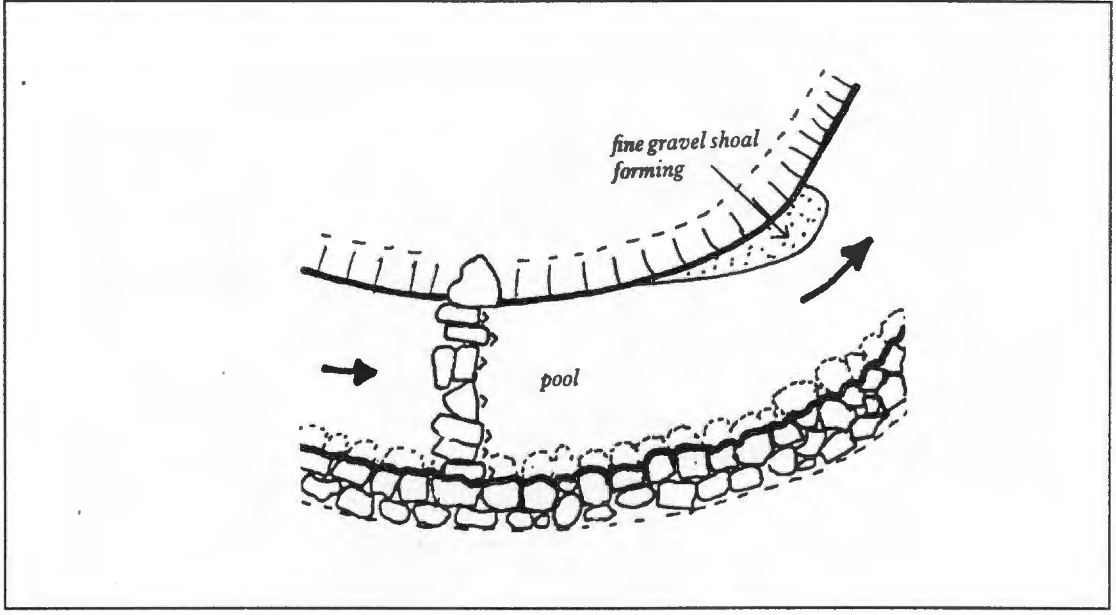
Dredging out the high spots (riffles) may be all that is required to increase the channel capacity. However, the elimination of riffle habitats will lead to habitat degradation and loss of species, and will lead to a more uniform "slack" channel (Holmes and Newbold, 1989). It is ideal, but more costly, to excavate a uniform amount of material from the whole length being dredged (Holmes and Newbold, 1989). Creating or retaining pools has no detrimental effect on flow efficiency (Brookes, 1988), but there are cost implications as additional material would need to be removed.

The natural frequency and dimensions of pools and riffles are interrelated with bed material size and gradation, discharge, and channel slope (Leopold *et al.*, 1964). An optimal spacing of pools and riffles, averaging about six times the channel width, would improve a modified stream by providing a channel morphology that is relatively stable, biologically productive, and aesthetically pleasing (Keller, 1975).

j) Channel grade control or step-weirs

Channelisation is associated with an increase in grade (Shields, 1982a). Typically an increase in gradient is accompanied by upstream degradation and downstream aggradation (Parker and Andres, 1976; Yearke, 1971 cited in Shields, 1982a). While bed incision may further increase the capacity of the channel, degradation can also damage aesthetic and ecological resources and threaten structures adjacent to the channel. Furthermore, achieving a stable grade is of primary importance since bank stability is impossible without bed stability (Shields, 1982a).

Figure 7.22: Grade control structures or step-weirs act like riffles and create deeper water upstream and a scour pond downstream (after Lewis and Williams, 1984)



If straightening is necessary, natural grade may be preserved in the excavated channel by using drop structures or weirs. Drop structures may also be required at the upstream end of the channel modification, and on tributaries.

A series of weirs can be used to absorb energy, thereby reducing the ability of the water to transport sediment (Harvey and Watson, 1988 cited in Brookes, 1988). The resulting stabilisation of the bed, provision of stable substrate, increased variability of flow, and the provision of a deep, permanent scour hole promotes biological diversity (Cooper and Knight, 1987 cited in Shields and Hoover, 1991). Furthermore, low weirs, especially gabions, increase the retention of organic matter and re-oxygenates the water. Boon (1988) found that the presence of weirs caused a dramatic increase in taxa. Ideally, vegetation such as *Phragmites australis* (fluitjies riet) should be encouraged to grow behind these weirs.

Grade control structures must be designed, built and maintained so that they do not create problems of downstream scour, upstream sedimentation, or reduction of flow capacity under high-flow conditions. In addition, structures should not prevent the migration of aquatic organisms. A 30cm^2 hole near the bottom of a weir permits waterflow and movement of aquatic organisms at low flow (Walker, 1979 cited in Shields, 1982a). Alternatively, drop structures constructed of large loose blocks (as opposed to concrete) allow fish and invertebrates to migrate upstream (Oesterreichischer Wasserwitschaftsverband, 1984 cited in Jaeggi, 1989).

The use of check dams or weirs, has been successfully applied to increase fish populations in the United States (Gard, 1961; Barton and Winger, 1973 cited in Brookes,

1989) and in West Germany (Januszewski and Range, 1983; Geiger and Schröter, 1983 cited in Brookes, 1989).

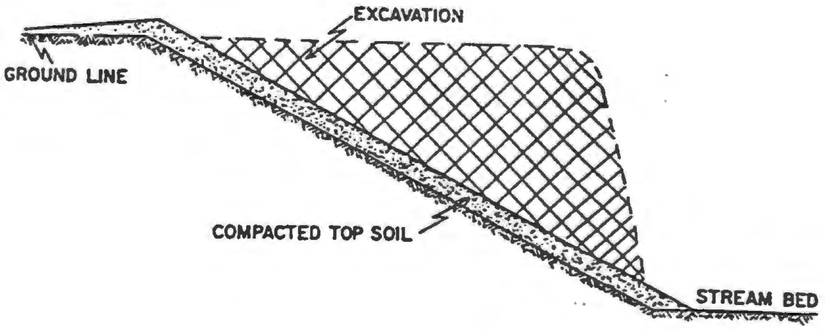
k) Regrading of the banks

Channelisation typically results in steep river banks graded to an even 1:2 slope. This increases bank failure, and the amount of material directly entering the channel. It also precludes many plants and animals.

Petersen *et al.* (1992) and Heath (1989) propose reducing the slope of channel sides from the present 1:2 to a minimum of 1:4. This would reduce the frequency of bank failure. Furthermore, the increased channel width would create an area that would function like a floodplain, allowing the stream to dissipate its energy and not erode the channel banks (Petersen *et al.*, 1992).

However, not all steep banks should be regraded. Vertical earth banks such as those that commonly form on the outer bank of meanders provide nesting sites for kingfishers and other birds, as well as habitats below the water-line (Newbold *et al.*, 1983; Lewis and Williams, 1984). To increase the habitat diversity further, a vegetated ledge should be created (Holmes and Newbold, 1989).

Figure 7.23: Regrading of river banks to reduce their steepness



An alternative to regrading the banks is to stabilise the toe of the bank of incised channels (Shields *et al.*, 1995). Bank failure landward of the toe would then create a stable angle.

l) Over-widening of the channel

Over-widening sections to create bays or off-channel wetlands is ecologically desirable. Although these sections will eventually silt up, this is a natural process and a series of bays of different serial stages, or ages since dredging, will maximise the number of habitats.

An existing straight, narrow channel that is down cutting could be restored by widening the cross-section to reduce the sediment transport capacity of the river (Jaeggi, 1989). This alternative avoids having to build a large number of drop structures, while the wide braided reaches have ecological advantages.

The increase in runoff from urbanised catchments may require that the size of a channel is doubled (Gardiner, 1992). It is therefore preferable to design for the future, and not for present flow requirements. There are additional benefits of this approach in that it allows for some environmental sensitivity to be incorporated into the design, at least until the full capacity of the channel is required.

Channel widening, as opposed to deepening, avoids lowering the water table, and is less destructive to the river bed habitat. It also avoids the problem of bank instability. However, a channel that is over-widened, in order to meet a particular design flow or for ecological purposes, may revert to its original width as it is out of equilibrium with the normal range of flows (Brookes, 1988). Channel widening generally leads to shallower flow depths which can be overcome by the use of two-stage channels, or by the construction of small weirs at suitable intervals to provide ponding. Moreover, channel widening requires more land, destroys riparian and floodplain vegetation. It is hydraulically inefficient, and increases the risk of siltation (Gardiner, 1992).

m) Substrate reconstruction

The substrate or bed material in a natural stream is usually well sorted, with a thin armour layer of coarse material overlying a layer of material with a wider size gradation (Shields, 1982a). Furthermore, the bed material in riffles is coarser than in pools. The aquatic community, particularly the benthic community, is adapted to the existing bed material.

Channelisation generally affects the substratum by causing a predominance of particles of small sizes, while the higher velocities create unstable substrate (Simpson *et al.*, 1982). Numerous authors, including Patrick (1959; Winger, 1972; Gore and Johnson, 1979; Wydoski and Helm,1980 cited in Simpson *et al.*, 1982) have reported that benthic recovery is primarily dependent on the return of stable substrate conditions.

One approach to hastening the recovery of channel substrate stability, and the populations of dependent aquatic organisms, is to line the modified channel with a biologically desirable bed material. However, the expense of lining a channel with rock or stone that will be relatively stable in modified channel velocities may be prohibitive (Shields, 1982a). Furthermore, the biological benefits would be minimal if the layer of material was blanketed by sediment deposition.

n) Instream habitat improvement devices (sills, deflectors and boulders)

Instream habitat devices are simple structures made of stone, gabions or logs which are used to increase the physical diversity of modified river channels by altering flow, channel morphology or substrate (Swales and O'Hara, 1980; Shields, 1982b). These devices increase the hydraulic roughness of the channel and may therefore reduce the discharge capacity. Habitat structures include sills, deflectors, or random rocks.

Instream habitat improvement devices have been used extensively in North America to provide a cheap and effective way of improving instream habitat conditions for fish and other river communities in both headwater and large lowland rivers (Swales, 1989). Various authors, such as Barton and Winger (1973a, b); Luedtke and Brusven (1976); Lund (1976); Winger *et al.* (1976) and Griswold *et al.* (1978 cited in Simpson *et al.*, 1982) have found that these devices accelerate the recovery of benthic macroinvertebrate and fish populations. They restore substrate composition and stability, create cover, increase habitat diversity, and re-create pools and riffles. However, they are prone to failure in aggrading streams (Holm, 1984 cited in Brookes, 1989).

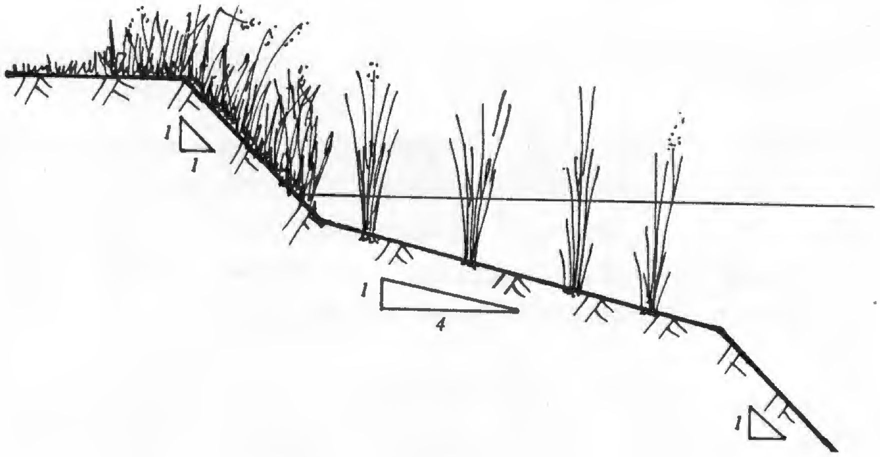
In most cases habitat structures placed in modified channels have produced conditions superior to conditions without habitat structures, but inferior to natural channel habitat (Barton and Winger, 1974; Griswold *et al.*, 1978 cited in Shields, 1982b).

Large boulders or gabions, randomly placed or grouped near the centre of the channel, provide habitat by producing small downstream scour holes and zones of reduced velocity (Shields, 1982a; Petts *et al.*, 1989). The use of boulders placed in the stream is one of the least costly and easiest ways to increase habitat diversity (Starnes, 1985).

The benefits of sills or low weirs have been described in the section on grade control structures. They can produce either a small pool upstream or a downstream scour hole, or both (Shields, 1982a; Lewis and Williams, 1984). Simple and cheap, low weirs can make a distinct improvement to habitats, increase oxygenation of the water and provide a hard, stable substrate for riffle organisms. A broad-crested sill may itself act as a riffle, particularly if it is submerged most of the time (Griswold *et al.*, 1978 cited in Shields, 1982a).

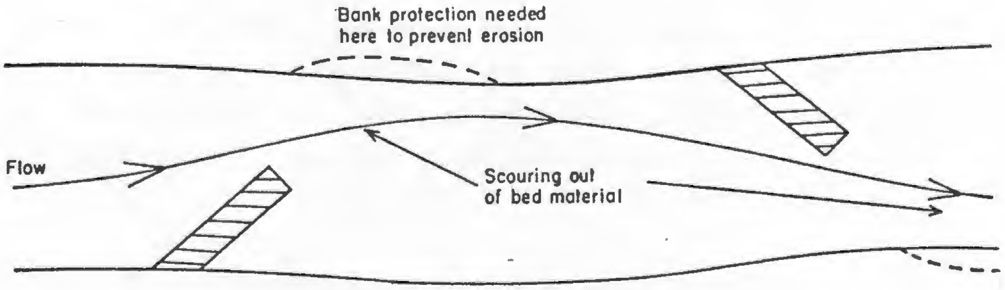
Shallow water berms involve creating a shallow underwater marginal shelf to the river channel. Berms increase the variety of water depths and flow conditions in the river channel. To be effective, at least half the width of the berm should be submerged during times of lowest water flow in order to encourage a range of aquatic plants (Bonham, 1980 cited in Lewis and Williams, 1984).

Figure 7.24: A cross-section of a berm supporting semi-aquatic vegetation (modified after Lewis and Williams, 1984)



Current deflectors are made of concrete, logs, rocks, or gabions and protrude perpendicularly, or at an angle downstream, from one bank (Swales and O'Hara, 1980; Shields, 1982a). They can protect eroding banks, or produce a meandering thalweg. Current deflectors can direct flow to create a scour pool and corresponding riffle downstream (Swales, 1989). Since current deflectors partially recreate the habitat characteristics associated with pools and riffles, they should, where possible, be installed at between five and seven stream widths part, imitating the natural river pattern (Swales and O'Hara, 1980).

Figure 7.25: Current deflectors can recreate habitat diversity (after Swales and O'Hara, 1980)



7.3.4 Mitigation measures for lined canals

The adverse environmental impacts of lining channels or canals, may be reduced by the incorporation of environmentally-sensitive features. Mitigation measures for lined canals include constructing low-flow channels, ponding water and creating weirs, the use of planting troughs, modification of the substrate, the incorporation of natural or more sections and utilising the canal for recreational purposes. The following section provides details of each of the mitigation measures.

a) Low-flow channels

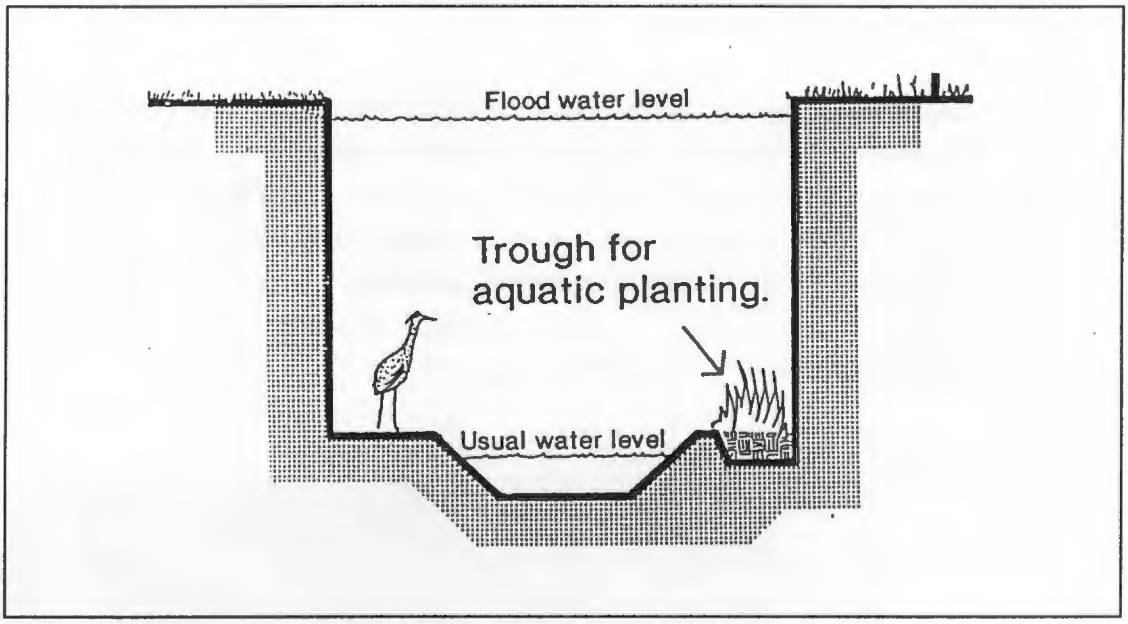
Low-flow channels may be constructed in the bottom of a lined channel. From an engineering perspective, they may reduce the deposition of material (Shields, 1982a, b; Brookes, 1989). Low-flow channels reduce adverse impacts on the aquatic community because they provide more desirable depths and velocities at low-to-normal flows (Shields, 1982a). However, in canals with a steeper gradient, the creation of low-flow channels may result in a further increase in water velocity and therefore have a detrimental effect on the aquatic community.

Figure 7.26: Low-flow channels within lined sections

Minimising large shallow areas of water in turn minimises the ecologically detrimental increase in water temperatures (Brookes, 1989). Aligning the low-flow channel close to the bank of the larger channel will increase shade from the canal wall and any structures or trees adjoining the canal.

Another option to reduce the cross-section of the canal is to create a planting trough. Precast L-shaped concrete retaining wall segments may incorporate a trough, or a low, possibly perforated, wall could be constructed in the floor of the canal. These troughs would trap silt and promote the growth of marginal plants (Heath, 1989). They could be located in areas of reduced flow, such as the inside of bends. This option could have major ecological and aesthetic benefits.

Figure 7.27: Section through a concrete channel showing a planting trough (after Heath, 1989)



b) Pools and riffles (weirs)

Pools can be created by excavating a hole through the concrete base of the canal, or by constructing low weirs. Weirs created of gabions, cobbles, concrete or riprap can be used to create riffles. The spacing of pools and riffles is not critical in lined channels, but individual pools and riffles should be between one and three channel widths in length (Brookes, 1989). Pools which are too wide, too deep or too long may trap silt. This is, however, ecologically beneficial, and the sediment should not be removed unless it becomes excessive.

A baffle or notch weir placed just upstream of a pool would concentrate low flows and promote self-cleaning (San Francisco District, 1980 cited in Shields, 1982a). Fishways, that is narrow, baffled channels, may be used to provide passage for migratory fish around obstructions such as drop structures, culverts, or unusually steep reaches (Shields, 1982a).

An alternative method is to impound water in the canal during low and normal flows using an inflatable or removable structure. The structure is attached to the canal and can be inflated with water or air to impound low flows, or deflated to allow high flows to pass

(Shields, 1982a, b). This method could provide aesthetic and ecological benefits. However, cost, reliability, durability and the potential to cause flood damage count against this option.

c) Gravel/ substrate/ rest stops

The low substrate diversity of lined canals is one of the major reasons for the depauparate aquatic communities. Therefore, one of the possible mitigation measures is to increase the substratum diversity. Boulders and sediment which accumulate in sections of canal downstream of unlined sections, should not be removed. Furthermore, gravel and boulders could be placed in the lined section. The transport of the gravels out of a section may be reduced by the use of gabions or low weirs across the channel. Cover and shelter for fish and habitat for some invertebrates may be increased by anchoring boulders in pools or inserting gabions in the floor of the canal.

Recent experience in the Liesbeek River with placing sections of pipe filled with rocks through the concrete floor has demonstrated significant increases in aquatic life (Snaddon, pers comm). This shows that substratum and associated flow velocity diversity represent one of the key limiting factors in canals. The provision of refugia from high flow velocities may also be important.

Figure 7.28: Improving the substrate conditions by means of boulders

Continuous lining of the banks and bed should be minimised. The Thames Water Authority has successfully broken-up sections of concrete to restore a more natural substratum (Brookes, 1992). Alternating concrete lining with short lengths of natural or semi-natural channel provides an acceptable habitat for invertebrates and fish (Brookes, 1988). In Hawaii these have been termed 'rest stops' (Parrish *et al.*, 1978 cited in Brookes, 1988).

Bank protection should be limited to areas of local high velocity and turbulence, such as the outsides of bends, areas near bridges and other structures (Shields, 1982a). The use of a variety of materials can maximise habitat by matching the potential erosion with the protection capability of the material (Henderson, 1986).

Another idea affording flexibility for future management, while retaining a degree of environmental sensitivity today, is to oversize any lined channel and then design in-channel habitat, reducing the conveyance to the level necessary. For example, an oversized canal could be built up with rocks and gravel, facilitating the development of a pool and riffle sequence. This technique proved successful on the River Roding (Weeks, 1982 cited in Gardiner, 1988).

d) Recreational usage

Many lined canals are located in high density urban areas. Moreover, these canals are nearly empty for most of the time. A low-flow channel, the use of textured concrete or other attractive materials, together with planting beside the channel, could transform a flood control project into an attractive amenity (Black, 1979 cited in Shields, 1982b).

Figure 7.29: Channels which do not convey flows on a regular basis can be used for amenity purposes

If a low-flow channel is incorporated into the canal, the high-flow section of the canal floor could be utilised for walkways and cycle paths. In addition, certain areas could be developed for skate-boarding, roller-blading or roller-skating.

7.4 SUMMARY

It is unlikely that catchment and floodplain management will be fully able to mitigate the increase in runoff and deterioration in water quality. As a result, urban rivers will become increasingly degraded, unless they are engineered and managed in an environmentally-sensitive manner.

