GEOMORPHOLOGICAL RESEARCH FOR THE CONSERVATION AND MANAGEMENT OF SOUTHERN AFRICAN RIVERS

VOLUME 1: GEOMORPHOLOGICAL IMPACTS OF RIVER REGULATION

KM Rowntree · AJE du Plessis

WRC Report No. 849/1/03

Water Research Commission

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VOLUME 1: GEOMORPHOLOGICAL IMPACTS OF RIVER REGULATION

by

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EXECUTIVE SUMMARY

INTRODUCTION

The need to protect the river ecosystem as a component of the water resource base is being increasingly brought to the attention of water resource managers world wide. An essential component of this ecosystem is the river channel and its associated riparian zone, now recognized in South Africa through the National Water Act (36 of 1998) as constituting part of the water resource. The physical characteristics of the river channel and riparian zone are determined by geomorphological processes responsible for eroding the channel bed and banks and supplying, transporting and depositing the sediments which comprise many channel features. Geomorphologists worldwide, therefore, are increasingly being called upon to act in a professional capacity with respect to water resource protection and rehabilitation.

The geomorphological research presented in this report has a strong applied thrust. In particular it aims to develop geomorphological tools which should be seen as part of a multi-disciplinary approach to management aimed at the conservation of the ecological integrity of our river systems. Much of the research has been co-sponsored by the Water Research Commission (WRC), the National Research Foundation (NRF) and the Department of Water Affairs and Forestry (DWAF). Specific research objectives were set as follows:

- **to refine the geomorphological component of the IFR methodology,**
- **to develop geomorphological indices and monitoring procedures to assess channel condition,**
- **to further assess the hydraulic biotope concept and its application to the assessment of habitat condition.**

Geomorphological Indices were developed as part of a separate initiative funded by the Department of Water Affairs and Forestry. Separate reports have been published as part of the River Health Programme series: Rowntree and Ziervogel (1999); Rowntree and Wadeson (2000). This report presents the results of research aimed at refining the geomorphological component of the IFR methodology through both fundamental research into geomorphological processes and the development of the hydraulic biotope concept.

The research is presented in two volumes. The first examines the geomorphological impact of water resource developments through impoundment behind dams and through interbasin transfers, two common activities in South Africa. These are both situations where an IFR (or the quantity aspects of the Reserve) would be required to mitigate the effects of the developments. Chapter 2 of Volume 1 presents a review of the international literature on impoundments studies undertaken by McGregor as part of her Masters thesis (McGregor, 2000). The main part of Volume 1 presents the work by Du Plessis on the impact of an interbasin transfer between the Fish River and Lake Darlington in the Eastern Cape. This is the first detailed study of the geomorphological impacts of an interbasin transfer scheme to be undertaken in South Africa. Indeed there are few if any similar studies reported in the international literature.

The second volume presents work which was undertaken with the specific objective of supporting the determination of the geomorphological flow requirement for the Environmental Reserve. Rowntree and Wadeson (1998) point out that the geomorphological contribution to the setting of IFRs has focussed on three groups of information requirements: the maintenance of channel form, the maintenance of substratum characteristics, and temporal availability of hydraulic habitat.

The time and space scales over which geomorphological processes operate is an important consideration in river management. The maintenance of channel form, the ultimate determinant of the in-stream flow environment, must consider processes that take place in the medium to long term (10 to 100 year period). Channel form is the long term response to movement of sediment through the river long profile and is the result of dynamic processes that take place within the geomorphological time scale and are manifested in the reach space scale. The maintenance of substratum characteristics involves, firstly, the seasonal flushing of fine materials from the surface matrix of the gravel-bed and, secondly, the over-turning and transport of the coarse matrix itself. These are essentially event driven processes which respond at the scale of the morphological unit. Seasonal inputs of sediment from the catchment are also important. Hydraulic habitat is determined by the response of the instantaneous discharge to a fixed channel morphology. Hydraulic habitat varies within the short term in response to the flow hydrograph and over small space scales determined by channel morphology and bed substratum.

Channel geomorphology is determined by the cumulative effects of events over geological, geomorphological and hydraulic time scales. Interpretation of channel form and recommendation of future flow regimes for managing form must take into account the environmental history. An in depth review of environmental change in South Africa as it relates to fluvial geomorphology is given in Chapter 2 of Volume 2.

A key concept underpinning geomorphological flow requirements to maintain channel form and channel substratum characteristics is that of magnitude and frequency. Setting the water quantity requirements for the Ecological Reserve is about recommending the flow regime to ensure that the resource quality is maintained. One component of the geomorphological flow requirement is the high flows or flood flows required to maintain channel form and bed conditions through the transport of sediment. The key question is 'what magnitude of flows are required to transport the incoming sediment without causing excessive erosion and channel enlargement and how often should they occur?'. The magnitude and frequency of channel forming flows has been an ongoing debate amongst geomorphologists. The application of this thinking to the Reserve determination is explored by Dollar in Chapters 3 to 10 of Volume 2.

The final section of Volume 2 addresses the relationship between magnitude and frequency of flows and available habitat within a stable channel. Wadeson developed the concept of the hydraulic biotope to describe discharge variant changes in hydraulic habitat within morphological units (Wadeson 1996; Rowntree and Wadeson 1999). The application of the hydraulic biotope concept to Reserve determination is taken further in the research presented in Chapter 11.

CHAPTER SUMMARY

CHAPTER 1: INTRODUCTION: GEOMORPHOLOGY AND WATER RESOURCE *PROTECTION IN SOUTH AFRICA*

Chapter 1 provides a common introduction to the two reports. The chapter begins by highlighting the contribution that geomorphologists are now making world wide to the field of river management. Geomorphology provides the physical template of the biophysical environment, so that geomorphological processes and geomorphological change can have a major impact on available habitat. For this reason geomorphologists have found an important niche in guiding measures for water resource protection, where the water resource is considered to encompass the whole river ecosystem. The importance of geomorphological space and time scales and their relevance to river management is emphasised in this chapter.

Although fluvial geomorphology is a well developed discipline internationally, the study of geomorphological processes has only made headway in South Africa over the last decade.Many international studies of process-form relationship have been empirical in nature: it is therefore inadvisable to apply the results directly to South African systems. Local field studies are needed before we can understand our own fluvial systems.

The aims of the research and an outline of the structure of the report are presented in Chapter 1. These have been presented above in the Introduction.

VOLUME 1

CHAPTER 2: DOWNSTREAM IMPACTS OF IMPOUNDMENTS: A PREDICTIVE MODEL FOR SOUTH AFRICA

Chapter 2 presents a review of impoundments in South Africa and their potential geomorphological impacts. The primary aim of the research was to develop a conceptual model of the geomorphological impacts of river regulation, based on a review of relevant international literature. It was motivated by the fact that there is little local information on the topic, and it was intended that the model might provide a starting point for assessing the impact of impoundments on South African river systems.

An analysis of the development of dam capacity in South Africa is presented in the first half of Chapter 2. This was based on an analysis of the data base on dams compiled by Midgley *et al.* (1994) Due to the variability of South Africa's climate, dams have to be larger than elsewhere in the world in order to trap most of the mean annual runoff and provide a reliable water store. These dams have been designed to reduce the variability of a naturally variable regime: in total 50% of the available runoff is impounded. Many large dams were built during the past century, reaching a peak in the 1970s, followed by a period when many smaller capacity dams were built. An assessment of the capacities of South African dams relative to the natural runoff in their catchments shows that many areas have been developed beyond their capacity.