However, there are a number of measures which could be applied at the river channel level to mitigate the negative ecological effects of river maintenance, channelisation and canalisation. Most of these measures aim to maintain or recreate the diversity of physical conditions, especially flow velocity and substratum, in order to increase the diversity of organisms.

The aim of environmentally-sensitive river channel engineering and management is to maintain or restore the ecological value of river systems. The objectives include retaining the natural habitat rather than destroying and recreating it; maximising physical diversity in order to maximise biological diversity; working with the natural system in order to ensure the sustainability of habitats, and tailoring channel designs and mitigation measures to each specific site.

Modifying river maintenance practices can result in significant ecological benefits. One of the basic measures is to reduce the frequency of maintenance activities, as maintenance offsets ecological recovery. Others include disposing spoil material away from the channel to prevent erosion and the leaching of nutrients back into the channel. Modifying only one bank, leaving patches of vegetation unmowed or sections of channel undredged, provides a reserve of flora and fauna to recolonise the disturbed area, and the diversity of serial stages promotes diversity. Terrestrial vegetation should be maintained or established as it stabilises the river banks, shades the channel, enhances water quality, provides a source of allochonous material and provides important habitat. Aquatic vegetation, on the other hand, oxygenates the water, stabilises the channel, enhances the water quality, and provides shelter and food and provides habitat for a myriad of fauna. Excessive aquatic vegetation should be controlled by cutting or draglining. Again, patches should be left undisturbed and operations undertaken at different times of the year. Marginal vegetation should be left intact and removal should take place in an upstream direction to facilitate rapid recolonisation. Riparian trees can control excessive aquatic weed growth by shading. Finally, sediment traps have numerous ecological benefits, as well as reducing maintenance costs, improving the water quality and enhancing aesthetics.

Environmentally-sensitive streambank protection includes indirect methods, or deflecting the flow away from the banks by the use of dikes, jetties or gabions placed perpendicular to the flow. Bioengineering makes use of the properties of living plants to stabilise river banks. Where more protection is required, vegetation may be combined with man-made materials such as concrete interlocking blocks. In such cases, it is important that the blocks provide drainage and enough soil, and that the filter layer laid beneath the blocks does not impede root penetration. Fabrics and mesh made of biodegradable or man-made materials may provide temporary or permanent assistance for vegetation. Rip-rap, or graded crushed stone, can be used to stabilise banks, and may increase the substrate heterogeneity. Lastly, gabions, or boulder-filled wire mesh baskets, provide relatively environmentally-sensitive stabilisation. However, the acid, corrosive waters of many rivers in the Cape Metropolitan Area, as well as rolling boulders, damage the wire mesh, leading to failure of the structure.

Mitigation measures for channelised rivers include creating levees away from the river channel. This would provide additional capacity so that either the natural channel could be conserved, or the channelised section could be managed in an environmentally-sensitive manner. Flood bypass channels or two-stage channels have similar benefits. The creation of off-channel pools and wetlands provides new habitats and improves the water quality. Creating wetlands on all inflows can have significant water quality benefits and protect the river system from water pollution. The retention of severed meanders can provide ideal, pool or wetland habitat and could also serve as a flood attenuation facility.

The following three mitigation measures aim to achieve the habitat diversity associated with the pool-riffle sequence. Pools and riffles are important erosional and depositional features which allow the stream to dissipate energy. From a habitat perspective, they create a range of substrate and flow conditions resulting in a diverse abiotic environment. Furthermore, pools and riffles are intimately related to a meandering alignment and therefore can be preserved or created by constructing a meandering course. A meandering alignment can also be induced by creating asymmetrical channel cross-sections - as riffles are symmetrical in cross-section, while bends and pools have asymmetrical cross-sections. Reinstating an appropriate channel grade or slope by means of low weirs can mitigate the problems of increased erosion, unstable banks and poor habitat quality. The weirs not only absorb energy, but also induce upstream and downstream pools, while the weir acts as a riffle, oxygenating the water. Weirs however should be designed to avoid acting as a barrier to aquatic invertebrate and fish migration. Regrading or creating less steep banks reduces bank erosion and provides more of the diverse riparian habitat type. A channel can be over-widened in order to create off-channel bays or wetlands. Constructing channels wide enough to convey the flows generated by the fully urbanised catchment allows the channel to be managed in an environmentally-sensitive manner in the interim, until the full capacity is required. Over-widening an incised channel would reduce the sediment transport potential of the river and therefore reduce further down cutting. Disturbance of the channel bed, combined with the increase in flow velocity typically results in an unstable bed. Substrate reconstruction, or the placing of participles with a larger size, would increase the stability of the channel, as well as increasing the habitat diversity. Lastly, instream habitat devices, such as sills, current deflectors and rocks can be used to increase the habitat diversity in channelised reaches.

Lined canals offer little habitat diversity and as a result support an extremely depauparate flora and fauna. Mitigation measures, can however, enhance the ecological and recreational potential of canals. Construction of a low-flow channel can have beneficial ecological effects, such as minimising the increase in water temperature. While the effect on the flow velocity may be positive or negative, the reduction in sediment deposition is likely to have negative effects on the flora and fauna. The incorporation of a planting trough could have significant ecological, as well as aesthetic benefits. The creation of pools, by impounding water behind a weir or inflatable structure, can increase the habitat diversity. Similarly, weirs can oxygenate the water, improve the amenity value and provide a further habitat type to the system. Another possible measure is to leave any silt or boulder material which is deposited in the canal. Boulders could also be added to improve the substrate. It is important that the concrete lining is not continuous and the ecological benefits of small sections of natural, or semi-natural channel can have significant ecological benefits and may assist in recolonisation. Lastly, lined canals typically occur in dense urban developments and could provide valuable open space. The drier section of the canal bed could be utilised for pedestrian or cycling paths, or for skate-boarding or roller-blading rinks.

In conclusion, many possible mitigation measures could be utilised to maintain or improve the ecological condition of river channels. In the following chapter, the Liesbeek River is used as a case study to illustrate how some of the mitigation measures described in Chapters Five to Seven could be applied.

CHAPTER EIGHT: CASE STUDY - THE LIESBEEK RIVER

CONTENTS

CHAPTER EIGHT: CASE STUDY - THE LIESBEEK RIVER

8.1 BACKGROUND

> *"So, fittingly, the Liesbeek owes its life to Table Mountain, the symbol of the Cape; and we can stand with van Riebeek on the banks of the Liesbeek, as he stood in October 1655, and agree that this stream is the "creator of the pleasant valleys through which it flows - a delight to the eye" (Jose Burman, 1962, p34).*

This chapter briefly describes the Liesbeek River and traces the effects which humans have had on the river and its catchment. Starting with the effect of the hunter-gatherers, the increasing impacts of the Khoikhoi pastoralists are described, followed by the development of colonial agriculture and subsequent urban development.

The purpose of this historical perspective is to gain an understanding of the long history of anthropogenic impact on the river system, and to use this information to inform management and rehabilitation. While detailed site-specific rehabilitation measures are beyond the scope of this dissertation, there are some general suggestions at the levels of the catchment, floodplain and channel. These mitigation measures aim to reduce further degradation of the system, and to enhance the aesthetic, recreation, education and conservation potential of the Liesbeek River.

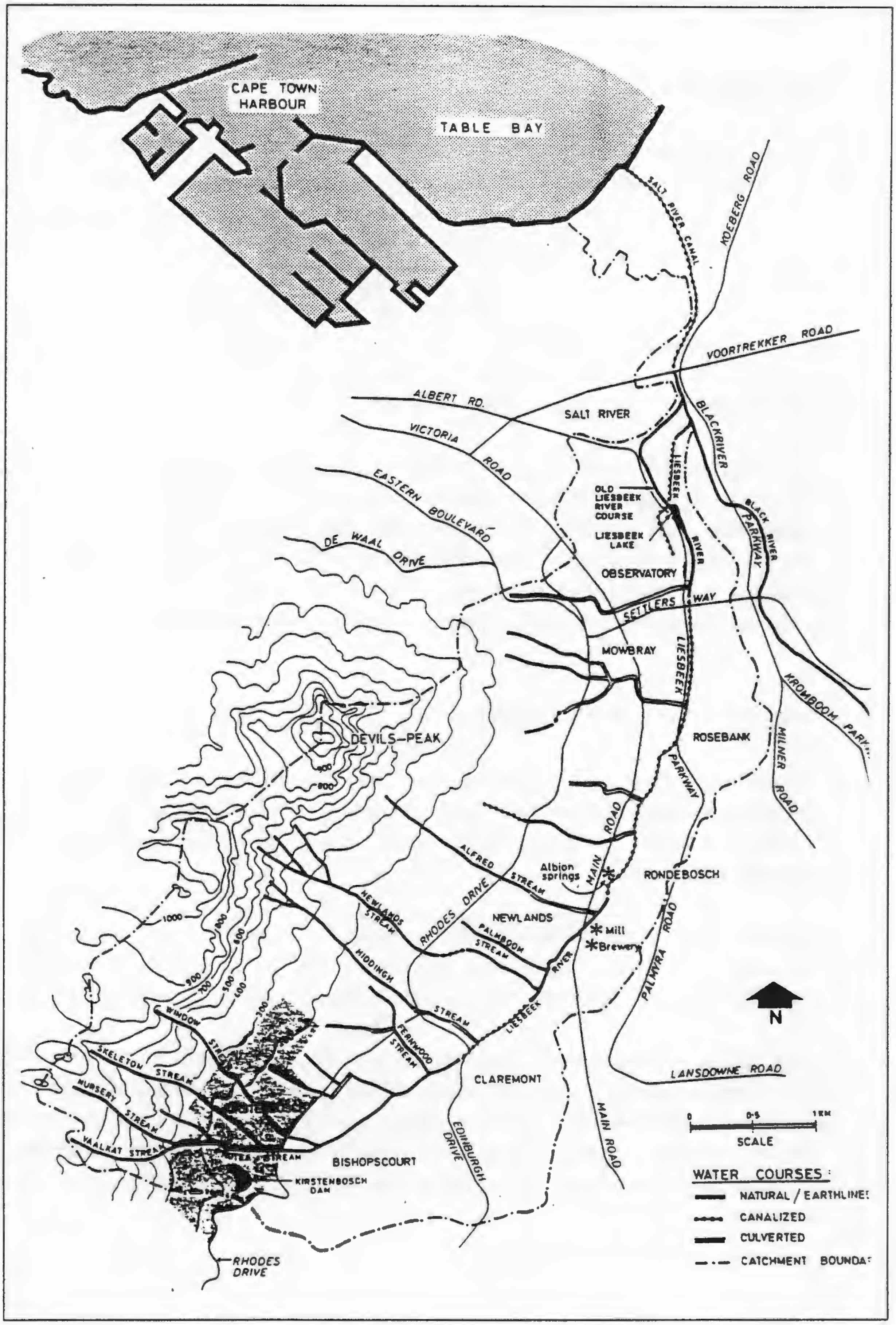
8.2 DESCRIPTION OF THE LIESBEEK RIVER

The Liesbeek River, probably named after "Lies" meaning reed and "beecq" meaning stream, arises on the east-facing slopes of Table Mountain. It is fed by tributary streams in Window, Nursery and Skeleton gorges and by a series of springs, including Cannon, Palmboom and Albion springs (Figure 8.1).

Although most of the tributaries only flow during the winter months, the main course of the Liesbeek is perennial. The Liesbeek joins the Black River near Hartleyvale and approximately 14km from its source enters Table Bay in the vicinity of Paarden Eiland (Figure 8.1).

The natural vegetation would have consisted of Mountain Fynbos on the upper slopes and afromontane/ riverine forest in the kloofs and river valley. The river is likely to have supported a dense growth of *Prionum serratum* (palmiet), while the extensive wetland areas nearer the mouth would have consisted of a variety of reeds and sedges such as *Phragmites australis* (fluitjies riet). The lower drier areas of the catchment would have supported Strandveld vegetation.

Figure 8.1: Map showing the Liesbeek River and its main tributaries (after Day, 1995)



Today, only the areas upstream of Kirstenbosch can be considered near pristine. Riverine trees in this reach include *Brabejum stellatifolium* (wild almond), *Rapanea melanophloeos* (boekenhout), *Ilex mitis* (wild holly), and *Rhoicissus tomentosa* (wild grape) (Day, 1995). Downstream of Kirstenbosch, the catchment is suburban or urban and little natural vegetation is left. The Liesbeek River is for most of its length a severely degraded urban river system. Nonetheless it still retains some of the features of natural riverine ecosystems and is also a valuable recreational and educational resource.

8.3 HISTORY OF THE LIESBEEK RIVER

8.3.1 Pre-colonial influences

> *"When man arrived, rivers shaped his history, and men, in turn, began to shape them" (Purseglove, 1989, p 7).*

The pre-Colonial environment of the Liesbeek valley is little known, but it is likely that the area was occupied by hunter-gatherers for tens of thousands of years. These people would have had little impact on the natural environment due to their small numbers and migratory mode of existence (Simmons, 1993 cited in Bottaro, 1996). Later, these hunter-gatherers were succeeded by Khoikhoi pastoralists.

The Khoikhoi moved to make optimal use of available grazing for their cattle. Their influence on the Liesbeek valley would have been far greater than that of the hunter-gatherers, as the grazing of stock, and especially the use of fire to encourage new growth, would have impacted on the natural environment. Grasses and annuals would have been favoured at the expense of perennial shrubs and forest elements.

8.3.2 Colonial influences

The first significant impacts on the Liesbeek River probably occurred in the late 17th century when the first European agriculturalists moved onto the fertile floodplains and planted crops. The destruction of the natural floodplain vegetation and the draining of wetlands would have destroyed large areas of natural vegetation and degraded the riverine ecosystem.

In 1652, Jan van Riebeeck recorded in his journal that the eastern slopes of Table Mountain, stretching down to the Liesbeek River, were covered by extensive forests which were "so dense from the top to the bottom, close to the river, that no opening could be found. Furthermore, the Liesbeek valley was described as "the finest and richest arable and pasture land in the world, wide and level" through which "countless fresh rivulets wind", the largest of which was "half as wide as the Amstel" and "quite deep".

The first farms adjacent to the Liesbeek River were granted to early settlers in 1657. Reports of flooding were recorded in Van Riebeek's journal on 28 June 1657: "Newly sown lands submerged, seemingly a regular inundation; wagon road to forest impassable".

The entry of 15 July 1658 discussed the need for defence to prevent the Khoi from stealing cattle: "For this purpose the Liesbeecq River seems to offer a favourable barrier: it can be forded only at a few places because of its depth and general marshiness" and, on 23 July, Van Riebeek "sailed all about it in a small boat, examining all the shallows for marshes and soft ground impassable to cattle". In addition, the lower reaches of the Liesbeek were described as "thickly grown with sharp nipah (Malay word- a type of stemless palm), water plants and wild rushes". In 1659, riparian landowners were instructed to clear the banks of undergrowth and deepen the river to prevent cattle from crossing. The land between De Schuer (Groote Schuur) and the Liesbeek River was inundated annually during winter floods and it was only in 1686 that Van der Stel strengthened the river banks and dug channels to drain the land (Bottaro, 1996). In 1744, and again in 1882, landowners were instructed to remove obstructions, including trees and bush which were impeding flow and causing flooding (Laidler, 1939, cited in Bottaro, 1996).

The necessity for vast quantities of timber for building, ship repairs, fuel, cooking, lime and charcoal burning had a devastating effect on the forests of Bosbergen (Rondebosch), Paradijs (Newlands) and Leendertsbosch (Kirstenbosch), as the forests along the Liesbeek came to be known (Bottaro, 1996). As the forests were cleared for agriculture and reeds were cut for thatching, stone and sand were increasingly removed from the river for building purposes. However, intensive agriculture in the valley did not flourish due to the lack of crop rotation, weeding and soil enhancement, and extensive pastoralism, trading, fishing, hunting and forestry supplemented the income derived from crops (Bottaro, 1996).

In 1693, the Free Burghers were granted permission to build a mill at Molenvliet (near Mowbray) on the Liesbeek, while beer brewing began in 1696 at Papenboom in Newlands (Bottaro, 1996). By the early 19th century, Rondebosch was a well established farming area with a number of private water mills. In 1842, a tannery was established and the Sasko mill built.

By the end of the 19th century, the Liesbeek valley had changed from an agricultural area to a more densely settled suburban area, with increasing industrial development. The demand for water was outstripping the capacity of the Liesbeek and the river had become polluted (Public Works Commission, 1902; Cape Peninsula Water Supply Bill, 1906 cited in Bottaro, 1996).

Upgrading the Main Road between Cape Town and Simons Town and building of the suburban railway during the 1860's encouraged further suburban development at Mowbray, Rondebosch, Newlands, Claremont and Wynberg. The early 1800's saw a spate of water mills being built along the Liesbeek; for example Papenboom (or Anneberg) Mill, De Hoop (or Albion) Mill, Ekelenberg (or Lothian) Mill and Dreyer's Mill (Walton, 1978 cited in Bottaro, 1996). The storage of water to supply the mills during the summer became a cause for complaint from downstream riparian landowners.

In 1889, Ohlsson's Cape Breweries was formed and utilised water from Albion Spring. Decreased river flow during the summer caused the river and many of the wells to become contaminated, resulting in regular outbreaks of diphtheria and typhoid. After 1888, most houses in the valley were supplied with pure water from the Albion Spring.

Further sources of pollution included the Mossop and Son's tannery in Rondebosch, and the washing of clothes in the river and its tributaries. As there was no official provision for water, sewerage or garbage disposal, people made their own arrangements, with the result that the Liesbeek River become "little better than a cesspool" (Rosenthal, 1957 cited in Bottaro, 1996) and "the open sewer and washerwomen's trough for the district" (Laidler, 1939 cited in Bottaro, 1996). "Hardening" of the catchment would have increased stormwater runoff and contributed to non-point source pollution of the river.

a) Water quality

One of the first of an endless stream of complaints about the deteriorating water quality of the Liesbeek River was made by 16 Rondebosch residents in 1837. Ordinance No 6 (1852) of the Cape of Good Hope was promulgated to prevent "nuisances in the River Liesbeek" and included certain following regulations :

- all dams to be provided with sluices;
- instructions on the regular raising of sluices;
- all dams to be reported to the resident magistrate;
- privies etc, blood, offal and carcases of dead animals, drowning of animals not to be allowed to pollute river;
- rubbish, washing water not be discharged into river, and
- washing not allowed in river.

Strict penalties were to be imposed with fines and imprisonment of up to three months, with or without hard labour. Further regulations forbade bathing, removing river stone and washing. Despite an investigation by the Rondebosch, Mowbray and Claremont Municipalities, water quality continued to deteriorate, allegedly due to effluent from Ohlssons Breweries, the lack of release from dams and the use of 500 000 gallons a day of water from Albion Spring for domestic consumption. In 1905, the lower reaches of the river were described as being "very slightly diluted sewage". In 1915, a petition was sent to the Council requesting them to "clean and disinfect the river" as the "vile odour emanating from it in its present state is overpowering, and is decidedly detrimental to the health of the occupants" (3/CT 44/1/3/27 cited in Bottaro, 1996). Complaints about flies and mosquitoes, and effluent from Mossop's Tanneries and Ohlsson's Brewery continued. A report on the sewerage of the suburbs of the City of Cape Town prepared in 1891 recommended that, because of the high death rates caused by the unsanitary system and the heavy rainfall, stormwater (excluding that from the backyards of trade premises and in closely built-up areas) be excluded from sewers and discharged instead to rivers. The sewerage system was started in 1916 and completed in 1928.

In 1925, a detailed report on the state of the Liesbeek was undertaken by the Minister of Health, including the identification of sources of pollution as well as a chemical and biological survey of the river. The report found that the main sources of pollution were from stormwater drains, the dumping of rubbish into the river and effluent from Ohlsson's Breweries, Pegram's Mineral Water Factory (later Schweppes) and Forrest's Grain Mills (Croghan, 1925 cited in Bottaro, 1996). Believing that it was "possible without much difficulty to restore it to something like its primitive condition of purity", the report recommended :

- that dumping of rubbish into the river be prohibited;
- that owners of properties not yet connected to the sewers should make the necessary alterations;
- that the discharge of industrial effluents into the river should cease;
- that Council clean the river bed each summer;
- that all dams (weirs) should be demolished and that all the water from Albion Spring be allowed to flow into the river (Croghan, 1925 cited in Bottaro, 1996).

These recommendations would appear to have improved the situation considerably as shortly afterwards the river was successfully stocked with trout. Meanwhile, notices prohibiting bathing in the river because of the risk of typhoid and other infectious diseases were erected in 1945 (3/CT 4/2/1/1/1085), and remain a feature of the river today (Figure 8.2).

A major transformation of the Liesbeek River valley occurred during the course of the 19th century, in that the river was no longer such a vital resource. It no longer played a decisive role, and there was less human dependence on it (Bottaro, 1996). More people, houses and industries were the cause of pollution and degradation of the river.

During the 20th century, the sub-division of land continued, resulting in more houses and more people. Large quantities of water continued to be abstracted for the irrigation of sports fields, nurseries and private gardens. Ohlsson's Cape Breweries and Pegrams (later Schweppes) Mineral Water Company utilised flow from Albion Spring, but in terms of a Supreme Court Order of 1892, 500 000 gallons of this spring water had to be allowed to flow into the river daily (Bottaro, 1996). Many of the pollution problems in the early decades of this century were exacerbated because water from Albion Spring was being utilised to augment the city's water supply while the Steenbras Dam was being upgraded. It was only after 1927 that this position was rectified (Medical Officer of Health, 1927 cited in Bottaro, 1996). Riparian landowners, including Kirstenbosch Botanical Gardens, continue to abstract water from the Liesbeek and its tributaries today.

Apart from water quality, flooding of property began to assume importance and was addressed by the canalisation of sections of the river.

Figure 8.2: The water quality in urban rivers is generally not suitable for contact recreation as this sign in the upper Liesbeek River warns

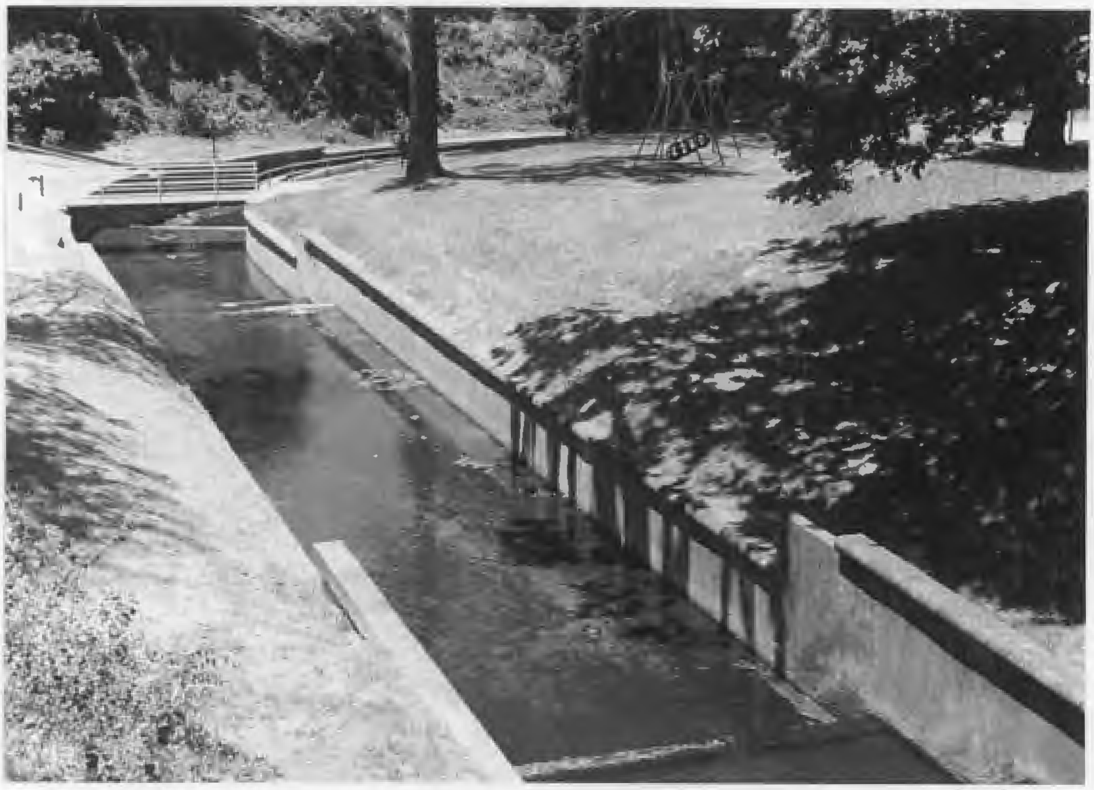
b) <u>Canalisation</u>

Historically, the entire area of Paarden Eiland was a series of mudflats, islands and estuarine wetlands forming a delta at the common mouths of the Salt, Black and Diep Rivers. In 1693, the Liesbeek flowed into the lagoon of the Zoete River, now Milnerton lagoon. By 1930, the Liesbeek joined the Black and, as the Salt River, it flowed to the present Ben Schoeman dock. This was later diverted by canalisation to the present Paarden Eiland mouth.

After the severe floods of 1917, many property owners claimed damages from the Cape Town City Council, stating that the roads and bridges built alongside or over the river had caused flooding of their properties (Cape Archives, 1917 cited in Bottaro, 1996). The next year, Council voted 8000 pounds to concrete the bed of the Liesbeek river between Westerford Bridge and Belmont Road Bridge, and 3300 pounds for the section between Belmont Road and Burg Road (Cape Archives, 1918 cited in Bottaro, 1996).

The Cape Times of 11 May 1933 carried a report that the Rondebosch Ratepayers Association was organising a petition for the Liesbeek River to be canalised as a solution to the polluted state in summer and flooding problems in winter. In 1949, residents in Esme Road, Newlands, requested that Council canalise the river to prevent damage to gardens (3CT 4/2/1/1/1085).

Figure 8.3: A typical section of concrete-lined channel in the middle reaches of the Liesbeek River



Prior to World War II, the section of river between Newlands Rugby grounds and Schweppes (Albion Spring) was concrete-lined to stop undercutting. This was extended further to Rondebosch station from 1945 to 1950, from where canalisation was extended to Durban Road between 1955 and 1960 (Kiemel, 1983). During the same period, the section from Edinburgh Drive to Sans Souci Road was canalised and several weirs were built due to the steep gradient. The Liesbeek was also diverted from upstream of the Royal Observatory to the Salt River (via a weir forming Liesbeek Lake, opposite Hartleyvale). The "original" channel still exists as a blind channel. It was reported that the Liesbeek Lake was a favourite fishing area with some "very fine rainbow trout" (City of Cape Town, 1951).

Figure 8.4: A typical section of concrete-lined channel in the lower reaches of the Liesbeek

In 1969, the Kildare Road to Blue Cross Hospital section was lined to prevent road damage and prevent undercutting. In addition to these formal concrete-lining schemes, many private landowners built, and are continuing to build, retaining walls of various designs on an ad hoc basis to protect "their" property from inundation or from "shrinkage" due to erosion.

8.4 CURRENT STATUS OF THE LIESBEEK RIVER

8.4.1 Introduction

Quick (1996, pers. comm.) regards erosion as a serious problem in the upper sections of the Liesbeek River, particularly upstream of Edinburgh Drive, and to a lesser extent, between this crossing and Main Road, Newlands. Sedimentation in Liesbeek Lake, weed growth and litter are problems in the lower reaches, while the old Liesbeek Channel is poorly flushed and contains litter. Bruwer (1977) concluded that nutrients in the Liesbeek catchment originated from non-point sources, in other words urban runoff. Factors contributing to the phosphorous content of urban runoff include lawn fertilizers, domestic animals, and leachate from leaves and petrol additives (Uttormark *et al.*, 1974 cited in Bruwer, 1977).

Bottaro (1996) describes the declining importance of the Liesbeek River as a factor in Cape Town's history. Once perceived as a key resource, a frontier, a determinant in the siting of roads and railways, the river played an important role until well into the 19th century. However, since then its role has declined and it has increasingly been ignored in planning, and subdued by technology.

8.4.2 Enlightened attitudes towards the Liesbeek river

One of the earliest records of objection to canalisation of the Liesbeek River comes from Mr ME Pillans and Mr VA van der Byl who wrote that "deprecating any proposal to canalise the Liesbeek River", and saying that the "natural beauty would be destroyed" (cited in Bottaro, 1996).

Canalisation of the upper sections was halted by the protests of residents, led by "The Wanderer" of the Cape Argus, who wrote that "the final indignity for the Liesbeek may come if the plan is carried out to treat the stream like a sewer and run a concrete throughway over its length from Bishopscourt to the Salt River mouth" (Talk of the Tavern, 1957 cited in Bottaro, 1996). Subsequently, an association of riparian owners was formed to halt further canalisation of the river, and in 1959 it received an undertaking from the Town Clerk that the river would be maintained in "as natural a state as possible" (Cape Argus, 1959 cited in Bottaro, 1996).

During the late 1980's and the 1990's, there was a general increase in environmental awareness. The Liesbeek River, being situated close to residential areas and especially educational institutions, received increasing attention. The Greening of the City Report (Cape Town City Council, 1982) advocated the recreational and aesthetic values of riverine corridors and proposed a 8 km riverside trail along the Liesbeek. Part of this trail was subsequently built, in part with private sector sponsorship (Figure 8.5). Restoration of the Josephine Mill and establishment of a museum and function venue, together with the recent Albion Springs townhouse development and restaurant that focuses on the river, are indications that the amenity value of the river is being rediscovered.

A "Friends of the Liesbeek" group was formed in 1992 under the auspices of the Wildlife and Environment Society of Southern Africa. Furthermore, research projects, such as Villet, 1974; School of Environmental Studies, 1980; Taylor, 1990; MacDonald, 1991; Saggeson, 1992; Bottaro, 1996 as well as numerous popular articles, including Davies and Luger, 1993; Luger and Davies, 1993; Van Niekerk, 1993a,b,c; and Luger and Davies, 1994, highlighted the plight of the river and generated public awareness.

Figure 8.5: The Southern Life section of the Liesbeek River walkway has increased the amenity value of the corridor

Talks, walks, displays and photographic competitions, together with river clean-ups, have further increased the awareness and profile of the Liesbeek River. In addition, the City has financed various studies on the cultural history of the area (Todeschini *et al.*, 1989 and 1990), the birds (Turpie, 1994), the first phase of a catchment management plan (Day, 1995) and a scoping exercise of the issues and concerns of the public (Crowther Campbell and Associates, 1996).

8.5 THREATS TO THE LIESBEEK RIVER

8.5.1 Introduction

Like most urban river systems, the Liesbeek River is under constant threat of further degradation. The following three sub-sections outline some of the possible threats at the levels of the catchment, floodplain and river channel. This section is not comprehensive, but merely highlights the diverse range of threats to the existing and potential ecological, aesthetic, amenity and recreational value of the river system. The following section illustrates how selected threats can be addressed in an environmentally-sensitive manner.

8.5.2 Catchment level threats

The greatest threat to the ecological integrity of the Liesbeek River is possibly the increase in runoff which would be generated by further sub-division, densification and urbanisation in the catchment. This is also likely to be the greatest impediment to adopting environmentally-sensitive river channel measures. One of the reasons why the river upstream of Paradise Road is not more degraded is because of the low density of urban development in upper Newlands, Bishopscourt and Kirstenbosch. Stormwater runoff has therefore not been increased to the same extent as in other urban areas. The relaxation of sub-division restrictions and other building regulations, together with high rates and the increasing cost of living, amongst other factors, is likely to result in a rapid increase in catchment hardening.

This trend is already evident. Possible measures to mitigate the impact of increased runoff have been described in Chapter Six, while selected examples of how they could be applied to the case study are described in Section 8.6.1.

Other potential threats to the Liesbeek River at catchment level include :

- a deterioration in water quality caused by the likely increase in urban densities;
- the input of toxic substances which can have a devastating effect on the riverine ecosystem; and
- a reduction in flow during the summer period due to the increased abstraction of water; both directly from the river and from the ground water system, by riparian landowners.

In order to address these threats, and others, an integrated catchment management plan should be compiled to derive specific mitigation measures. This plan should take cognisance of the findings of this dissertation, and, in particular, the mitigation measures described in Section 6.2. The need to address both the quantity and quality of stormwater runoff at the catchment level is vital in maintaining the existing "natural" sections of the Liesbeek, and enhancing the ecological value of the canalised sections.

8.5.3 Floodplain level threats

The greatest threat at the floodplain level is probably further urban encroachment into flood-prone areas (Figure 8.6). However, as this requires legal and administrative solutions, it is not covered in this dissertation. From an ecological perspective, the incision of the channel, canalisation, and draining and infilling of the floodplain have significantly reduced the area of floodplain and wetland habitat (Figure 8.7). General measures to mitigate this loss of habitat are described in Section 6.3, while some specific examples that are applicable to the Liesbeek are described in Section 8.6.2.

Figure 8.6: Urban development close to the river channel forecloses environmentally-sensitive options and requires that the banks are stabilised

Further threats to the Liesbeek River at the floodplain level include:

- the private ownership of the floodplain and, in many cases, the river bed;
- specific development proposals on the Culemborg site and especially in the Liesbeek/ Black River confluence area;
- further sub-division and urban development in flood-prone areas;
- further urban development in close proximity to the river banks, and
- the proliferation of invasive exotic flora and fauna.

While many of these threats require a legal or administrative solution, which is again beyond the scope of this dissertation, promotion of environmentally-sensitive river management, as described in Chapters Five and Six, combined with education of the public and authorities and public pressure, would be required.

Figure 8.7: Rapid down cutting of the river bed has resulted in the loss of large areas of floodplain habitat

8.5.4 Channel level threats

At the level of the river channel, almost every section of the Liesbeek which is not yet canalised, faces the threat of further hard engineering mainly in order to increase the capacity of the channel and to control erosion. As described in Chapter Four, canalisation has significant impacts on the aquatic ecosystem and results in the loss of ecological integrity. In addition, the existing reaches of "natural" channel provide important refuges and assist in recolonisation of the aquatic community after disturbance. The particular area selected to demonstrate possible mitigation measures is in the reach upstream of Paradise Road where the river bed has been eroded and the channel is now deeply incised, resulting in bank slumping or collapse. Section 8.6.3 illustrates how the channel has been rehabilitated.

Further threats to the Liesbeek River channel relate to:

- the widening of the lower reaches of the Black or Salt River;
- ad hoc "engineering" of river banks and bed by private landowners;
- "demands" by riparian landowners for protection from flooding resulting in increased hard engineering of the banks and bed;
- excessive erosion of bed and banks, and
- the aesthetic impact of litter and solid waste.

General measures to address these threats, and to enhance the ecological value of the Liesbeek River, are described in Chapters Five to Seven.

8.6 APPLICATION OF ENVIRONMENTALLY-SENSITIVE MEASURES TO THE LIESBEEK RIVER

This section shows how the mitigation measures described in Chapters Five to Seven can be applied to address the selected threats to the Liesbeek at a catchment, floodplain and river channel level.

8.6.1 River catchment mitigation measures

In order to address the increase in stormwater runoff, it is essential that it is restricted to pre-development levels. This is especially applicable in the upper portions of the catchment, namely in Kirstenbosch, Bishopscourt, Newlands and Rondebosch. Appropriate measures to minimise runoff from new urban development in the upper catchment include minimising impermeable areas, and using porous paving for the driveway, patio and paths. Runoff from roofs should be discharged into soak aways or possibly into the garden; the use of roof gutters should be restricted to where required only; there should be no connections to the stormwater system, and the discharge of stormwater into the Liesbeek or its tributaries should not be allowed. Small wetlands should be constructed in low lying areas, and grassed channels should be used, as opposed to pipes or concrete gutters, to lead water away from houses.

8.6.2 Floodplain mitigation measures

Large areas of publicly-owned land occur in the upper reaches in Boschenheuwel Arboretum. There are many opportunities, therefore, to recreate floodplain and wetland habitats. In this case, as well as in most others, an environmentally-sensitive solution demands that the cause of the problem, as well as the result, be treated. The cause of the accelerated erosion, namely the increase in stormwater runoff, should therefore be minimised at the catchment level. Furthermore, steps need to be taken to reverse incision of the channel, and to prevent further bed erosion.

The first step would be to prevent further bed degradation. This will reduce the concentration of flow in the over-large channel, and also facilitate overbank flows. Measures to achieve this include the creation of boulder step weirs (Figure 8.8). Due to the dynamic boulder nature of the river bed in this reach, and the corrosive nature of the water, the use of natural rocks is preferable to gabions.

Furthermore, the channel should be over-widened or a section excavated (Figure 8.9). Ideal sites for the location of these "secondary floodplains", are on the inside of meanders, where there are naturally lower areas, or in old meanders. A number of such sites exist within Boschenheuwel Arboretum and downstream to Paradise Road.

Figure 8.8: A number of boulder weirs should be constructed in the upper Liesbeek River to control bed degradation

Figure 8.9: Over-widening of the river channel can recreate floodplain habitat such as shown in this photograph

Restoring floodplain habitat to the upper Liesbeek should increase the diversity of the flora and fauna significantly. Due to the lack of a source of plant material, suitable indigenous vegetation would have to be established on the floodplain.

8.6.3 River channel engineering

There has been rapid bank erosion on the outside of a meander in the reach upstream from Paradise Road (Figure 8.10).

Figure 8.10: This photograph shows rapid bank erosion on the outside of a meander in the reach upstream of Paradise Road prior to rehabilitation.

The recommended method of rehabilitation would have involved regraded to at least a 1 in 4 slope and revegetating the area with appropriate indigenous riverine vegetation. In addition, boulders should also be placed at the toe of the slope to limit undercutting and erosion. Many of these measures were subsequently implemented as shown in Figure 8.11.

The above bank stabilisation has been relatively successful, even although the bank was only regraded to a slope of approximately 1 in 2. However, insufficient stabilisation of the river bed was undertaken and this is likely to threaten the stability of the slope. As described in the previous section, it is also necessary to stabilise the bed level by constructing a series of boulder weirs. This example shows that environmentally-sensitive channel engineering is easy to achieve, but that a thorough understanding of the mitigation measures and their correct application is required in order to be successful and sustainable.

Figure 8.11: The same bank after regrading, showing the establishment of indigenous vegetation and the placing of boulders

8.7 SUMMARY

This chapter has emphasised the long history of degradation of the Liesbeek River and its catchment. While early hunter-gatherers had little impact upon the landscape, stock pressure, and especially the use of fire to promote grazing, by the Khoikhoi pastoralists, resulted in degradation of the catchment. The early Colonial settlers had a greater impact as the forests were felled for timber, while the floodplains were cleared and drained for agriculture. In addition, the river channel itself was cleared repeatedly in order to prevent cattle from crossing and to reduce flooding. Furthermore, stone, sand and reeds were removed for building purposes.

During the late half of the 19th century, suburban development increased rapidly. As there was no sewerage or garbage disposal system, the Liesbeek River became an open sewer. Complaints regarding poor water quality in the Liesbeek River have been recorded since 1837. Regulations passed in 1852 aimed to improve the situation and included strict penalties. However, effluent from the breweries, tanneries, and other industries continued to pollute the river resulting in flies, mosquitoes and the spread of disease. Water quality improved with the installation of a sewage system from 1916 onwards. The abstraction of water from the river, including the inflow from Albion Spring, delayed any real improvements in water quality until the 1950's.

The lower reaches of the Liesbeek River formed extensive mudflats and estuarine wetlands in the vicinity of Paarden Eiland. Not only were the wetlands reclaimed, but the course of the river moved. The 20th century saw further urban development and associated increases in stormwater runoff. In 1917, widespread flooding resulted in damage claims by riparian landowners from the city. In consequence, the Liesbeek was canalised from Westerford bridge to Burg Road. In 1933, the Rondebosch Ratepayers Association held a petition to canalise the Liesbeek as a solution to the polluted state in summer, and flooding in winter. This led to further canalisation. In addition, in the 1950's, Liesbeek Lake was constructed and the lower reaches diverted via a canal to the Black River. The last major section of river to be canalised, that between Kildare Road and the Blue Cross Hospital, occurred in 1969. However, continuous ad hoc river bank stabilisation has been undertaken, by private landowners.

At present, the upper reaches of the Liesbeek River are subject to excessive erosion, while the lower reaches have excessive sedimentation. However, the water quality in the Liesbeek River, while not of a high standard, is likely to be better today than at any time during the last two centuries. Habitat diversity, rather than water quality, is therefore likely to be the limiting factor affecting the biodiversity of the system. This emphasises the importance of physical habitat rehabilitation.

Once viewed as a vital resource, human dependence on the Liesbeek River has decreased over time. However, enlightened attitudes towards the river by a number residents halted plans to canalise the upper reaches of the Liesbeek in the late 1950's. The following decades saw an increasing awareness of environmental issues and recognition of the importance of conservation in urban areas. In the 1980's, trails along the Liesbeek River were developed. Increasing interest in the river is reflected in the number of studies and articles published, the involvement of schools, and the formation of the "friends of the Liesbeek".

The Liesbeek, like most urban rivers, is under constant threat of further environmental degradation. Sub-division and densification threaten to increase stormwater runoff foreclosing environmentally-sensitive engineering and management of the floodplain and river channel. This is exacerbated by urban encroachment onto the floodplain, the private ownership of riparian land and the proliferation of exotic flora and fauna. Particular habitat types have been lost, including the floodplain and wetlands. At the channel level, all the "natural" sections are vulnerable to further engineering works. Measures to mitigate these threats are described as they apply to particular situations.

The final chapter contains conclusions and recommendations regarding the management of urban rivers.

CHAPTER NINE: CONCLUSIONS AND RECOMMENDATIONS

CONTENTS

CHAPTER NINE: CONCLUSIONS AND RECOMMENDATIONS

9.1 INTRODUCTION

> *"We still cling to the belief that we can ultimately manage our rivers, we should also aspire to manage our relationships with them" (Regier et al., 1989).*

This dissertation has shown that urbanisation, channelisation and canalisation have significant negative impacts on the conservation, water quality enhancement and amenity value of urban rivers. It is also demonstrated how these negative impacts can be mitigated by environmentally-sensitive river management. However, such management cannot be achieved solely by sensitive channel designs, but requires control of floodplain land use and management of the quality and quantity of stormwater runoff at a catchment level.

In addition, there is a need for multi-disciplinary planning, appropriate legislation and support from both the public and authorities. Finally, all role-players should be involved in order to reconcile the often conflicting engineering and ecological requirements in an efficient, equitable and sustainable manner which satisfies the needs and aspirations of society.

This chapter draws conclusions regarding ecological theories, and the impacts of urbanisation, channelisation and canalisation. Findings concerning the case study (the Liesbeek River) are also highlighted. Finally, some recommendations are proposed on how to achieve environmentally-sensitive river management.

9.2 ECOLOGICAL THEORY UNDERPINNING THE ASSESSMENT OF IMPACTS AND PROPOSED MITIGATION MEASURES

The ecological theory with regard to the structure and functioning of river ecosystems is complex and not yet fully developed. However, it is possible to apply this theory in order to predict the impacts which urbanisation, channelisation and canalisation are likely to have on the river ecosystem. Furthermore, these theories can be utilised to predict the benefits of environmentally-sensitive mitigation measures. The key concepts include:

- the dependence of organisms in the upper reaches on organic material produced outside the river channel;
- the dependence of downstream organisms on the processing of organic material by upstream organisms;
- the importance of flood events as reset mechanisms;
- the resilience of the riverine ecosystem and its ability to recover from disturbance or a degraded condition;
- the adaptation of organisms to the natural magnitude and frequency of the flood regime;

- that intermediate levels of disturbance result in maximum species diversity;
- that habitat heterogeneity increases species diversity;
- that the maximum number of species is synonymous with ecological integrity and should be the aim of ecological river management; and
- that the river ecosystem is determined by abiotic factors, including flow velocity, substrate composition, and water quality; rather than biotic factors.

9.3 THE IMPACTS OF URBANISATION, CHANNELISATION AND CANALISATION ON THE RECEIVING RIVER

The following three sub-sections describe the impacts of urbanisation, channelisation and canalisation on the receiving river system. Furthermore, potential mitigation measures are listed in italics below each impact. Table 9.1 highlights the impacts, while Table 9.2 describes potential mitigation measures.

9.3.1 Urbanisation

The effect of urbanisation is :

- to increase flood peaks
  (*on-site retention and detention; for example, permeable paving, grass channels, storing water on flat roofs, detention ponds*);
- initially to increase sediment production
  (*on-site retention and detention of stormwater runoff and the application of an environmental management programme during the construction phase*);
- to decrease sediment production relative to discharge once the construction phase is complete
  (*maintaining the balance by limiting the increase in discharge*);
- to degrade the water quality
  (*retention, enforcement of standards, education, riparian and aquatic vegetation*).

9.3.2 Channelisation

The effect of channelisation is :

- to reduce substratum diversity, and therefore flow diversity
  (*instream habitat structures, aquatic and riparian vegetation, meandering alignment*);
- to increase flow velocity resulting in accelerated erosion
  (*aquatic and riparian vegetation, bank stabilisation, grade control structures, widening of channel*);
- to reduce the level of the water table
  (*grade control structures*);

- to reduce the area of instream and riparian habitat
(*reinstating meanders, off-channel bays, wetlands, ponds, etc.*);
- to reduce the area of floodplain habitat
(*land-use controls, re-connecting with channel, reinstating meanders, off-channel bays, wetlands, ponds, grade control structures*);
- to remove and reduce the abundance of aquatic and riparian plants
(*minimising maintenance, plant vegetation, bioengineering, single bank modification, etc.*).

9.3.3 Canalisation

The effect of canalisation is :

- effectively to eliminate instream and riparian habitat
(*planting trays, cores, rest stops, weirs, introduce substrate, instream habitat devices, etc.*);
- effectively to eliminate interaction with hyporheos
(*cores, rest stops, alternative bank and bed materials*);
- to increase flow velocity so that the natural suite of plants and animals cannot survive
(*instream habitat structures, weirs, boulders, substrate, over-design, etc*);
- to provide a uniform substrata and little flow diversity, thereby limiting biodiversity
(*instream habitat structures, weirs, boulders, substrate, over-design, etc.*);
- to prevent the establishment of plants
(*allowing sediment to accumulate, silt traps, bioengineering, alternative bank and bed materials, rest stops, cores*);
- to limit the retention of leaves or sediment
(*providing boulders, instream habitat structures, weirs, coarse substrate*);

9.4 CONCLUSIONS DRAWN FROM THE CASE STUDY ON THE LIESBEEK RIVER

The key findings are summarised concerning the case study of the Liesbeek River system, and it was concluded that :

- the river has a long history of disturbance and degradation, including floodplain clearing and channel modification;
- water pollution from sewage and industrial effluents was exacerbated by abstraction of Albion Spring water for breweries, mineral water and municipal water supply until the late 1920's;
- much of river was canalised between 1940 to 1970;
- increasing environmental awareness could contribute towards the adoption of environmentally-sensitive management measures;
- there are a number of threats to the river, including further hardening of the upper catchment, due to subdivision of land;

- in the absence of strong public support advocacy, it is likely that the amenity and especially the ecological integrity, of the Liesbeek River will deteriorate further;
- the absence of stormwater retention at the catchment level precludes the adoption of environmentally-sensitive options at the level of the floodplain and channel;
- physical habitat diversity, due to canalisation and not poor water quality, is likely to be the limiting factor determining the biodiversity of the Liesbeek. This emphasises the importance of physical habitat rehabilitation;
- increasing awareness of environmental issues and recognition of the importance of conservation in urban areas could facilitate rehabilitation of the Liesbeek River;
- environmentally-sensitive river management measures at the catchment, floodplain and river channel levels are available and should be implemented.

9.5 RECOMMENDATIONS

Environmentally-sensitive river management aims to avoid the cycle of degradation typically associated with rivers draining urban areas and to reverse such degradation which has already occurred. It stresses that urban rivers should be managed for their conservation, amenity, water quality and stormwater conduit functions. In an environmentally-sensitive approach it is recommended that a number of steps be taken at the catchment, floodplain and river channel levels.

9.5.1 Catchment and floodplain level

Firstly, at the catchment level, means to minimise the increase in stormwater runoff and the degradation of water quality are required. Secondly, sensitive treatment of the floodplain requires controlling urban development and reserving flood-prone land for conservation, amenity and stormwater attenuation functions.

If these two recommendations are successful, then the necessity to modify the river channel is minimised and a relatively natural, or environmentally-sensitive, river channel can be achieved. However, if the increase in flood peaks cannot be satisfactorily mitigated, then increasingly "hard" or environmentally-unsensitive engineering of the river channel would be required.

9.5.2 River channel level

It is recommended that environmentally-sensitive river channel management :

- maximises the heterogeneity of current velocity by maximising substratum diversity;
- maintains flows of water, nutrients and organisms between the river channel, the hyporheos and the ground water;
- maintains relatively natural water retention times to improve biological functioning and hence water quality;
- maximises the area of aquatic, riparian and floodplain habitat;

- manages rivers during the quasi-equilibrium conditions between major channel forming flood events;
- maintains disturbance within the natural range of frequency and magnitude of disturbance events, so not as to exceed the natural biota's resilience;
- maximises the diversity of physical habitat (flow and substratum) as it will maximise species diversity (the goal of ecological river management);
- avoids the engineering of rivers so that they look and function like drains, as this results in a spiral of degradation which also impacts on downstream reaches and users, the estuary and the marine environment; and
- maximises the aesthetic and water quality enhancement functions of aquatic ecosystems.

9.5.3 General recommendations

This dissertation has highlighted the complexity of riverine ecosystems and subsequently, the prediction of impacts, let alone their quantification, is difficult. It is therefore recommended that further research, experimentation and monitoring of urban rivers be undertaken in order to gain a clearer understanding of the impacts.

Numerous environmentally-sensitive mitigation measures at the catchment, floodplain and river channel levels have been described in Chapters Six and Seven. Ecological theory has shown that these measures should improve the environmental and ecological value of urban rivers. It is therefore recommended that particular mitigation measures be selected and implemented on a pilot project basis so that the benefits can be assessed and the designs optimised.

Urban rivers cannot be pristine and they require human intervention or management. How they are managed will determine whether they become assets or liabilities to society.

BIBLIOGRAPHY

BIBLIOGRAPHY

Anon (1985): Detention/retention drainage cuts costs for Boksburg, *Municipal Engineer*, March/April, 16(2), 37.

Anon (1989): Cape Town tames the Diep River floods, *Municipal Engineer*, April, 47-48.

Anon (1994a): Stormwater masterplan for Verwoerdburg, *Municipal Engineer*, 25(1), 16.

Anon (1994b): Flood danger in urban areas, *Municipal Engineer*, 25(1), 18-21.

Anon (1994c): Water and the environment, *Municipal Engineer*, 25(1), 34.

Aldrich, R.B. (1993): Design of aquatic treatment systems, 742-746, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Alexander, W.J.R. (1976): *An introduction to river mechanics and channel stabilisation*, Department of Water Affairs, Division of Hydrology, Technical Note 70, March 1976, 42pp.

Alexander, W.J.R. (1985): Hydrology of low latitude Southern Hemisphere land masses, *Hydrobiologia*, 125, 75-83.

Allanson, B.R. (1975): *Planning for environmental conservation in water areas: Ecology of water areas*, Dept of Zoology and Entomology, Rhodes University, Grahamstown.

Allanson, B.R. and Rabie, M.A. (1983): Freshwater systems, 237-259, In: Fuggle, R.F. and Rabie, M.A. (eds): *Environmental concerns in South Africa - Technical and legal perspectives*, Juta, Cape Town.

Allanson, B.R., Hart, R.C., O'Keeffe, J.H. and Robarts, R.D. (1990): *Inland waters of southern Africa: An ecological perspective*, Kluwer, The Netherlands.

Allen, H.H. (1982a): *Nonstructural streambank erosion protection measures - Planted vegetation*, Unpublished paper, Lecture F-3.

Allen, H.H. (1982b): *Nonstructural streambank erosion protection measures - Management of native vegetation*, Unpublished paper, Lecture F-4.

Anderson, D. (1989): Our rivers and streams - do we deserve them?, *Landscape Australia*, 4/89, 348-354.

Andrews, W.A. (ed) (1972): *A guide to the study of freshwater ecology*, Prentice-Hall, New Jersey, United States of America.

Andrews, E. (1989): Assessment of the value of rivers for otters (Lutra lutra), *Regulated Rivers: Research and Management*, 4(2), 199-202.

Aoyama, I. and Nishizaki, H. (1993): Uptake of nitrogen and phosphate, and water purification by water hyacinth *Eichhornia crassipes* (Mart.) solms., *Water Science and Technology*, 28(7), 47-53.

Argue, J.R. (1994): A new streetscape for stormwater management in Mediterranean-climate cities: the concept explored, *Water Science and Technology*, 30(1), 23-32.

Armitage, P.D. (1989): The application of a classification and prediction technique based on macroinvertebrates to assess the effects of river regulation, 267-294, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida.

Arthington, A.H., King, J.M., O'Keeffe, J.H., Bunn, S.E., Day, J.A., Pursey, B.J., Bluhdorn, D.R. and Tharme, R. (1991): Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems, 69-76, In: Pigram, J.J. and Hooper, B.P. (eds): *Water allocation for the environment, Proceedings of an international seminar and workshop*, The Centre for Water Policy Research, University of New England, Armidale.

Ash, J.R.V. and Woodcock, E.P. (1988): The operational use of river corridor surveys in river management, *Water and Environmental Management,* 2(4), 423-428.

Ashton, P.J., Appleton, C.C. and Jackson, P.B.N. (1986): Ecological impacts and economic consequences of alien invasive organisms in southern African aquatic ecosystems, 247-260, In: Macdonald, I.A.W, Kruger, F.J. and Ferrar, A.A. (eds): *The ecology and management of biological invasions in southern Africa*, Proceedings of the National Synthesis Symposium on the ecology of biological invasions, Oxford University Press, Cape Town.

Baker, R. (1990): Precast concrete blocks for high-velocity flow applications, *Water and Environmental Management,* 4(6), 552-557.

Barmuta, L.A, Marchant, R. and Lake, P.S. (1992): Degradation of Australian streams and progress towards conservation and management in Victoria, In: Boon, P.J., Calow, P and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Barnard, J.R. (1978): Externalities for urban growth: the case of increased storm runoff and flooding, *Land Economics*, 54(3), 298-315.

Bames, J.R. and Minshall, G.W. (eds)(1983): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York, 399pp.

Barnes, R.S.K. and Mann, K.H. (eds)(1980): *Fundamentals of aquatic ecosystems*, Blackwell Scientific Publishers, Great Britain.

Bames, R.S.K and Mann, K.H. (eds)(1991): *Fundamentals of aquatic ecology*, second edition, Blackwell Scientific Publishers, Great Britain, 270pp.

Barneveld, H.J., Nieuwkamer, R.L.J. and Klaassen, G.J. (1994): Secondary channels: opportunities for and limitations of habitat restoration, In: Van de Kraats, J.A. (ed): Rehabilitation of the River Rhine. *Water Science and Technology*, 29(3).

Barrett, S.C.H. (1989): Waterweed invasions, *Scientific American*, October, 90-97.

Bath, A.J. and Marias, G.V.R. (1993): Phosphorus export from nonpoint sources in the Berg River, Western Cape Province, South Africa, *Water Science and Technology*, 28(3-5), 713-718.

Baumli, G.R. (1993): Water management by endangered species, 320-323, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Beanlands, G.E. and Duinker, P.N. (1983): *An ecological framework for environmental impact assessment in Canada*, Institute for Resource and Environmental Studies Dalhousie University and Federal Environmental Assessment Review Office, Nova Scotia, 132pp.

Beaumont, R.D. (1981): The effects of land-use changes on the stability of the Hout Bay River, *Municipal Engineer*, March/April, 79-89.

Beaumont, R.D. (1986): Water in the environment, *Landscape Southern Africa*, November 1986, 33-35.

Beaumont, R.D. (1988): Urban river systems, *IMIESA*, March 1988, 11-17.

Beaumont, R.D. (1989): *Engineering of rivers - what is good and what is bad engineering practice?*, Paper delivered at the Metropolitan Open Space System Symposium, 25 August 1989, Pinetown, 9pp.

Beaumont, R.D. and Heydenrych, P.J. (1980): The effects of development on the Diep River estuarine system near Cape Town, *S.A. Waterbulletin*, April, 10-18.

Beck, M.B, Chen, J. , Saul, A.J. and Butler, D. (1994): Urban drainage in the 21st century: assessment of new technology on the basis of global material flows. *Water Science and Technology*, 30(2), 1-12.

Beers, G.D. (1973): *Management of storm water runoff in suburban environments*, Office of Water Resources Research, US Dept. of the Interior.

Begg, G. (1986): *The wetlands of Natal (Part 1)*, Natal town and regional planning report, vol 68.

Bell, D.T. and Smith, R.H. (1978): Hickory Creek dry reservoir: a compromise design for both flood control and natural area protection, *Water Resources Bulletin* (Urbana Ill.), 14(1), 119-132.

Berger, J.J. (ed)(1990): *Environmental restoration: Science and strategies for restoring the earth*, Papers from Restoring the Earth Conference, University of California, Berkeley, Island Press, Washington, 398pp.

Berry, B.J.L. and Horton, F.E. (1974): *Urban environmental management: Planning for pollution control*, Prentice-Hall, New Jersey.

Beschta, R.L. and Platts, W.S. (1986): Morphological features of small streams: significance and function, *Water Resources Bulletin*, June, 22(3), 369-379.

Best, G.A. and Ross, S.L. (1977): *River pollution studies*, Liverpool University Press, Great Britain.

Beven, K. and Carling, P. (eds)(1989): *Floods: Hydrological, sedimentological and geomorphological implications*, John Wiley and Sons, Great Britain.

Binder, W., Jürging, P. and Karl, J. (1983): Natural river engineering - characteristics and limitations, *Garten und Landschaft*, 2/83, 91-94.

Bingham, A. (1985): Singapore traps urban run-off, *World Water*, May, 33-35.

Bird, G.A. and Kaushik, N.K. (1981): Coarse particulate organic matter in streams, In: Lock, M.A. and Williams, D.D. (eds): *Perspectives in running water ecology*, Plenum, New York.

Bjork, J.C. and Way, A.W. (1993): Juanita Creek channel restoration King County, Washington, 92-95, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Boddington, G. (1989): Cape Town's drainage and sewerage by-laws and its relationship to water quality control, *South African Journal of Aquatic Sciences*, 16(2), 258-269.

Boon, P.J. (1988): The impact of river regulation on the invertebrate communities in the U.K., *Regulated Rivers: Research and Management*, 2(3), 389-410.

Boon, P.J. (1992a): Essential elements in the case for river conservation, In: Boon, P.J., Calow, P and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Boon, P.J. (1992b): Channelling scientific information for the conservation and management of rivers, *Aquatic Conservation: Marine and freshwater ecosystems*, 2(1), 115-123.

Boon, P.J., Calow, P and Petts, G.E. (1992): *River conservation and management*, John Wiley and Sons, England.

Borchardt, D. (1993): Effects of flow and refugia on drift loss of benthic macroinvertebrates: implications for habitat restoration in lowland streams, *Freshwater Biology*, 29(2), 221-228.

Bosman, E.J. (1983): *Stedelike vloedwaterbeheer - aantekeninge oor die praktiese aanwending van 'n vloedwaterbeheerstelsel*, (Urban stormwater management in SA - Notes on the practical application of a stormwater management system), Paper presented at the Winter School of the SA Institute of Civil Engineers, Pretoria, 27-30 June, 1983, 23pp.

Bott, T.L. (1983): Primary productivity in streams, 29-54, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Bottaro, J.A. (1996): The changing history of the Liesbeek River valley: an investigation of the use of an environmental history approach in historical research and in classroom practice, Unpublished M.Ed thesis, University of Cape Town.

Boulton, A.J. and Lloyd, L.N. (1991): Macroinvertebrate assemblages in floodplain habitats of the Lower River Murray, South Australia, *Regulated Rivers: Research and Management*, 6(3), 183-202.

Bowie, A.J. (1982): Investigations of vegetation for stabilizing eroding streambanks, *Transactions of the ASAE*, 1601-1611.

Bradshaw, A.D. (1987): Restoration: an acid test for ecology, In: Jordan, W.R. (III), Gilpin, M.E. and Aber, J.D. (eds): *Restoration ecology, a synthetic approach to ecological research*, Cambridge University Press, Great Britain.

Braune, E. (ed)(1984): *Integrated catchment management: approaches and information requirements based on pilot study in the Upper-Mooi/Mgeni catchments*, Hydrological Research Institute, Department of Environment Affairs.

Bravard, J.P., Amoros, C. and Pautou, G. (1986): Impact of civil engineering works on the successions of communities in a fluvial system, *OIKOS*, 47(1), 92-111.

Breen, P.F. (1990): A mass balance method for assessing the potential of artificial wetlands for wastewater treatment, *Wat. Res.*, 24 (6), 689-697.

Briggs, D. and Smithson, P. (1986): *Fundamentals of physical geography*, Hutchinson, Great Britain, 558pp.

Britton, D.L. (1990): Fire and the dynamics of allochthonous detritus in a South African mountain stream, *Hydrobiologia*, 218, 177-192.

Brooker, M.P. (1985): The ecological effects of channelization, *The Geographical Journal*, 151(1), 63-69.

Brookes, A. (1985): Downstream morphological consequences of river channelization in England and Wales, *The Geographical Journal*, 151(1), 57-62.

Brookes, A. (1986): Responce of aquatic vegetation to sedimentation downstream from river channelisation works in England and Wales, *Biological Conservation*, 38(4), 351-367.

Brookes, A. (1987a): Recovery and adjustment of aquatic vegetation within channelization works in England and Wales, *Journal of Environmental Management,* 24, 365-382.

Brookes, A. (1987b): The distribution and management of channelized streams in Denmark, *Regulated Rivers: Research and Management*, 1(1), 3-16.

Brookes, A. (1988): *Channelized rivers - perspectives for environmental management*, John Wiley, Great Britain, 326pp.

Brookes, A. (1989): Alternative channelization procedures, 139-162, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida.

Brookes, A. (1990): Restoration and enhancement of engineered river channels: some European experiences, *Regulated Rivers: Research and Management*, 5(1), 45-56.

Brookes, A. (1992): Recovery and restoration of some engineered British channels, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Brookes, A. and Hanbury, R.G. (1990): *Environmental impacts on navigable river and canal systems: a review of the British experience*, Unpublished, 91-103.

Brookes, A. and Gregory, K. (1988): Channelization, river engineering and geomorphology, 145-167, In: Hooke, J.M. (ed): *Geomorphology in environmental planning*, John Wiley and Sons, Chichester.

Brown, A.L. (1971): *Ecology of fresh water*, Heinemann Educational Books, London, 129pp.

Bruce, J.P. and Clark, R.H. (1975): *Introduction to hydrology*, Pergamon, Great Britain.

Brumback, B.C. and Brumback, R.A. (1984): Land acquisition for restoration and protection, 306-311, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Brundtland, G.H. (1987): *Our common future*, Report of the World Commission on Environment and Development, Oxford University Press, Oxford.

Brussock, P.P., Brown, A.V. and Dixon, J.C. (1985): Channel form and stream ecosystem models, *Water Resources Bulletin*, 21(5), 859-866.

Bruton, M.N. (1986): The life history styles of invasive fishes in southern Africa, 201-208, In: Macdonald, I.A.W, Kruger, F.J. and Ferrar, A.A. (eds): *The ecology and management of biological invasions in southern Africa*, Proceedings of the National Synthesis Symposium on the ecology of biological invasions, Oxford University Press, Cape Town.

Bruton, M.N. and Van As, J.G. (1986): Faunal invasions of aquatic ecosystems in southern Africa, with suggestions for their management, 47-62, In: Macdonald, I.A.W, Kruger, F.J. and Ferrar, A.A. (eds): *The ecology and management of biological invasions in southern Africa*, Proceedings of the National Synthesis Symposium on the ecology of biological invasions, Oxford University Press, Cape Town.

Bruwer, C.A. (1979): *The economic impact of eutrophication in South Africa*, Technical Report No. TR 94, Hydrological Research Institute, Department of Water Affairs, Pretoria, 48pp.

Buckner, D.L. and Wheeler, R.L. (1984): Construction of cattail wetlands along the east slope of the front range in Colorado, 258-264, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Burman, J. (1962): *Safe to the sea*, Human and Rousseau, Cape Town, 167pp.

Burman, J. (1970): *Waters of the western Cape*, Human and Rousseau, Cape Town, 176pp.

Burt, T.P. (1992): The hydrology of headwater catchments, 3-28, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Butler, M.G. (1984): Life histories of aquatic insects, 24-55, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Byren, B.A. (1990a): *Kuilsriver flood management study: Ecological/ Water quality aspects - Driftsands detention dam*, Final report no. 1: June.

Byren, B.A. (1990b): *Kuilsriver flood management study: Ecological/ Water quality aspects.-* Kuilsriver catchment, Final report no. 2: August.

Cairns, J. (Jr.)(1991): The status of the theoretical and applied science of restoration ecology, *The Environmental Professional*, 13, 186-194.

Cairns, J. (Jr) and Pratt, J.R. (1986): On the relation between structural and functional analysis of ecosystems, *Environmental toxicology and chemistry*, 5, 785-786.

Canter, L.W. (1985): *Environmental impact of water resources projects*, Lewis Publishers, United States of America.

Cape Metropolitan Council (1996). *Metropolitan spatial development framework. A guide for spatial development in the Cape Metropolitan Functional Region.* Technical report, April 1996.

Cape Town City Council (1982): *Greening the city: Open space and recreation plan for Cape Town*, City Engineers Department, Report No. 214/1982, Cape Town.

Cape Town City Council (1985): *Greening the city: Stormwater Drainage Report (Draft)*, City Engineers Department, Cape Town.

Cape Town City Council (1988): Integrated catchment management programme becoming a reality at Zandvlei, City Engineer's Department and City Planner's Department, SA Waterbulletin, Aug/Sept 1988, In: *Fifth South African National Hydrological Symposium*, Urban Catchment Tour, November, 1991.

Cape Town City Council, (1989): Diep River/ Sand River flood control scheme, City Engineers Annual Report 1988/1989, In: *Fifth South African National Hydrological Symposium*, Urban Catchment Tour, November, 1991.

Carling, P. (1989): The well-being of Britain's water, *Landscape Design*, 182, July/August, 23-24.

Carter, C.A. and Ritchie, A.J. (1985): Stormwater master planning, *Municipal Engineer*, January/ February, 16(1), 30-32.

Chang, H.H. (1988): *Fluvial processes in river engineering*, John Wiley and Sons, New York.

Chapman, D. (ed)(1992): *Water quality assessments*, Chapman and Hall, London, 585pp.

Chorley, R.J. (ed) (1974): *Introduction to geographical hydrology*, Methuen, London.

Chorley, R.J. (ed) (1976): *Introduction to physical hydrology*, Methuen, London.

Chunnett, E.P. (1969): *River meanders and man's endeavours, Progress in river engineering*, The S.A. Institute of Civil Engineers, Hydraulics Division, Papers presented at the River Engineering Symposium, University of Natal, July, 1969.

Church, M. (1992): Channel morphology and typology, 126-143, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Chutter, F.M. (1969): The effects of silt and sand on the invertebrate fauna of streams and rivers, *Hydrobiologia*, 34, 57-76.

Chutter, F.M. (1972): An empirical biotic index of the quality of water in South African streams and rivers, *Water Research*, 6, 19-30.

Chutter, F.M. (1985): Seasonality/aseasonality: chairman's summary, *Hydrobiologia*, 125, 191-194.

Chutter, F.M. (1991): *Biological monitoring of water quality - a new approach*, Seminar and workshop on environmental waste management and technology, 22-24 October, 1991, 229-240, The S.A. Institution of mechanical engineers institute of waste management, South Africa.

Cocks, J. (1993): A fishway on the Nokomi, *New Zealand Engineering*, March, 18-20.

Coffman, L., Green, R., Clar, M. and Bitter, S. (1993): Design considerations associated with bioretention practices, 130-133, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Coffman, L., Green, R., Clar, M. and Bitter, S. (1993): Development of bioretention practices for stormwater management, 126-129, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Coleman, T.J. and Simpson, D.E. (1996): *Adaptation and calibration of an urban runoff quality model*. Water Research Commission, WRC report no. 299/1/96, ISBN 1 86845 205 0.

Coles, T.F., Southey, J.M., Forbes, I. and Clough, T. (1989): River wildlife databases and their value for sensitive environmental management, *Regulated Rivers: Research and Management*, 4(2), 179-190.

Connell, J.H. (1978): Diversity in tropical rain forests and coral reefs, *Science*, 199, 1302-1310.

Cooke, R.U. and Doornkamp, J.C. (1978): *Geomorphology in environmental management - an introduction*, Clarendon, Oxford.

Copp, G.H. (1991): Typology of aquatic habitats in the Great Ouse, a small regulated lowland river, *Regulated Rivers: Research and Management*, 6(2), 125-134.

Costa, J.E. and Fleisher, P.J. (eds)(1984): *Developments and applications of geomorphology*, Springer-Verlag, Berlin.

Council for the Environment (1989): *Guidelines for the planning and management of natural open space in urban areas*, Council for the Environment, Department of Environment Affairs, Joan Lötter, Pretoria.

Coyle, K.J. (1993): The new advocacy for aquatic species conservation, *Journal of the North American Benthological Society*, 12(2), 185-188.

Creuze Des Chatelliers, M. and Reygrobellet, J.L. (1990): Interactions between geomorphological processes, benthic and hyporheic communities: first results on a by-passed canal of the French Upper Rhône River, *Regulated Rivers: Research and Management*, 5(2), 139-158.

Crickmay, C.H. (1974): *The work of the river*, Macmillan Press, London, 271pp.

Cross, H.C., Wettin, P.D. and Keenan, F.M. (1991): Corridors for wetland conservation and management? Room for conjecture, 159-165, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

Cummins, K.W. (1974): Structure and function of stream ecosystems, *BioScience*, 24(11), 631-641.

Cummins, K.W. (1979): The natural stream ecosystem, 7-24, In: Ward, J.V. and Stanford, J.A (eds): *The ecology of regulated streams*, Proceedings of the First International Symposium on Regulated Streams, Plenum Press, New York.

Cummins, K.W. (1992): Catchment characteristics and river ecosystems, In Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Cummins, K.W. (1992): Invertebrates, 234-250, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Cummins, K.W., Minshall, G.W., Sedell, J.R., Cushing, C.E. and Petersen, R.C. (1984): Stream ecosystem theory, *Verh. Internat. Verein. Limnol,.* 22(3), 1818-1827.

Dallas, H.F. and Day, J.A. (1993): *The effect of water quality variables on riverine ecosystems: a review*, Water Research Commission, TT 61/93, 240pp.

Dalton-Morgan, J., Rowe, K.A. and Walker, K. (1992): *River Torrens faunal survey*, Report to Land Systems EBC, Adelaide, 17pp.

Dance, K.W. (1981): Seasonal aspects of transport of organic and inorganic matter in streams, In: Lock, M.A. and Williams, D.D. (eds): *Perspectives in running water ecology*, Plenum, New York.

Dansereau, P. (ed) (1970): *Challenge for survival: Land, air, and water for man in megalopolis*, Columbia University Press, New York.

Davies, B.R. (1979): Stream regulation in Africa: A review, 113-142, In: Ward, J.V. and Stanford, J.A. (eds): *The ecology of regulated streams*, Proceedings of the First International Symposium on Regulated Streams, Pennsylvania, Plenum Press, New York.

Davies, B.R. and Behrens, T. (1995): *Landscaping and ecological rehabilitation of an urban riverway: the Liesbeek River, Albion Springs, Rondebosch.* Interim report to the City of Cape Town, City Planner's Department by the Freshwater Research Unit, June.

Davies, B.R. and Day, J.A. (1986): *The biology and conservation of South Africa's vanishing waters*, The centre for Extra-Mural Studies, University of Cape Town, and the Wildlife Society of Southern Africa, Western Cape Branch, Cape Town, 186pp.

Davies, B.R. and Hart, R.C. (undated): Invertebrates, In: Symoens, J.J., Burgis, M. and Gaudet, J.J. (eds): *The ecology and utilization of African inland waters*, United Nations Environment Programme, Reports and Proceedings Series 1.

Davies, B.R. and Luger, M.K. (1993): The plight of an urban river, *Earthyear*, 6, 18-21.

Davies, B.R. and Walker, K.F. (eds)(1986): *The ecology of river systems*, Junk, The Netherlands, 793pp.

Davies, B.R. and Walmsley, R.D. (eds) (1985): *Perspectives in Southern Hemisphere Limnology*, Proceedings of a symposium, held in Wilderness, South Africa, July 3-13, 1984, (Developments in Hydrobiology 28), Reprinted from, *Hydrobiologia*, 125 (1985), Junk, Dordrecht.

Davies, B.R., O'Keeffe, J.H. and Snaddon, C.D. (1993): *A synthesis of the ecological functioning, conservation and management of South African river ecosystems*, Water Research Commission, Report No. TT 62/93, 232pp.

Day, J.A. (1995): *Liesbeek River - A report on the state of the river.* May 1995 for the City Planners Department.

Day, J.A., Siegfried, W.R., Louw, G.N. and Jarman, M.L. (eds) (1979): *Fynbos ecology: a preliminary synthesis*, South African National Scientific Programmes Report Number 40, CSIR, Pretoria.

Dawson, F.H. (1978): Aquatic plant management in semi-natural streams: the role of marginal vegetation, *Journal of Environmental Management*, 6, 213-221.

Dearsley, A.F. (1984): *Environmentally sensitive techniques for river flood alleviation*, Winston Churchill Memorial Trust, Travelling Fellowships, 1983, 90pp.

de Jong, J. and de Wit, J.A.W. (1994): Conclusions and recommendations of the International Conference on Rehabilitation of the River Rhine, March 15-19, 1993, Arnhem, The Netherlands, 387-390, In: Van de Kraats, J.A. (ed): Rehabilitation of the River Rhine, *Water Science and Technology*, 29(3).

de Moor, I.J. and Bruton, M.N. (eds)(1989): *The management of invasive aquatic animals in southern Africa*, Proceedings of a symposium organised by the Foundation for Research Development in collaboration with the JLB Smith Institute of Ichthyology, CSIR Occasional Report No. 44, Republic of South Africa, 118pp.

Denning, J. (1994): When the levee breaks, *Civil Engineering*, 64(1), 38-41.

Department of Community Development (1983): *Guidelines for the provision of engineering services in residential townships*, Department of Community Development, Pretoria, Part D: Urban Stormwater Management.

Department of Development Planning (1988): *Cape Metropolitan Guide Plan: Volume 1: Peninsula*, Government Printer, Pretoria.

Department of Environment Affairs (1992): *The Integrated Environmental Management Guideline Series.*

Department of Water Affairs (1986): *Management of the water resources of the Republic of South Africa*, Department of Water Affairs, Pretoria.

Department of Water Affairs and Forestry (1995). *Scope and function of water boards.* Discussion document. Steward Scott Inc. in association with Coopers & Lybrand and Afrosearch. August 1995.

Department of Water Affairs and Forestry (1996a): *Water law principles.* Document for discussion. April 1996.

Department of Water Affairs and Forestry (1996b). *Workshop on institutional arrangements and enabling legislation for integrated river basin management.* 23-24 February 1996. Constantia conference centre, Midrand.

Diamant, R., Eugster, J.G. and Duerksen, C.J. (1984): *A citizen's guide to river conservation*, The Conservation Foundation, Washington.

Diamond, J. (1987): Reflections on goals and on the relationship between theory and practice, In: Jordan, W.R. (III), Gilpin, M.E. and Aber, J.D. (eds): *Restoration ecology, a synthetic approach to ecological research*, Cambridge University Press, Great Britain.

Dissner, D. (1993): Storm water utility experience in Bellevue, Washington, 817-820, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Dinges, R. (1982): *Natural systems for water pollution control*, Van Nostrand Reinhold, New York.

Downes, B.J., Lake, P.S. and Schreiber, E.S.G. (1993): Spatial variation in the distribution of stream invertebrates: implications of patchiness for models of community organization, *Freshwater Biology*, 30, 119-132.

Drews, R.J.L.C. (1983): *Pond systems for the purification and disposal of domestic wastewater from small communities: Use, design, operation and maintenance*, Technical guide K69, National Institute for Water Research, CSIR, Pretoria.

Duda, A.M., Lenat, D.R. and Penrose, D.L. (1982): Water quality in urban streams - what we can expect, *Journal of the Water Pollution Control Federation*, 54(7), 1139-1147.

Duda, A.M. (1993): Addressing nonpoint sources of water pollution must become an international priority, *Water Science and Technology*, 28(3-5), 1-12.

Dudgeon, D. (1989): The influence of riparian vegetation on the functional organization of four Hong Kong stream communities, *Hydrobiologia*, 179: 183-194.

Duel, H., Specken, B.P.M., Denneman, W.D. and Kwakemaak, C. (1995): The habitat evaluation procedure as a tool for ecological rehabilitation of wetlands in the Netherlands, *Water Science and Technology*, 31(8), 387-391.

Dunne, T. and Leopold, L.B. (1978): *Water in environmental planning*, Freeman and company, San Francisco, 818pp.

Durban Focus (1986): *Nature in our city*, Durban Focus, 9, March, 3pp.

Du T de Villiers, G. and Maharaj, R. (1994): Human perceptions and responses to floods with specific reference to the 1987 flood in the Mdloti River near Durban, South Africa, *Water SA*, 20(1), 9-13.

Duvel, W.A.(Jr.), Volkmar, R.D., Specht, W.L. and Johnson, F.W (1979): Environmental impact of stream channelization, *Water Resources Bulletin*, 12(4), 799-812.

Earth, Marine and Atmospheric Science and Technology (1988): *Feasibility study into the hydraulic applications of Terraforce 'G' and 'HD' blocks*, CSIR report EMA - C 8874, Sept. 1988, 19pp.

Edwards, C.J., Hanbury, R.G. and Burt, A.J. (eds)(1987): *The ecology of the Oxford Canal (south)*, A British Waterways Board Report, Environmental Advisory Unit, 185pp.

Edwards, R.T., Meyer, J.L. and Findlay, S.E.G. (1990): The relative contribution of benthic and suspended bacteria to system biomass, production, and metabolism in a low-gradient blackwater river, *Journal of the North American Benthological Society*, 9(3), 216-228.

Ellis, J.B. (1989): The management and control of urban runoff quality, *Water and Environmental Management,* 3(2), 116-124.

Emerson, J.W. (1971): Channelization: a case study, *Science*, 173, 325-326.

Emmerling-DiNovo, C. (1995): Stormwater detention basins and residential locational decisions, *Water Resources Bulletin*, 31(3), 515-521.

Ennis, D.B., Clar, M.L. and Coffman, L.S. (1993): The Kettering Community demonstration project non-point pollution control and environmental enhancement program, 778-781, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Ethier, W.H. (1993): New wetlands standards - providing great tools for policy makers, *ASTM Standardization News*, April, 26-29.

Everett, P. (1980): *Biological monitoring of freshwater streams*, Wildlife Society of Southern Africa, Linden.

Exton, D.M. and Crompton, J.L. (1990): The use of audit surveys in river maintenance, *Water and Environmental Management,* 4(6), 524-529.

Falkenmark, M. (1986): Fresh water - time for a modified approach, AMBIO 15(4), 192-200.

Ferrar, A.A. (ed)(1989): *Ecological flow requirements for South African rivers*, South African National Scientific Programmes Report Number 162, CSIR, Pretoria, 121pp.

Field, R. (1987): Urban stormwater management, legislation is necessary, 363-364, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Fisher, S.G. (1983): Succession in streams, 7-28, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Fisher, S.G. (1990): Recovery processes in lotic ecosystems: limits of successional theory, *Environmental Management*, 14(5), 725-736.

Fleckseder, H., Hausperger, M. and Kadrnoska, H. (1993): Liesing Creek - sewerage and wastewater treatment in the context of river restoration in Southern Vienna, Austria, *Water Science and Technology*, 27(12), 237-240.

Fox, A.M. (1992): Macrophytes, 216-233, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Frissell, C.A., Liss, W.J., Warren, C.E. and Hurley, M.D. (1986): A hierarchical framework for stream habitat classification: viewing streams in a watershed context, *Environmental Management*, 10(2), 199-214.

Fuchs, U. and Statzner, B. (1990): Time scales for the recovery potential of river communities after restoration: lessons to be learned from smaller streams, *Regulated Rivers: Research and Management*, 5(1), 77-88.

Fuggle, R.F. and Rabie, M.A. (eds)(1983): *Environmental concerns in South Africa - Technical and legal perspectives*, Juta, Cape Town, 587pp.

Fuggle, R.F. and Rabie, M.A. (eds)(1992): *Environmental management in South Africa*, Juta, Cape Town.

Fujita, S. (1994): Infiltration structures in Tokyo, *Water Science and Technology*, 30(1), 33-41.

Furness, H.D. (1983): Wetlands as accreting systems: inorganic sediments, *J. Limnol. Soc. sth. Afr.*, 9(2), 90-95.

Galloway, G.E. (1995): New directions in floodplain management. *Water Resources Bulletin*, 31(3), p 351-357.

Gardiner, J.L. (1988): Environmentally sound river engineering - examples from the Thames Catchment, *Regulated Rivers: Research and Management*, 2(3), 445-469.

Gardiner, J.L. (1990): River catchment planning for land drainage, flood defence and the environment, *Water and Environmental Management,* 4(5), 442-450.

Gardiner, J.L. (ed)(1991): *River projects and conservation: a manual for holistic appraisal*, John Wiley and Sons, Chichester, 272pp.

Gardiner, J.L and Cole, L. (1992): Catchment planning: the way forward for river protection in the UK, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Gardiner, J.L., Dearsley, A.F. and Woolnough, J.R. (1987): The appraisal of environmentally sensitive options for flood alleviation using mathematical modelling, *Water and Environmental Management,* 1(2), 171-184.

Gasson, B. (1980): *The future management of False Bay*, False Bay Conservation Society, Cape Town.

Gehrels, J. and Mulamoottil, G. (1989): The transformation and export of phosphorus from wetlands, *Hydrological processes*, 3, 365-370.

Genetti, A.J. (Jr.)(ed.)(1989): *Environmental engineering and local flood control channels*, US Army Corps of Engineers, Engineer Manual, No. 1110-2-1205, Engineering and Design, November 1989, Washington, 86pp.

Gillette, R. (1972): Stream channelization: conflict between ditchers, conservationists, *Science*, 176, 890-894.

Goldman, C.R. and Horne, A.J. (1983): *Limnology*, McGraw-Hill, United States of America.

Gomez, B. (1984): Typology of segregated (armoured/paved) surfaces: some comments, *Earth Surface Processes and Landforms*, 9, 19-24.

Gordon, D. (ed)(1990): *Green cities - ecologically sound approaches to urban space*, Black Rose, Canada.

Gordon, N.D., McMahon, T.A. and Finlayson, B.L. (1992): *Stream hydrology: an introduction for ecologists*, John Wiley and Sons, England, 526pp.

Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts, 280pp.

Gore, J.A. (1985): Mechanisms of colonization and habitat enhancement for benthic macroinvertebrates in restored river channels, 81-102, In: Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Gore, J.A. (1989): Models for predicting benthic macroinvertebrate habitat suitability under regulated flows, 253-266, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida, 344pp.

Gore, J.A. and Nestler, J.M. (1988): Instream flow studies in perspective, *Regulated Rivers: Research and Management*, 2(2), 93-101.

Gore, J.A. and Petts, G.E. (eds)(1989): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida, 344pp.

Gore, J.A. and Milner, A.M. (1990): Island biogeographical theory: can it be used to predict lotic recovery rates?, *Environmental Management (New York)*, 14(5), 737-753.

Gore, J.A., Layzer, J.B. and Russell, I.A. (1992): Non-traditional applications of instream flow techniques for conserving habitat of biota in the Sabie River of Southern Africa, In: Boon, P.J., Calow, P., and Petts, G.E.: *River Conservation and Management*, Wiley.

Görgens, A. and Lee, J. (1992): *Kruger National Park Rivers Research Programme. Situation statement and management assessment*, Ninham Shand Inc., Report number 1977/5967, Water Research Commission.

Goudie, A. (1984): *The nature of the environment, an advanced physical geography*, Basil Blackwell, Oxford.

Goyen, A.G., Phillips, B.C. and Neal, J.F. (1987): Urban stormwater quality - Australian control structures, 135-136, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water* *quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Gracie, J.W., Szabad, C. and Green, R.I. (1993): Double Rock park stream restoration project, 98-100, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Gradilone, F. and Rothenberg, M.D. (1993): Seasonal rates - the pros and cons: a case study, 717- , In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Graf, W.L. (1980): Riparian management: a flood control perspective, *Journal of Soil and Water Conservation*, July-August, 158-161.

Green, C. and Suleman, M. (1987): Investment appraisal for urban storm drainage systems, 351-356, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Green, C.H. and Tunstall, S.M. (1992): The amenity and environmental value of river corridors in Britain, 425-441, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Gregg, W.W. and Rose, F.L. (1985): Influences of aquatic macrophytes on invertebrate community structure, guild structure, and microdistribution in streams, *Hydrobiologia*, 128, 45-56.

Gregory, K.J. (ed)(1977): *River channel changes*, John Wiley and Sons, Chichester.

Gregory, K.J. (1985): The impact of channelization, *The Geographical Journal*, 151(1), 53-74.

Gregory, K.J. (1987): Environmental effects of river channel changes, *Regulated Rivers: Research and Management*, 1(4), 358-363.

Gregory, K.J. (1992): Vegetation and river channel process interactions, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Greig, D.A. (1992): Taking a fresh look at stormwater, *New Zealand Engineering*, December, 26-27.

Greyvenstein, F.S. and De Villiers, C.P.M. (1975): *Common reed as a reclamation plant*, Farming in South Africa, Department of Agricultural Technical Services, Engineering Series no. E.1/1975, 4pp.

Grindley, S.A. (1984): *A study of land-use patterns in the Hout Bay river catchment with reference to the degradation of the river channel*, Unpublished MSc thesis, University of Cape Town.

Groeneveld, D.P. and French, R.H. (1995): Hydrodynamic control of an emergent aquatic plant (*Scirpus acutus*) in open channels, *Water Resources Bulletin*, 31(3), 505-514.

Gujer, W. and Krejci, V. (1987): Urban storm drainage and receiving waters ecology, 1-19, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Gupta, A. (1984): Urban hydrology and sedimentation in the humid tropics, 240-265, In: Costa, J.E. and Fleisher, P.J. (eds): *Developments and applications of geomorphology*, Springer-Verlag, Berlin.

Hails, J.R. (ed)(1977): *Applied geomorphology - a perspective of the contribution of geomorphology to interdisciplinary studies and environmental management*, Elsevier Scientific publishing, New York.

Hall, C.G. and Burger, A.P. (1974): *Hall on water rights in South Africa*, Fourth Edition, Juta, Cape Town.

Hall, D.J. (1990): *The biology and control of Typha capensis in the South-Western Cape Flats*, Final Report for the Cape Town City Council (City Planners Department) and the Divisional Council of the Cape (Rondevlei Bird Sanctuary).

Hampson, P.S. (1987): Adverse effects of aerobic exposure of shallow detention pond sediments, 175-176, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Harding, W.R. (1992): Zeekoevlei - water chemistry and phytoplankton periodicity, *Water SA*, 18(4), 237- .

Harper, D.M., Smith, C.D. and Barham, P.J. (1992): Habitats as the building blocks for river conservation assessment, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Harris, T. and Harris, C. (1989): Waterscapes rediscovered, *Landscape Design*, 182, July/Aug, 39-41.

Harrison, A.D. (1965): Geographical distribution of riverine invertebrates in Southern Africa, *Archiv für Hydrobiologie*, 61, 387-394.

Hart, B.T. and Campbell, I.C. (1991): Water quality guidelines and the maintenance of Australian river ecosystems, 61-67, In: Pigram, J.J. and Hooper, B.P. (eds): *Water allocation for the environment*, Proceedings of an international seminar and workshop, The Centre for Water Policy Research, University of New England, Armidale.

Hart, D.D. (1983): The importance of competitive interactions within stream populations and communities, 99-136, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Hart, R.C. (1985): Seasonality of aquatic invertebrates in low-latitude and Southern Hemisphere inland waters, *Hydrobiologia,* 125, 151-178.

Hart, R.C. and Allanson, B.R. (eds)(1984): *Limnological criteria for management of water quality in the southern hemisphere*, South African National Scientific Programmes Report Number 93, CSIR, Pretoria, 175pp.

Harvey, M.D. and Watson, C.C. (1988): Channel response to grade-control structures on Muddy Creek, Mississippi, *Regulated Rivers: Research and Management*, 2(2), 79-92.

Harvey, M.D., Watson, C.C. and Schumm, S.A. (1983): *Channelized streams: an analog for the effects of urbanization*, International Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, 401-409.

Hasfurther, V.R. (1985): The use of meander parameters in restoring hydrologic balance to reclaimed stream beds, 21-40, In: Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Hayes, D.F., Crockett, T.A. and Arends, M.T. (1993): Wetland engineering, design, and construction: state-of-the-science and research needs, 88-91, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Heath, D. (1989): *Environmental aspects of the Ford Brook improvement scheme*, by Walsall Metropolitan Borough Council, Paper presented at Conference of River and Coastal Engineers, Loughborough, July, 1989, 6pp.

Hellawell, J.M. (1986): *Biological indicators of freshwater pollution and environmental management*. Elsevier Applied Science, London.

Hellawell, J.M. (1988): River regulation and nature conservation, *Regulated Rivers: Research and Management*, 2(3), 425-443.

Hemphill, N. and Cooper, S.D. (1984): Differences in the community structure of stream pools containing or lacking trout, *Verh. Internat. Verein. Limnol.*, 22(3), 1858-1861.

Hemphill, W.R. and Bramley, M.E. (1989): *Protection of river and canal banks - a guide to selection and design*, CIRIA Water Engineering Report, Butterworths, London.

Henderson, J.E. (1986): Environmental designs for streambank protection projects, *Water Resources Bulletin* (Minneapolis), 22(4), 549-558.

Henderson, J.E. and Shields, F.D. (Jr.)(1982): *Site investigation and environmental considerations* - Lecture J-3, Streambank protection, Unpublished.

Hendricks, S.P. (1993): Microbial ecology of the hyporheic zone: a perspective integrating hydrology and biology, *Journal of the North American Benthological Society*, 12(1), 70-75.

Herricks, E.E. and Osborne, L.L. (1985): Water quality restoration and protection in streams and rivers, 1-20, In: Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Herricks, E.E. and Schaeffer, D.J. (1987): Selection of test systems for ecological analysis, *Water Science and Technology,* 19(11), 47-54.

Hewlett, H.W.M., Boorman, L.A. and Bramley, M.E. (1987): *Design of reinforced grass waterways*, CIRIA Report 116, London, 116pp.

Hey, R.D. (1990): Environmental river engineering, *Water and Environmental Management*, 4(4), 335-340.

Hey, R.D. and Winterbottom, A.N. (1990): River engineering in National Parks: the case of the River Wharfe, U.K., *Regulated Rivers: Research and Management*, 5(1), 35-44.

Higgins, R.J. (1990): Off-river storages as sources and sinks for environmental contaminants, *Regulated Rivers: Research and Management*, 5(5), 401-412.

Higler, L.W.G. (1993): The riparian community of north-west European lowland streams, *Freshwater Biology*, 29(2), 229-242.

Hildrew, A.G. (1992): Food webs and species interactions, 309-330, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Hill, A.R. (1976): The environmental impacts of agricultural land drainage, *Journal of Environmental Management*, 4, 251-274.

Hill, H.C. (1989): Creating a river, *Landscape Design* (London UK), 182, (July), 36-38.

Hill, M.P. and O'Keeffe, J.H. (1992): Some aspects of the ecology of the freshwater crab (*Potamonautes perlatus* Milne Edwards) in the upper reaches of the Buffalo River, Eastern Cape Province, South Africa. *Southern African Journal of Aquatic Sciences*, 18, 42-50.

Hipp, B., Alexander, S. and Knowles, T. (1993): Use of resource-efficient plants to reduce nitrogen, phosphorus and pesticide runoff in residential and commercial landscapes, *Water Science and Technology*, 28(3-5), 205-214.

Hocking, D.L. (1985): Channelization: some engineering aspects, *The Geographical Journal*, 151(1), 54-57.

Hocking, D.L, Whittle, I.R. and Bailey, R.A. (1988): Managing and engineering rivers for the benefit of man, *Water and Environmental Management*, 2(2), 151-158.

Holland, B. (1994): Stream erosion protection at Johannesburg Botanical Gardens, *Imiesa*, April, 29.

Hollis, G.E. (1974): River management and urban flooding, 201-216, In: Warren, A. and Goldsmith, F.B. (eds): *Conservation in practise*, John Wiley and Sons, Great Britain.

Holmes, N.T.H. and Newbold, C. (1989): Nature conservation (A) - rivers as natural resources, 275-326, In Brandon, T.W. (ed): *River engineering - Part 2, structures and coastal defence works*, Water Practice Manual, Institution of water and environmental management, London, England.

Hortle, K.G. and Lake, P.S. (1982): Macroinvertebrate assemblages in channelized and unchannelized sections of the Bunyip River, Victoria, *Aust. J. Mar. Freshw. Res.*, 33(6), 1071-1082.

House, M.A., Ellis, J.B., Herricks, E.E., Hvitved-Jacobsen, T., Seager, J., Lijklema, L., Aalderink, H. and Clifforde, I.T. (1993): Urban drainage - impacts on receiving water quality, *Water Science and Technology*, 27(12), 117-158.

Howard-Williams, C. (1983): Wetlands and watershed management: the role of aquatic vegetation, *J. Limnol. Soc. sth. Afr.*, 9(2), 54-62.

Howard-Williams, C. (1985): Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective, *Freshwater Biology*, 15, 391-431.

Hoyt, W.G. and Langbein, W.B. (1955): *Floods*, Princeton University Press, New Jersey.

Hvitved-Jacobsen, T., Keiding, K. and Yousef, Y.A. (1987): Urban runoff pollutant removal in wet detention ponds, 137-142, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Hydraulics Research Limited (1988): *Assessing the hydraulic performance of environmentally acceptable channels*, Report EX 1799, Wallingford, Oxfordshire.

Hynes, H.B.N. (1966): *The biology of polluted waters*, Liverpool University Press, England.

Hynes, H.B.N. (1970): The ecology of flowing waters in relation to management, *Water Pollution Control Federation Journal*, 42(3), 418-424.

Hynes, H.B.N. (1972): *The ecology of running waters*, University of Toronto Press, Canada, 555pp.

Hynes, H.B.N. (1983): Groundwater and stream ecology, *Hydrobiologia*, 100, 93-99.

Hynes, H.B.N. (1984): The relationships between the taxonomy and ecology of aquatic insects, 9-23, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Illies, J. (1961): Versuch einer allgemein biozonatischen gleiderung der Fliessgewasser. *Internationale Revue der Gesamten*, 27, 401-213.

International Union for the Conservation of Nature (1980): *World Conservation Strategy*, IUNC, Gland, Switzerland.

Iversen, T.M., Kronvang, B., Madsen, B.L., Markmann, P. and Nielsen, M.B. (1993): Re-establishment of Danish streams: restoration and maintenance measures, *Aquatic Conservation*, 3(2), 73-92.

Jaeggi, M.N.R. (1989): Channel engineering and erosion control, 163-184, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida, 344pp.

Jeffries, M. and Mills, D. (1990): *Freshwater ecology principles and applications*, Belhaven, London.

Johnson, E.H. (1995): Water demand management, *Water Sewage and Effluent*, 15(1), 29-34.

Jones, R.C. and Clark, C.C. (1987): Impact of watershed urbanization on stream insect communities, *Water Resources Bulletin*, 23(6), 1047-1055.

Jordaan, J.M., Plate, E.J., Prins, J.E. and Veltrop, J.A. (1993): *Water in our common future. A research agenda for sustainable development of water resources*. Report prepared for the Committee on Water Research. UNESCO, Paris, April 1993.

Jordan, W.R. (III), Gilpin, M.E. and Aber, J.D. (eds)(1987): *Restoration ecology, a synthetic approach to ecological research*, Cambridge University Press, Great Britain.

Jowett, I. (1991): Modelling and predicting instream flow requirements - a New Zealand perspective, In: Pigram, J.J. and Hooper, B.P. (eds): *Water allocation for the environment*, Proceedings of an international seminar and workshop, The Centre for Water Policy Research, University of New England, Armidale, November 1991.

Judy, R.D. (Jr) (1985): Enhancement of urban water quality through control of nonpoint source pollution: Denver, Colorado, 247-276, In: Gore, J.A. (ed): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Junk, W.J., Bayley, P.B. and Sparks, R.E. (1989): The flood pulse concept in river-floodplain systems, 110-127, In: Dodge, D.P. (ed): Proceedings of the International Large River Symposium, *Can. Spec. Publ. Fish. Aquat. Sci.*, 106.

Jutila, E. (1992): Restoration of Salmonid rivers in Finland, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Kaufman, M.M. (1995): Community response to stormwater pollution in an urbanized watershed, *Water Resources Bulletin*, 31(3), 491-504.

Karpiscak, M.M., Brittain, R.G. and Emelity, M.A. (1993): Residential water conservation and reuse demonstration: Casa del agua and desert house, 694- , In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Kelbe, B., Mulder, G.J., Bodenstein, B., Hattingh, D. and Verwey, A. (1991): *An investigation of the hydrological response to third world settlements in periurban areas of Natal/Kwazulu*, Vol. 1, Hydrological Research Unit, University of Zululand, report no. 1/91, Water Research Commission Project No. 233, 111pp.

Kelcey, J.G. (1985): Nature conservation, water and urban areas in Britain, *Urban Ecology*, 9(2), 99-143.

Keller, E.A. (1975): Channelization: a search for a better way, *Geology*, 3, 246-248.

Keller, E.A. (1978): Pools, riffles and channelization, *Environmental Geology*, 2(2), 119-127.

Keller, E.A. and Hoffman, E.K. (1977): Urban streams: sensual blight or amenity?, *Journal of soil and water conservation*, Sept-Oct, 237-240.

Kellerhals, R. and Church, M. (1989): The morphology of large rivers: characterization and management, 31-48, In: Dodge, D.P. (ed): Proceedings of the International Large River Symposium, *Canadian Special Publication of Fisheries and aquatic sciences,* 106.

Kern, K. (1992): Rehabilitation of streams in South-west Germany, 321-335, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Kem , K. (1992): Restoration of lowland rivers: the German experience, 279-297, In: Carling, P.A. and Petts, G.E. (eds): *Lowland floodplain rivers: geomorphological perspectives*, John Wiley and Sons.

Kern, K., Bostelmann, R. and Hinsenkamp, G. (1992): *Naturnahe Umgestaltung von Fleißgewässern - Leitfaden und Dokumentation ausgeführter Projekte*, Ministry of the Environment Baden-Württemberg, Germany, (ed.), Stuttgart, 228pp.

King, J.M. (1982): *An ecological study of the macro-invertebrate fauna of the Eerste River*, Western Cape Province, South Africa, Unpublished PhD. thesis, University of Cape Town.

King, J.M. (ed)(1986): *Hydrology and hydrobiology in the Fynbos biome*, Foundation for Research Development, Ecosystem Programmes, Occasional Report No. 26, Republic of South Africa, 60pp.

King, J.M., Day, J.A., Davies, B.R. and Henshall-Howard, M-P. (1987): Particulate organic matter in a mountain stream in the south-western Cape, South Africa, *Hydrobiologia*, 154, 165-187.

King, J.M. and Tharme, R.E. (1994): *Assessment of the instream flow incremental methodology and initial development of alternative instream flow methodologies for South Africa*, Water Research Commission, Report No. 295/1/94. ISBN No. 1 86845 056 2.

Knight, D.W. (1985): Advances in river engineering, 278-288, In: Tebbutt, T.H.Y. (ed): *Advances in water engineering*, Elsevier Applied Science Publishers, London.

Knight, D.W. (1987): Dissemination of research information to practising engineers and researchers in the water industry, *Water and Environmental Management*, 1(3), 315-324.

Kondolf, G.M. (1984): Hydrologic and channel stability considerations in stream habitat restoration, 214-227, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Kulshreshtha, S.N. and Gillies, J.A. (1993): Economic evaluation of aesthetic amenities: a case study of river view, *Water Resources Bulletin*, April, 29(2), 257-265.

Kuo, Ch.Y. and Zhu, J.L. (1987): Diversion box and detention basin system to manage first flush, 117-118, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Kusler, J.A. (1983): *Our national wetland heritage - A protection guidebook*, Environmental Law Institute, United States of America.

Lamb, B.L. (1995): Criteria for evaluating state instream-flow programs: deciding what works. *Journal of water resources planning and management*. May/June, 270-274.

Lamberth, S.J., Stewart, B.A. and Davies, B.R. (1994): The processing of unconfined, naturally entrained leaves in two low-order southern African mountain streams, *South African Journal of Aquatic Scientists*, 20(½), 23-32.

Lamberti, G.A. and Moore, J.W. (1984): Aquatic insects as primary consumers, 164-195, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Larsen, P.(ed)(1991): *Mitteilungen, Beiträge zur naturnahen Umgestaltung von Fließgewässern*, Universität Fridericiana zu Karlsruhe, Institut für Wasserbau und Kulturtechnik, 180/1991, 303pp.

Lawrence, A.I. and Goyen, A.G. (1987): Improving urban stormwater quality - an Australian strategy, 129-134, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Lemley, A.D. (1982): Modification of benthic insect communities in polluted streams: combined effects of sedimentation and nutrient enrichment, *Hydrobiologia*, 87, 229-245.

Leopold, L.B., Wolman, M.G. and Miller, J.P. (1964): *Fluvial processes in geomorphology*, Freeman and Company, San Francisco, United States of America, 522pp.

Leversedge, F.M. (ed) (1974): *Priorities in water management*, Western Geographical Series, Vol 8, University of Victoria, Canada.

Lewis, G. and Williams, G. (eds) (1984): *Rivers and wildlife handbook - a guide to practices which further the conservation of wildlife on rivers*, Royal Society for the Protection of Birds and the Royal Society for Nature Conservation, Bedfordshire, 295pp.

Likens, G.E. and Bormann, F.H. (1974): Linkages between terrestrial and aquatic ecosystems, *BioScience*, 24(8), 447-456.

Lindh, G. (1972): Urbanization: a hydrological headache, *AMBIO*, 1(6), 185-201.

Little, A.M. (1983): Planning the rational use of wetlands, *J. Limnol. Soc. sth. Afr.*, 9(2), 146-148.

Little, W.C. and Daniel, R.C. (1982): *Design and construction of low drop structures*, Proceedings of the Conference Applying Research to Hydraulic Practice, ASCE, 21-31.

Lock, M.A. and Williams, D.D. (eds) (1981): *Perspectives in running water ecology*, Plenum, New York.

Loepfe, R. (1982): *Protection contre les crues des cours d'eau*, Département fédéral des transports, des communications et de l'énergie Office fédéral de l'économie des eaux, Berne.

Loganathan, G.V, Watkins, E.W., Small, A.B. and Kibler, D.F. (1993): Utilization of roadway crossings as BMP's in urban areas, 785- , In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Low, A.B. (1991): Management of urban corridors, 412-413, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

Lowe, R.L. (1979): Phytobenthic ecology and regulated streams, In: Ward, J.V and Stanford, J.A. (eds): *The ecology of regulated streams*, Plenum Press, New York.

Luger, M.K. (1991): *South African law and the conservation of urban rivers and riparian land: the Keysers River case study*, Unpublished MPhil paper, University of Cape Town.

Luger, M.K. (1994): Environmental Management Study - Kuils River, Western Cape. *Environmental Planning and Management*, 5(5), 4-11.

Luger, M.K. and Davies, B.R. (1993): Environmentally insensitive design and construction: the Liesbeek River walkway, Cape Town, *Environmental Planning and Management*, 5(1), 4-11.

Luger, M.K. and Davies, B.R. (1994): The rehabilitation of over-engineered urban rivers, options for the Liesbeek River in Cape Town, *Earthyear, 7, 32-35.*

Luiten, J.P.A. (1995): The water system explorations - a new Dutch project (the aquatic outlook) for combining monitoring, research and policy analysis for integrated water management, *Water Science and Technology*, 31(8), 329-344.

Lusher, J.A. and Ramsden, H.T. (1992): Water pollution, 456-492, In: Fuggle, R.F. and Rabie, M.A. (eds), *Environmental management in South Africa*, Juta, Cape Town.

MacDonald, A.J. (1991): *Sources of sediments accumulating in the lower Black and Vygekraal Rivers*, Cape Town, South Africa, Unpublished MPhil thesis, University of Cape Town.

Magsig, J. (1984): Volunteer stream restoration on an agricultural watershed in northwest Ohio, 228-233, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Martin, E. and Miller, R.A. (1987): Efficiency of an urban stormwater detention system, 143-148, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

McDowell, C.R., Low, A.B. and McKenzie, B. (1991): Natural remnants and corridors in Greater Cape Town: their role in threatened plant conservation, 27-39, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

McHarg, I.L. (1971): *Design with nature*, The American Museum of Natural History, Doubleday/Natural History Press, New York, 198pp.

Maitland, P.J. (1978): *Biology of fresh waters*, Blackie, London.

Magenis, S.E. (1988): Trash screens on culverts in urban areas, *Water and Environmental Management*, 2(5), 476-483.

Maret, T.J., Parker, M. and Fannin, T.E. (1987): The effect of beaver ponds on the nonpoint source water quality of a stream in southwestern Wyoming, *Water Research*, 21(3), 263-268.

Maristany, A.E. (1993): Long-term performance of wet detention ponds, 138-141, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Marsalek, J., Bamwell, T.O., Geiger, W., Grottker, M., Huber, W.C., Saul, A.J., Schilling, W. and Tomo, H.C. (1993): Urban drainage systems: design and operation, *Water Science and Technology*, 27(12), 31-70.

Maskell, A.D (ed) (1992): *Scope for control of urban runoff*, Volumes 1-4, CIRIA Report No. 123 and 124.

Mason, C.F. and MacDonald, S.M. (1990): The riparian woody plant community of regulated rivers in eastem England, *Regulated Rivers: Research and Management*, 5(2), 159-166.

McCuen, R.H. and Moglen, G.E. (1988): Multicriterion stormwater management methods, *Journal of water resources planning and management*, 114(4), 414-431.

McKee, M.H. and Wrona, F.J. (1992): Mosquito biological control using Turbellarian predators, 299-300, In: Robarts, R.D. and Bothwell, M.L. (eds): *Aquatic ecosystems in semi-arid regions: implications for resource management*, NHRI symposium series 7.

McVeigh, S. (1981a): Save our rivers and streams, *Tight Lines*, July, 22(7), 14-15.

McVeigh, S. (1981b): Save our rivers and streams, *Tight Lines*, August, 22(8), 26-29.

Meiring, P.G.J., Drews, R.J.L.C., Van Eck, H. and Stander, G.J. (Jan 1968): *A guide to the use of pond systems in South Africa for the purification of raw and partially treated sewage*, Special Report WAT 34, National Institute for Water Research, CSIR, Pretoria.

Mellquist, P. (1992): River management - objectives and applications In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Meredith, C., Goss, H. and Seymour, S. (1989): *Nature conservation values of the rivers and catchments of Gippsland*, A report to the Department of Water Resources Victoria, Water Resource Management Report Series, Report No. 44, 89pp.

Mericas, D., Gremillion, P. and Terczak, E. (1984): Aquatic weed removal as a nutrient export mechanism in Lake Okeechobee, Florida, 203-211, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Merritt, R.W., Cummins, K.W. and Burton, T.M. (1984): The role of aquatic insects in the processing and cycling of nutrients, 134-163, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Meyer, J.L., McDowell, W.H., Bott, T.L., Elwood, J.W., Ishizaki, C., Melack, J.M., Peckarsky, B.L., Peterson, B.J. and Reblee, P.A. (1988): Elemental dynamics in streams, *Journal of the North American Benthological Society*, 7(4), 410-432.

Midgly, D.C., Pitman, W.V. and Middleton, B.J. (1983): *A guide to surface water resources of South Africa (1981) and its addendum (1983)*, Water Research Commission, Pretoria.

Miles, L.C. (1979): Stormwater drainage in urban areas, *Municipal Engineer*, March/April, 25-35.

Miles, L.C. (1984): *Hydraulic components of stormwater management*, Paper presented at a seminar on guidelines for the provision of engineering services in residential townships, February 1984, National Building Research Institute of the CSIR, Report number R/BOU 1214, 17pp.

Miller, D.G. and Tetlow, J.A. (1989): The assessment and management of surface water quality in England and Wales, *Regulated Rivers: Research and Management*, 4(2), 129-138.

Mills, D.H. (1972): *An introduction to freshwater ecology*, Oliver and Boyd, Edinburgh, 101pp.

Minshall, G.W. (1984): Aquatic insect-substratum relationships, 358-400, In Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Minshall, G.W. (1988): Stream ecosystem theory: a global perspective, *Journal of the North American Benthological Society*, 7(4), 263-288.

Minshall, G.W., Andrews, D.A. and Manuel-Faler, C.Y. (1983): Application of island biogeographic theory to streams: macroinvertebrate recolonization of the Teton River, Idaho, 279-298, In: Bames, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Mitchell, D.S. and Rogers, K.H. (1985): Seasonality/aseasonality of aquatic macrophytes in Southern Hemisphere inland waters, *Hydrobiologia,* 125, 137-150.

Mitchell, P. (1990): *The environmental condition of Victorian streams*, Department of Water Resources Victoria, 102pp.

Mitsch, W.J. and Jorgensen, S.E. (eds) (1989): *Ecological engineering: An introduction to ecotechnology*, John Wiley and Sons, United States of America.

Mitsch, W.J. (1995): Restoration of our lakes and rivers with wetlands - an important application of ecological engineering, *Water Science and Technology*, 31(8), 167-177.

Montgomery, D.R., Grant, G.E. and Sullivan, K. (1995): Watershed analysis as a framework for implementing ecosystem management, *Water Resources Bulletin*, 31(3), 369-386.

Moon, B.P. and Dardis, G.F. (eds)(1988): *The geomorphology of southern Africa*, Southern Book, Johannesburg.

Morrison, G.M., Wei, C. and Engdahl, M. (1993): Variations of environmental parameters and ecological response in an urban river, *Water Science and Technology*, 27(12), 191-194.

Mosher, C.D. (1993): Federal efficiency and effectiveness - it's up to all of us!!!, *Water Resources Bulletin*, 29(3), iii.

Mosley, M.P. (1985): River channel inventory, habitat and instream flow assessment, *Progress in physical geography,* 9(4), 494-523.

Mosley, M.P. (1987): The classification and characterization of rivers, In: Richards, K. (ed): *River channels: environment and process*, The Institute of British Geographers Special Publication Series, no. 18, Basil Blackwell, Oxford.

Moore, W.L. and Morgan, C.W. (eds) (1969): *Effects of watershed changes on streamflow*, University of Texas, United States of America.

Moss, B. (1980): *Ecology of fresh waters*, Blackwell, Oxford.

Mulder, G.J. and Kelbe, B. (1991): *An investigation of the hydrological response to third world settlements in periurban areas of Natal/Kwazulu*, vol. 2, Hydrological Research Unit, University of Zululand, report no. 1/91, Water Research Commission, Project no. 233, 87pp.

Muller, E., Décamps, H. and Dobson, M.K. (1993): Contribution of space remote sensing to river studies, *Freshwater Biology*, 29, 301-312.

Murphy, D.D. (1988): Challenges to biological diversity in urban areas, 71-76, In: Wilson, E.O. (ed): *Biodiversity*, National Academy Press, Washington, D.C.

Murray, A.S. and Shand, M.J. (1994): *Integrated stormwater and environmental management in the catchment area of the Kuils River*, Unpublished paper for the 50 years of water engineering conference.

Naiman, R.J., Décamps, C.A., Pastor, J. and Johnson, C.A. (1988): The potential importance of boundaries to fluvial ecosystems, *Journal of the North American Benthological Society*, 7(4), 289-306.

Naiman, R.J., Lonzarich, D.G., Beechie, T.J. and Ralph, S.C. (1992): General principles of classification and the assessment of conservation potential in rivers, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

National Transportation Research Board (1993): *Stormwater management for transportation facilities*, National Cooperative Highway Program Synthesis of Highway Practice, 174, Washington DC, 81pp.

Nature Conservancy Council (1989): *Urban habitat network 1989 - wetlands workshop*, Nature Conservancy Council, Great Britain Headquarters, Peterborough, 46pp.

Neuhold, J.M. (1981): Strategy of stream ecosystem recovery, 261-268, In: Barrett, G.W. and Rosenberg, R. (eds): *Stress effects on natural ecosystems*, John Wiley and Sons, Great Britain.

Newbold, C., Purseglove, J. and Holmes, N. (1983): *Nature conservation and river engineering*, Nature Conservancy Council, Peterborough, London, 36pp.

Newbold, J.D. (1987): Phosphorus spiralling in rivers and river-reservoir systems: implications of a model, 303-627, In: Craig, J.F. and Kemper, J.B. (eds): *Regulated streams: advances in ecology*, Plenum Press, New York and London.

Newbold, J.D. (1992): Cycles and spirals of nutrients, 379-400, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Newbury, R.W. (1984): Hydrologic determinants of aquatic insect habitats, 323-357, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Newbury, R. and Gaboury, M. (1993): Exploration and rehabilitation of hydraulic habitats in streams using principles of fluvial behaviour, *Freshwater Biology*, 29(2), 195-210.

Newson, M.D. (1986): River engineering in the drainage basin - contributions from fluvial geomorphology, *Journal of the Institute of Water Engineering and Scientists*, 40(4), 307-324.

Newson, M. (1992): *Land, water and development - river basin systems and their sustainable management*, Routledge, London, 351pp.

Newson, M.D. (1992): River conservation and catchment management: a UK perspective, 385-396, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Nicholls, A.O. and Margules, C.R. (1991): The design of studies to demonstrate the biological importance of corridors, 49-61, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

Niemczynowicz, J. (1994): New aspects of urban drainage and pollution reduction towards sustainability, *Water Science and Technology*, 30(5), 269-277.

Ninham Shand (1979): *Flow in the Kuils River and drainage of the catchment.* Report No. 543/3200.

Ninham Shand (1990): *Kuils River Flood Management Study - Final Report*, Report No. 1669/4978, November 1990.

Ninham Shand (1992): *Midrand town council - stormwater management policy*, Draft report.

Ninham Shand (1993): *Environmental assessment of the proposed canalisation of the Kuils and Bottelary Rivers*, Internal Report No. 2038/5919.

Ninham Shand (1994): *Kuils River environmental management study*, Report No. 2194/6124.

Ninham Shand, Kantey and Templer and Chris Mulder Assoc. (1992): *Randburg town council: Management module for water quality standards and environmental aspects*, Working draft.

Ninham Shand in association with MLH and Bernard Oberholzer (1993): *Constantia Valley riverine open space study, Phase 1, Westlake and Diep Rivers*, 86pp, report no. 2035.

Noble, R.G. and Hemens, J. (1978): *Inland water ecosystems in South Africa - a review of research needs*, South African National Scientific Programmes, Report Number 34, CSIR, Pretoria, 150pp.

Norris, R.H., McElravy, E.P. and Resh, V.H. (1992): The sampling problem, 282-306, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Nunes, K.D. (1975): Sources of public streams in South African Law, *Acta juridica*, 298-331.

Nunnally, N.R. (1978): Stream renovation: an alternative to channelization, *Environmental Management*, 2(5), 403-411.

Nunnally, N.R. (1985): Application of fluvial relationships to planning and design of channel modifications, *Environmental Management*, 9(5), 417-426.

Nunnally, N.R. (1989): ENDOW: An expert system for selecting environmental features for flood control and streambank protection projects, *Operational Geographer*, 7(3), 9-12.

O'Connor, N.A. (1991): The effects of habitat complexity on the macroinvertebrates colonising wood substrates in a lowland stream, *Oecologia*, 85, 504-512.

Odum, E.P. (1969): The strategy of ecosystem development, *Science*, 164, 262-270.

Odum, E.P. (1971): *Fundamentals of ecology*, third edition, Saunders College Publishing, Philadelphia.

O' Keeffe, J.H. (1986a): *Ecological research on South African rivers - a preliminary synthesis*, South African National Scientific Programmes Report Number 121, CSIR, Pretoria.

O'Keeffe, J.H. (ed)(1986b): *The conservation of South African rivers*, South African National Scientific Programmes Report Number 131, CSIR, Pretoria, 117pp.

O'Keeffe, J.H. and O'Keeffe, C. (1986): *An annotated bibliography of ecological research on South African rivers*, Foundation for Research Development, Ecosystems Programmes, Occasional Report No. 10, CSIR Pretoria, 184pp.

O'Keeffe, J.H., Danilewitz, D.B. and Bradshaw, J.A. (1987): An "Expert System" approach to the assessment of the conservation status of rivers, *Biological Conservation*, 40, 69-84.

O'Keeffe, J.H., Davies, B.R., King, J.M. and Skelton, P.H. (1989): The conservation status of southern African rivers, 266-289, In: Huntley, B.J. (ed): *Biotic diversity in southern Africa: concepts and conservation*, Oxford University Press, Cape Town.

O'Keeffe, J.H., Palmer, R.W., Byren, B.A. and Davies, B.R. (1990): The effects of impoundment on the physicochemistry of two contrasting southern African river systems, *Regulated Rivers: Research and Management*, 5(2), 97-110.

O'Keeffe, J.H. and Davies, B.R. (1991): Conservation and management of the rivers of the Kruger National Park: suggested methods for calculating instream flow needs, *Aquatic Conservation*, 1(1), 55-71.

O'Keeffe, J.H., Uys, M. and Bruton, M.N. (1992): Freshwater systems, 277-315, In: Fuggle, R.F. and Rabie, M.A. (eds), *Environmental management in South Africa*, Juta, Cape Town.

Oksiyuk, O.P., Oleynik, G.N. and Kovrizhnykh, A.I. (1978): Water quality in lined canals, *Hydrobiol. J.*, 14(6), 40-45.

Opie, F.W.J. (1986): *A river in the city: Liesbeek resource*, Cape Town Teachers' College, 59pp.

Orth, D.J. and Maughan, O.E. (1983): Microhabitat preferences of benthic fauna in a woodland stream, *Hydrobiologia*, 106, 157-168.

Osbome, L.L., Bayley, P.B., Higler, L.W.G., Statzner, B., Triska, F. and Moth Iversen, T. (1993): Restoration of lowland streams: an introduction, *Freshwater Biology*, 29(2), 187-194.

Osborne, L.L. and Kovacic, D.A. (1993): Riparian vegetated buffer strips in water-quality restoration and stream management, *Freshwater Biology*, 29(2), 243-258.

Padmanabhan, G. and Erdrich, P. (1993): Characterizing urban runoff quantity and quality, 789-792, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Pandit, A.K. (1984): Role of macrophytes in aquatic ecosystems and management of freshwater resources, *Journal of Environmental Management,* 18(1), 73-88.

Partridge, T.C. (1969): *Some aspects of the relationship between discharge and channel pattern in rivers*, Progress in river engineering, The S.A. Institute of Civil Engineers, Hydraulics Division, Papers presented at the River Engineering Symposium, University of Natal, July, 1969.

Pearce, F. (1993): Greenprint for rescuing the Rhine, *New Scientist*, 26 June, 25-29.

Peckarsky, B.L., Horn, S.C. and Statzner, B. (1990): Stonefly predation along a hydraulic gradient: a field test of the harsh-benign hypothesis, *Freshwater Biology*, 24(1), 181-191.

Pennak, R.W. (1971): Toward a classification of lotic habitats, *Hydrobiologia,* 38(2), 321-334.

Perkins, C. and Munves, S. (1993): The water and waste water savings achieved by ultra low flush toilets in Santa Monica, California, 670-673, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Perry, J.A., Schaeffer, D.J., Kerster, H.W. and Herricks, E.E. (1985): The environmental audit. II. Application to stream network design, *Environmental management*, 9(3), 199-208.

Petersen, R.C. (1992): The RCE: a riparian, channel and environmental inventory for small streams in the agricultural landscape, *Freshwater Biology*, 27(2), 295-306.

Petersen, R.C., Petersen, L.B.M. and Lacoursiére, J. (1992): A building-block model for stream restoration, 293-309, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Petts, G.E. (1984): *Impounded rivers - Perspectives for ecological management*, John Wiley and Sons.

Petts, G.E. (1988): Regulated rivers in the United Kingdom, *Regulated Rivers: Research and Management*, 2(3), 201-232.

Petts, G.E., Imhof, J.G., Manny, B.A., Maher, J.F.B. and Weisberg, S.B. (1989): Management of fish populations in large rivers: a review of tools and approaches, 578-588, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Petts, G.E. (1989): Perspectives for ecological management of regulated rivers, 3-26, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida.

Pigott, S. (1993): When the well runs dry: paying for storm water, 813-816, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Pinay, G. and Decamps, H. (1988): The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface water: a conceptual model, *Regulated Rivers: Research and Management*, 2(4), 507-516.

Power, M.E., Stout, R.J., Cushing, C.E., Harper, P.P., Hauer, F.R., Matthews, W.J., Moyle, P.B., Statzner, B. and Wais De Badgen, I.R. (1988): Biotic and abiotic controls in river and stream communities, *Journal of the North American Benthological Society*, 7(4), 456-479.

Poynton, J.C. and Roberts, D.C. (1985): Urban open space planning in South Africa: a biological perspective, *South African Journal of Science*, 81, 33-37.

Pratt, C.J. (1995): A review of source control of urban stormwater runoff, *J.CIWEM*, April, 9, 132-139.

Preul, H.C. and Ruszkowski, J.A. (1987): Storm drainage detention basin sediment removal model, 197-198, In: Gujer, W. and Krejci, V. (eds): *Topics in urban storm water quality, planning and management*, Proceedings of IV International Conference in Urban Storm Drainage, International Association for Hydraulic Research, Switzerland.

Pringle, C.M., Naiman, R.J., Bretschko, G., Karr, J.R., Oswood, M.W., Webster, J.R., Welcomme, R.L. and Winterbourn, R.L. (1988): Patch dynamics in lotic systems: the stream as a mosaic, *Journal of the North American Benthological Society*, 7(4), 503-524.

Pringle, C.M., Rabeni, C.F., Benke, A.C. and Aumen, N.G. (1993): The role of aquatic science in freshwater conservation: cooperation between the North American Benthological Society and organizations for conservation and resource management, *Journal of the North American Benthological Society*, 12(2), 177-184.

Pritchett, D.A. (1984): Creation and monitoring of vernal pools at Santa Barbara, California, 282-292, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Purseglove, J. (1989): *Taming the flood - A history and natural history of rivers and wetlands*, Oxford University Press in association with Channel Four Television Company, 307pp.

Quick, A.J.R. (ed)(1992): *Water quality status and management of Cape Town's waters*, River Day Committee, Unpublished Wildlife Society of SA, 8pp.

Quick, A.J.R. (ed)(1993): *Status and management of Cape Town's waters*, Inland Waters Management Team, Unpublished draft copy.

Quick, A.J.R. (1995): Issues facing water resource managers and scientists in a rapidly growing coastal city: Cape Town, South Africa, *South African Journal of Science*, 91, 175-183.

Quick, A.J.R. and Johanssom, A.R. (1992): User assessment survey of a shallow freshwater lake, Zeekoevlei, Cape Town, with particular emphasis on water quality, *Water SA*, 18(4), 247-.

Rabeni, C.F. and Minshall, G.W. (1977): Factors affecting microdistribution of stream benthic insects, *Oikos*, 29 (1), 33-43.

Rabeni, C.F. and Jacobsen, R.B. (1993): The importance of fluvial hydraulics to fish-habitat restoration in low-gradient alluvial streams, *Freshwater Biology*, 29(2), 211-220.

Rabie, M.A. (1976): *South African environmental legislation*, IFCOL, Pretoria.

Rabie, M.A. (1989): The conservation of rivers in South African Law, *SA Publiekreg/Public Law*, 4(1), 1-18 and 186-204.

Rabie, M.A. (1991): Sources of public rivers - status and control, *Tydskrif vir Hedendaagse Romeins-Hollandse Reg*, Band 54, Nommer 1, Feb 1991.

Rabie, M.A. and Day, J.A. (1992): Rivers, 647-668, In: Fuggle, R.F. and Rabie, M.A. (eds), *Environmental management in South Africa*, Juta, Cape Town.

Ramsden, H.T. (1990): *Southern African approaches to legislation for fresh water systems*, Unpublished paper from "A workshop to formulate a national policy and strategy for the fresh water systems of South Africa".

Ractliffe, S.G. (1991): *The effects of suspended sediments on the macroinvertebrate community structure of a river system.* Unpublished Honours Thesis. Department of Zoology, University of Cape Town.

Reeve, C.E. (1988): Changing the shape of rivers, *Water Bulletin* (London), 297 (Feb.), 10-11.

Regier, H.A., Welcomme, R.L., Steedman, R.J. and Henderson, H.F. (1989): Rehabilitation of degraded river ecosystems, 86-97, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Reice, S.R. (1984): The impact of disturbance frequency on the structure of a lotic riffle community, *Verh. Internat. Verein. Limnol.*, 22(3), 1906-1910.

Reice, S.R., Wissmar, R.C. and Naiman, R.J. (1990): Disturbance regimes, resilience, and recovery of animal communities and habitats in lotic ecosystems, *Environmental Management*, 14(5), 647-659.

Resh, V.H. and Rosenberg, D.M. (eds)(1984): *The ecology of aquatic insects*, Praeger, United States of America.

Resh, V.H., Brown, A.V., Covich, A.P., Gurtz, M.E., Li, H.W., Minshall, G.W., Reice, S.R., Sheldon, A.L., Wallace, J.B. and Wissmar, R. (1988): The role of disturbance in stream ecology, *Journal of the North American Benthological Society*, 7(4), 433-455.

Reynolds, C.S. (1988): The development of ecological concepts in limnology, with particular reference to the last twenty-five years, Address to the society, *J. Limnol. Soc. sth. Afr.*, 14(2), 54-59.

Reynolds, C.S. (1992): Algae, 195-215, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Rhodes, H.A. and Hubert, W.A. (1991): Submerged undercut banks as macroinvertebrate habitat in a subalpine meadow stream, *Hydrobiologia*, 213, 149-153.

Richards, C., Host, G.E. and Arthur, J.W. (1993): Identification of predominant environmental factors structuring stream macroinvertebrate communities within a large agricultural catchment, *Freshwater Biology*, 29(2), 285-294.

Richards, K. (ed)(1987): *River channels, environment and process*, The Institute of British Geographers Special Publication, Basil Blackwell, Great Britain.

Richter, B.D. (1993): Ecosystem-level conservation at The Nature Conservancy: growing needs for applied research in conservation biology, *Journal of the North American Benthological Society*, 12(2), 197-200.

Riggs, H.C. (1985): *Streamflow characteristics*, Developments in water science 22, Elsevier, Amsterdam.

Risser, R.J. and Harris, R.R. (1989): Mitigation for impacts to riparian vegetation on western montane streams, 235-252, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida.

River Torrens Study (undated): *River Torrens Study, Summary Report*, Prepared for the South Australian Government River Torrens Committee by Land Systems Pty Ltd, South Australia, 36pp.

Roberts, C.P.R. (1981): *Environmental considerations of water projects*, Department of Water Affairs, Technical Note 114, Pretoria, 106-123.

Roberts, D.C. and Poynton, J.C. (1985): Central and peripheral urban open spaces: need for biological evaluation, *South African Journal of Science*, 81, 464-466.

Roberts, D.C. (1987): *An ecological approach to open space planning in municipal Durban*, Paper presented at Metropolitan Open Space Conference, Feb. 1987, Durban, 15pp.

Robins, N. (1990): *The application of integrated catchment management to water resource problems in South Africa - a case study of the Eerste River*, Unpublished Honours thesis, University of Cape Town.

Rogers, F.E.J. (1983): Wetlands as accreting systems: wastewater treatment, *J. Limnol. Soc. sth. Afr.*, 9(2), 110-116.

Rogers, F.E.J., Rogers, K.H. and Buzer, J.S. (1985): *Wetlands for wastewater treatment with special reference to municipal wastewaters*, Olifantsvlei Working Group, Witwatersrand University Press, Johannesburg, 122pp.

Rogers, K.H. (1983): Wetlands as accreting systems: organic carbon, *J. Limnol. Soc. sth. Afr.*, 9(2), 96-103.

Rooseboom, A. and le Grange, A. (1992): Equilibrium scour in rivers with sandbeds, *Water SA*, 18(4), 287- .

Rothmann, C.E. (ed)(1991): *Development options: upper Olifants River, Impacts of proposed dams on the aquatic environment upstream of Clanwilliam Dam: Western Cape*, Report on proceedings of Olifants River workshop, Feb. 1991, Ceres, Department of Water Affairs and Forestry, 109pp.

Rothmann, C.E. (ed) (1992): *Water resource development options on the ecological environment*, Report on proceedings of Palmiet Ecological Work Session, July, 1991, Kleinmond, Department of Water Affairs and Forestry, Pretoria.

Russell, H. (1992): Banking on nature, *New Civil Engineer*, 11 Nov., 20-21.

Ruttner, F. (1975): *Fundamentals of Limnology*, University of Toronto, Canada.

Ryder, R.A. and Pesendorfer, J. (1989): Large rivers are more than flowing lakes: a comparative review, 65-85, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Saggerson, D. (1992): *Liesbeek environmental study*, Unpublished Eng (civil) thesis, University of Cape Town, 110pp.

Saunders, D.A. and Hobbs, R.J. (eds)(1991): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia, 442pp.

Schaeffer, D.J., Herricks, E.E. and Kerster, H.W. (1988): Ecosystem health: I. Measuring ecosystem health, *Environmental Management*, 12(4), 445-455.

Schiemer, F. and Waidbacher, H. (1992): Strategies for conservation of a Danubian fish fauna, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

School of Environmental Studies (1980): *Environmental impact statement of the proposed cycleway Kirstenbosch-Rondebosch Common*, Unpublished Masters Students Report, University of Cape Town, 42pp.

Schumm, S.A. (1977): Applied fluvial geomorphology, 119-155, In: Hails, J.R. (ed): *Applied geomorphology: a perspective of the contribution of geomorphology to interdisciplinary studies and environmental management*, Elsevier Scientific Publishing, Oxford.

Scrimgeour, G.J. and Winterbourn, M.J. (1989): Effects of floods on epilithon and benthic macroinvertebrate populations in an unstable New Zealand river, *Hydrobiologia*, 171, 33-44.

Schiechtl, H. (1980): *Bioengineering for land reclamation and conservation*, University of Alberta Press, Canada, 144-153pp.

Schmid, A.S. (1983): Design in the river landscape, *Landscape Planning*, 10, 31-41.

Scholze, R., Novotny, V. and Schonter, R. (1993): Efficiency of best management practices for controlling priority pollutants in runoff, *Water Science and Technology*, 28(3-5), 215-224.

Schropp, M.H.I. (1995): Principles of designing secondary channels along the river Rhine for the benefit of ecological restoration. *Water Science and Technology*, 31(8), 379-382.

Schwab, G.O., Frevert, R.K., Edminster, T.W. and Barnes, K.K. (1976): Soil and water conservation engineering, 3rd edition.

Schwarze, M. and Zeh, W. (1984): *Landschaft und natÜrliche lebensgrundlagen anregungen fÜr die ortsplanung*, Bundesamt fÜr Raumplanung, Bundesamt fÜr Forstwesen, Bern.

Sedell, J.R., Reeves, G.H., Hauer, F.R., Stanford, J.A. and Hawkins, C.P. (1990): Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems, *Environmental Management* (New York), 14(5), 711-724.

Sedell, J.R., Richey, J.E. and Swanson, F.J. (1989): The river continuum concept: a basis for the expected ecosystem behavior of very large river?, 49-55, In: Dodge, D.P. (ed):

Proceedings of the International Large River Symposium, Canadian Special Publication of Fisheries and aquatic sciences 106.

Segarra-Garcia, R. and Loganathan, V.G. (1992): Storm-water detention storage design under random pollutant loading, *Journal of Water Resources Planning and Management*, 118(5), 475-491.

Sellin, R.H.J., Giles, A. and van Beesten, D.P. (1990): Post-implementation appraisal of a two-stage channel in the River Roding, Essex, *Water and Environmental Management*, 4(2), 119-130.

Serageldin, I. (1995). *Toward sustainable management of water resources*. Directions in development. The World Bank, Washington. ISBN 0-8213-3413-1.

Shields, F.D. (Jr.)(1982a): Environmental features for flood control channels, *Water Resources Bulletin*, 18(5), 779-784.

Shields, F.D. (Jr.) (1982b): *Environmental features for flood-control channels*, Environmental and Water Quality Operational Studies, Technical Report E-82-7, July 1982, US Army Engineers, Environmental Laboratory, Vicksburg, 133pp.

Shields, F.D. (Jr.) and Nunnally, N.R. (1984): Environmental aspects of clearing and snagging, *Journal of environmental engineering*, 110(1), 152-164.

Shields, F.D. (Jr.) and Abt, S.R. (1989): Sediment deposition in cutoff meander bends and implications for effective management, *Regulated Rivers: Research and Management*, 4(4), 381-396.

Shields, F.D. (Jr.) and Hoover, J.J. (1991): Effects of channel restabilization on habitat diversity, Twentymile Creek, Mississippi, *Regulated Rivers: Research and Management*, 6(3), 163-182.

Shields, F.D. (Jr), Cooper, C.M., and Knight, S.S. (1993): Initial habitat response to incised channel rehabilitation, *Aquatic Conservation*, 3(2), 93-104.

Shields, F.D. (Jr), Bowie, A.J. and Cooper, C.M. (1995): Control of streambank erosion due to bed degradation with vegetation and structure, *Water Resources Bulletin*, 31(3), 475-489.

Shiozawa, D.K. (1983): Density independence versus density dependence in streams, 55-78, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Shonman, D. (1984): Resolving coastal restoration conflicts: environmental protection guarantees, 321-327, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

Simons, D.B. (1979): Effects of stream regulation on channel morphology, 95-111, In: Ward, J.V. and Stanford, J.A (eds): *The ecology of regulated streams*, Proceedings of the First International Symposium on Regulated Streams, Plenum Press, New York.

Simpson, D.E. and Hemens, J. (1978): Nutrient budget for a residential stormwater catchment in Durban, South Africa, *Progress in Water Technology*, 10(5/6), 631-643.

Simpson, G. (1991): Gabion structures, *Municipal Engineer*, May: 24-31.

Simpson, P.W., Newman, J.R., Keirn, M.A., Matter, R.M. and Guthrie, P.A. (1982): *Manual of stream channelization impacts on fish and wildlife*, Office of Biological Services, Fish and Wildlife Service, U.S. Department of the Interior, FWS/OBS - 82/24, Washington, 155pp.

Skaife, S.H., Ledger, J. and Bannister, A. (1979): *African insect life*, Struik, Cape Town.

Sloat, M.S. and Hwang, R.B. (1989): Sensitivity of detention basins in urbanized watershed, *Journal of urban planning and development*, 115(3), 135-155.

Smith, C.D., Harper, D.M. and Barham, P.J. (1990): Engineering operations and invertebrates: linking hydrology with ecology, *Regulated Rivers: Research and Management*, 5(1), 89-96.

Smith, K.V.H. (1984): *Channels and channel control structures*: Proceedings of the first international conference, South Hampton, England, April 1984, Springer Verlag, England.

Smith, R.L. (1980): *Ecology and field biology*, Harper and Row, New York.

Soulé, M.E. and Gilpin, M.E. (1991): The theory of wildlife corridor capability, 3-8, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

Speaker, R., Moore, K. and Gregory, S. (1984): Analysis of the process of retention of organic matter in stream ecosystems, *Verh. Internat. Verein. Limnol.*, 22(3), 1835-1841.

Stalnaker, C.B., Milhous, R.T. and Bovee, K.D. (1989): Hydrology and hydraulics applied to fishery management in large rivers, 13-30, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Stanford, J.A. and Ward, J.V. (1983): Insect species diversity as a function of environmental variability and disturbance in stream systems, 265-278, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Stanford, J.A. and Ward, J.V. (1988): The hyporheic habitat of river ecosystems, *Nature*, 335, 64-67.

Stanford, J.A. and Ward, J.V. (1993): An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor, *Journal of the North American Benthological Society*, 12(1), 48-60.

Stanier, R.Y., Edward, A.A., Ingraham, J.L. and Wheelis, M.L. (1979): *Introduction to the microbial world*, Prentice-Hall Inc., New Jersey.

Stanley, E.H. and Fisher, S.G. (1992): Intermittency, disturbance, and stability in stream ecosystems, 271-280, In: Robarts, R.D. and Bothwell, M.L. (eds): *Aquatic ecosystems in semi-arid regions: implications for resource management*, NHRI symposium series 7.

Starnes, L.B. (1985): Aquatic community response to techniques utilized to reclaim eastern U.S. surface coal mine-impacted streams, 193-222, In: Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Statzner, B. and Higler, B. (1986): Stream hydraulics as a major determinant of benthic invertebrate zonation patterns, *Freshwater Biology*, 16(1), 127-139.

Statzner, B., Gore, J.A. and Resh, V.H. (1988): Hydraulic stream ecology: observed patterns and potential applications, *Journal of the North American Benthological Society*, 7(4), 307-360.

Statzner, B. and Sperling, F. (1993): Potential contribution of system-specific knowledge (SSK) to stream-management decisions: ecological and economic aspects, *Freshwater Biology*, 29(2), 313-342.

Steedman, R.J. (1988): Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario, *Can. J. Fish. Aquat. Sci.*, 45(3), 492-501.

Stephenson, D. (1981): *Stormwater hydrology and drainage*, Developments in water science 14, Elsevier, The Netherlands, 276pp.

Stephenson, D. and Meadows, M.E. (1986): *Kinematic hydrology and modelling*, Developments in water science 26, Elsevier, The Netherlands.

Stewart, B.A. and Davies, B.R. (1990): Allochthonous input and retention in a small mountain stream, South Africa, *Hydrobiologia,* 202, 135-146.

Stewart Scott Inc. (1994): *Improving the trophic and aesthetic status of Zoo Lake*, Supplement to Munisipale en Openbare Dienste, July, 49-53.

Stirton, C.H. (ed)(1980): *Plant invaders: beautiful, but dangerous*, Department of Nature and Environmental Conservation of the Cape Provincial Administration, Cape Town, 175pp.

Stumm, W. (1986): Water, an endangered ecosystem, *AMBIO*, 15(4), 201-207.

Sundborg, A. and Rapp, A. (1986): Erosion and sedimentation be water: problems and prospects, *AMBIO,* 15(4), 215-223.

Sutcliffe, J. (1968): *Plants and Water*, Edward Arnold (Publishers) Ltd, London.

Swales, S. and O'Hara, K. (1980): Instream habitat improvement devices and their use in freshwater fisheries management, *Journal of Environmental Management,* 10, 167-179.

Swales, S. (1982): Environmental effects of river channel works used in land drainage improvements, *Journal of Environmental Management,* 14, 103-126.

Swales, S. (1989): The use of instream habitat improvement methodology in mitigating the adverse effects of river regulation on fisheries, 185-208, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida.

Taylor, L. (1990): *Re-development proposals for the Liesbeeck/Black River area*, Department of Urban and Regional Planning, University of Cape Town, Unpublished Thesis.

Taylor, R.H. and Cunningham, A.B. (1983): The conservation of wetlands, *J. Limnol. Soc. sth. Afr.*, 9(2), 141-145.

Tharme, R., Ractliffe, G. And Day, E. (1997): *An assessment of the present ecological condition of the Lourens River, Western Cape, with particular reference to proposals for stormwater management.* Southern Waters, for the Somerset West Municipality.

Thibert, N.F. (1993): Seattle's storm water application, 801-804, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Thoms, M.C. (1987): Channel sedimentation within the urbanized River Tame, U.K., *Regulated Rivers: Research and Management*, 1, 229-246.

Thoms, M.C. and Walker, K.F. (1992): Channel changes related to low-level weirs on the River Murray, South Australia, 235-249, In: Carling, P.A. and Petts, G.E. (eds): *Lowland floodplain rivers: geomorphological perspectives*, John Wiley and Sons.

Thoms, M.C. and Walker, K.F. (1992): Sediment transport in a regulated semi-arid river: the river Murray, Australia, 239-, In: Robarts, R.D. and Bothwell, M.L. (eds): *Aquatic ecosystems in semi-arid regions: implications for resource management*, NHRI symposium series 7.

Thorn, R.B. (ed) (1966): *River engineering and water conservation works*, Butterworths, London.

Tobin, G.A. (1995): The levee love affair: a stormy relationship? *Water Resources Bulletin*, 31(3), 359-367.

Toerien, D.F. (1977): *A review of eutrophication and guidelines for its control in South Africa*, Special Report WAT 48, National Institute for Water Research, CSIR, Pretoria.

Toth, L.A. (1989): *Kissimmee River channelization: environmental impacts and restoration criteria*, International Association for Hydraulic Research, Conference, IAHR 23rd Congress, Ottawa, 21-25 August 1989, Proceedings of technical session D: Environmental hydraulics, National Research Council Canada, 395-402.

Townsend, C.R. (1989): The patch dynamics concept of stream community ecology, *Journal of the North American Benthological Society*, 8(1), 36-50.

Townshend, P.D. (1991): *Automatic equipment to clean up urban rivers*, Seminar and workshop on environmental waste management and technology, 22-24 October, 1991, 215-227, The S.A. Institution of mechanical engineers institute of waste management, South Africa.

Townshend, P.D. (1993): Urban water course pollution control, *Imiesa*, March, 10-13.

Triska, F.J., Duff, J.H. and Avanzino, R.J. (1993): Patterns of hydrological exchange and nutrient transformation in the hyporheic zone of a gravel-bottom stream: examining terrestrial-aquatic linkages, *Freshwater Biology*, 29(2), 259-274.

Tundisi, J.G. and Straskraba, M. (1995): Strategies for building partnerships in the context of river basin management: the role of ecotechnology and ecological engineering. *Lakes and Reservoirs: research and management*, 1, 31-38.

Turpie, J. (1993): *The biological value of the lower reaches of the Black River and adjacent wetlands and consequent management imperatives*, University of Cape Town, Cape Town City Council, 36pp.

Twinch, A.J. and Ashton, P.J. (1983): Wetlands as accreting systems: nutrient cycling in wetlands, *J. Limnol. Soc. sth. Afr.*, 9(2), 104-109.

Tyson, J.M. and Foster, V. (1996): Valuing environmental benefits from river quality improvements. *Water Science and Technology,* 33 (9), 285-293.

Tyson, W. (1984): "Economology": the merging of economics and ecology, 371, In: Diamant, R., Eugster, J.G. and Duerkson, C.J. (eds): *A citizen's guide to river conservation*, Washington DC, Conservation Foundation.

United Nations: (1953): River training and beach protection, Flood control series no. 6.

United States Department of the Interior (1992): *Economic impacts of protecting rivers, trails, and greenway corridors - a resource book.* Rivers, trails and conservation assistance, National Park Service. Third edition.

Vadas, R.G., Garcia, L.A. and Labadie, J.W. (1995): A methodology for water quantity and quality assessment for wetland development, *Water Science and Technology*, 31(8), 293-300.

Valett, H.M., Fisher, S.G. and Stanley, E.H. (1990): Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream, *Journal of the North American Benthological Society*, 9(3), 201-215.

Van Niekerk, L. (1993a): Wandel aan die Liesbeek, *Muniviro,* 10(2), 15.

Van Niekerk, L. (1993b): Face-lift for the Liesbeek, *Conserva*, May/June, 8(3), 14-17.

Van Niekerk, L. (1993c): *Liesbeeck-projek stel 'n voorbeeld*, Unpublished.

Van Splunder, I., Coops, H. and Schoor, M.M. (1994): Tackling the bank erosion problem: (re-)introduction of willows on riverbanks, 379-381, In: Van de Kraats, J.A. (ed): Rehabilitation of the River Rhine, *Water Science and Technology*, 29(3).

Van Warmelo, W. (ed)(1989): *Typha: its status, problems, economic benefits, control*, Report on symposium held at Cape Town, 9 March 1989, 40pp.

Van Warmelo, W. (ed)(1991): *"Corridor Conservation"*, Workshop held in Cape Town, 6 September 1991, Flora conservation committee, The Botanical Society of South Africa, 57pp.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. and Cushing, C.E. (1980): The river continuum concept, *Can. J. Fish. Aquat. Sci.*, 37, 130-137.

Vervier, P., Dobson, M. and Pinay, G. (1993): Role of interaction zones between surface and ground waters in DOC transport and processing: considerations for river restoration, *Freshwater Biology*, 29(2), 275-284.

Viljoen, F.C. (1993): *An input-output study of various physical and chemical constituents in water after passage through a section of the Natalspruit wetland*, Unpublished Rand Water Board Paper, 13pp.

Villet, H. (1974): *An examination of open space in urban planning*, Unpublished MPhil thesis, Town and Regional Planning, University of Cape Town.

Vindimian, E. and Garric, J. (1993): Ecotoxicological effects of urban drainage: a few proposals based on results obtained in similar situations, *Water Science and Technology*, 27(12), 213-217.

Vischer, D.L. (1987): Lessons from 19th century river training works, International Association for Hydraulic Research, *Symposium on Water for the future: Water resources developments in perspective*, Rome, 6-11 April 1987, Wunderlich, W. and Prins, J. (eds), AA Balkema, Rotterdam, 45-52.

Vos, W.J. (1978): *Principles of South African water law*, Juta, Cape Town.

Wadeson, R.A. (1994): A geomorphological approach to the identification and classification of instream flow environments, *South African Journal of Aquatic Science*, 20(½), 38-61.

Wagner, A. and Geiger, W.F. (1996): New criteria for stormwater discharges into urban streams, *Water Science and Technology*, 34(3-4), 41-48.

Walker, K.F. (undated): *Meeting the instream flow needs of aquatic fauna.* Unpublished lecture notes.

Walker, K.F. (1985): A review of the ecological effects of river regulation in Australia, *Hydrobiologia*, 125, 111-129.

Walker, K.F, Thoms, M.C. and Sheldon, F. (1992): Effects of weirs on the littoral environment of the river Murray, South Australia, 271-292, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Walker, K.F. and Thoms, M.C. (1993): Environmental effects of flow regulation on the lower River Murray, Australia, *Regulated Rivers: Research and Management*, 8, 103-109.

Wallace, K.J. (1991): Role of corridors in education for nature conservation, 398-400, In: Saunders, D.A. and Hobbs, R.J. (eds): *Nature conservation 2: The role of corridors*, Surrey Beatty and Sons, Australia.

Walling, D.E. and Webb, B.W. (1992): Water quality: Physical characteristics, 48-72, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Wallis, P.M. (1981): The uptake of dissolved organic matter in groundwater by stream sediments - a case study, In: Lock, M.A. and Williams, D.D. (eds): *Perspectives in running water ecology*, Plenum, New York.

Wanielista, M.P., Yousef, A.Y. and Taylor, J.S. (1982): *Stormwater management to improve lake water quality*, Project Summary, US Environmental Protection Agency, Order number. PB 82-227 711, Edison.

Wang, L.K., Terlecky, P.M.(Jr.) and Leonard, R.P. (1977): Engineering and management aspects of dredge disposal and treatment, *Journal of Environmental* Management, 5(2), 181-203.

Ward, J.V. (1984): Ecological perspectives in the management of aquatic insect habitat, 558-577, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Ward, J.V. (1985): Thermal characteristics of running waters, *Hydrobiologia*, 125, 31-46.

Ward, J.V. (1989): The four-dimensional nature of lotic ecosystems, *Journal of the North American Benthological Society*, 8(1), 2-8.

Ward, J.V. (1992): A mountain river, 493-510, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Ward, J.V and Stanford, J.A. (eds)(1979): *The ecology of regulated streams*, Plenum Press, New York.

Ward, J.V. and Stanford, J.A. (1979): Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams, In: Ward, J.V and Stanford, J.A. (eds): *The ecology of regulated streams*, Plenum Press, New York.

Ward, J.V and Stanford, J.A. (1983a): The serial discontinuity concept of lotic ecosystems, 24-42, In: Fontaine, T.D. and Bartell, S.M. (eds) *Dynamics of lotic ecosystems*, Ann Arbor Science Publishers Inc., Ann Arbor, Michigan, United States of America.

Ward, J.V and Stanford, J.A. (1983b): The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems, 347-356, In: Fontaine, T.D. and Bartell, S.M. (eds) *Dynamics of lotic ecosystems*, Ann Arbor Science Publishers Inc., Ann Arbor, Michigan, United States of America.

Ward, J.V and Stanford, J.A. (1987): The ecology of regulated streams: past accomplishments and directions for future research, 391-409, In: Craig, J.F. and Kemper, J.B. (eds): *Regulated streams: advances in ecology*, Plenum Press, New York and London.

Ward, J.V and Stanford, J.A. (1989): Riverine ecosystems: the influence of man on catchment dynamics and fish ecology, 56-64, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Watson, D. (1987): Hydraulic effects of aquatic weeds in U.K. rivers, *Regulated River: Research and Management*, 1(3), 221-227.

Webster, J.R., Gurtz, M.E., Hains, J.J., Meyer, J.L., Swank, W.T., Waide, J.B. and Wallace, J.B. (1983): Stability of stream ecosystems, 355-395, In: Barnes, J.R. and Minshall, G.W. (eds): *Stream ecology: application and testing of general ecological theory*, Plenum Press, New York.

Welcomme, R.L. (1989): Floodplain fisheries management, 209-234, In: Gore, J.A. and Petts, G.E. (eds): *Alternatives in regulated river management*, CRC Press, Boca Raton, Florida, 344pp.

Welcomme, R.L. (1992): River conservation - future prospects, 453-462, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Welcomme, R.L., Ryder, R.A. and Sedell, J.A. (1989): Dynamics of fish assemblages in river systems - a synthesis, 569-577, In: Dodge, D.P. (ed): *Proceedings of the International Large River Symposium*, Canadian Special Publication of Fisheries and aquatic sciences 106.

Wesche, T.A. (1985): Stream channel modifications and reclaimation structures to enhance fish habitat, 103-164, In Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Wessels, W.P.J. (1981): Hydrology of the Western Cape lowlands with special reference to the Cape Flats, In: Moll, E. (ed) *Proceedings of a symposium on coastal lowlands of the Western Cape*, University of the Western Cape.

Wetzel, R.G. and Ward, A.K. (1992): Primary production, 354-369, In: Calow, P. and Petts, G.E. (eds): *The rivers handbook*, Blackwell, London.

Whigham, D.F., Chitterling, C. and Palmer, B. (1988): Impacts of freshwater wetlands on water quality: a landscape perspective, *Environmental Management*, 12(5), 663-671.

Whitaker, G.A., McCuen, R.H. and Brush, J. (1979): Channel modification and macroinvertebrate community diversity in small streams, *Water Resources Bulletin*, 15(3), 874-879.

White, D.S. (1993): Perspectives on defining and delineating hyporheic zones, *Journal of the North American Benthological Society*, 12(1), 61-69.

White, W.R. (ed)(1988): *International conference on river regime*, Hydraulics research limited, Wallingford, Wiley and Sons, Great Britain.

Whitlow, J.R. and Gregory, K.J. (1989): Changes in urban stream channels in Zimbabwe, *Regulated Rivers: Research and Management*, 4(1), 27-42.

Whitton, B.A. (ed) (1984): *Ecology of European rivers*, Blackwell Scientific Publications, Oxford.

Wiederholm, T. (1984): Responces of aquatic insects to environmental pollution, 508-557, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Wildlife Society of Southern Africa (undated): *Engineering aspects of stormwater pollution control*, Unpublished, 5pp.

Williams, D.D. (1981): Migrations and distributions of stream benthos, In: Lock, M.A. and Williams, D.D. (eds): *Perspectives in running water ecology*, Plenum, New York.

Williams, D.D. (1984): The hyporheic zone as a habitat for aquatic insects and associated arthropods, 430-455, In: Resh, V.H. and Rosenberg, D.M. (eds): *The ecology of aquatic insects*, Praeger, United States of America.

Williams, G.N. (1993): Implementing a watershed plan for Lake Stevens, 738-741, In: Hon (ed): *Water management in the '90s: a time for innovation*, ASCE.

Williams, P.B. (1990): Rethinking flood-control channel design, *Civil Engineering, ASCE*, 60(1), 57-60.

Williams, P.B. (1994): Flood control vs. flood management, *Civil Engineering, ASCE*, 64(5), 51-54.

Wils, C., Schneiders, A., Bervoets, L., Nagels, A., Weiss, L. and Verheyen, R.F. (1994): Assessment of the ecological value of rivers in Flanders (Belgium). *Water Science and Technology*, 30(10), 37-47.

Winget, R.N. (1985): Methods for determining successful reclamation of stream ecosystems, 165-192, In Gore, J.A. (ed)(1985): *The restoration of rivers and streams: theory and practise*, Butterworths, Boston, Massachusetts.

Winterbourn, M.J., Rounick, J.S. and Cowie, B. (1981): Are New Zealand stream ecosystems really different?, *New Zealand Journal of Marine and Freshwater Research*, 15, 321-328.

Wise, D.H. and Molles, M.C. (Jr.)(1979): Colonization of artificial substrates by stream insects: influence of substrate size and diversity, *Hydrobiologia*, 65(1), 69-74.

Wiseman, K. (1990): Stormwater management and land use planning in river systems, *Municipal Engineer*, June 1990, 22-31.

Wiseman, K. and Simpson, J. (1989): Degradation of the Eerste river system: Legal and administrative perspectives, *South African Journal of Aquatic Sciences*, 15(2), 282-299.

Wolman, M.G. (1967): A cycle of sedimentation and erosion in urban river channels, *Geografiska Annaler*, 49(2-4), 385-395.

Wolman, M.G. and Gerson, R. (1978): Relative scales of time and effectiveness of climate in watershed geomorphology, *Earth Surface Processes*, 3, 189-208.

Wood, A. (1993): The application of artificial wetlands in South Africa, *Imiesa*, (May), 15-18.

Wood, A. (1994a): Natural wastewater treatment - with specific reference to constructed wetlands, *Water Sewage and Effluent*, March, 14(1), 16-21.

Wood, A. (1994b): Localising wastewater treatment opportunities, *Municipal Engineer*, March, 25(2), 38-41.

Woody, T. (1993): Grassroots in action: the Sierra Club's role in the campaign to restore the Kissimmee River, *Journal of the North American Benthological Society*, 12(2), 201-205.

Wright, J.F., Blackburn, J.H., Westlake, D.F., Furse, M.T. and Armitage, P.D. (1992): Anticipating the consequences of river management for the conservation of macroinvertebrates, In: Boon, P.J., Calow, P. and Petts, G.E. (eds): *River conservation and management*, John Wiley and Sons, England.

Wyatt, J. (1995): Wetland fix: assessment, management and restoration of South African wetlands. Parts 1 to 6. Renfreight Wetlands Campaign.

Young, W.J. (1991): Flume study of the hydraulic effects of large woody debris in lowland rivers, *Regulated Rivers: Research and Management*, 6(3), 203-211.

Yu, S.L. (1993): *Stormwater management for transportation facilities*, National cooperative highway research program, Transportation Research Board, Report No. 174, 81pp.

Zimmer, D.W. and Bachmann, R.W. (1978): Channelization and invertebrate drift in some Iowa streams, *Water Resources Bulletin*, 14(4), 868-883.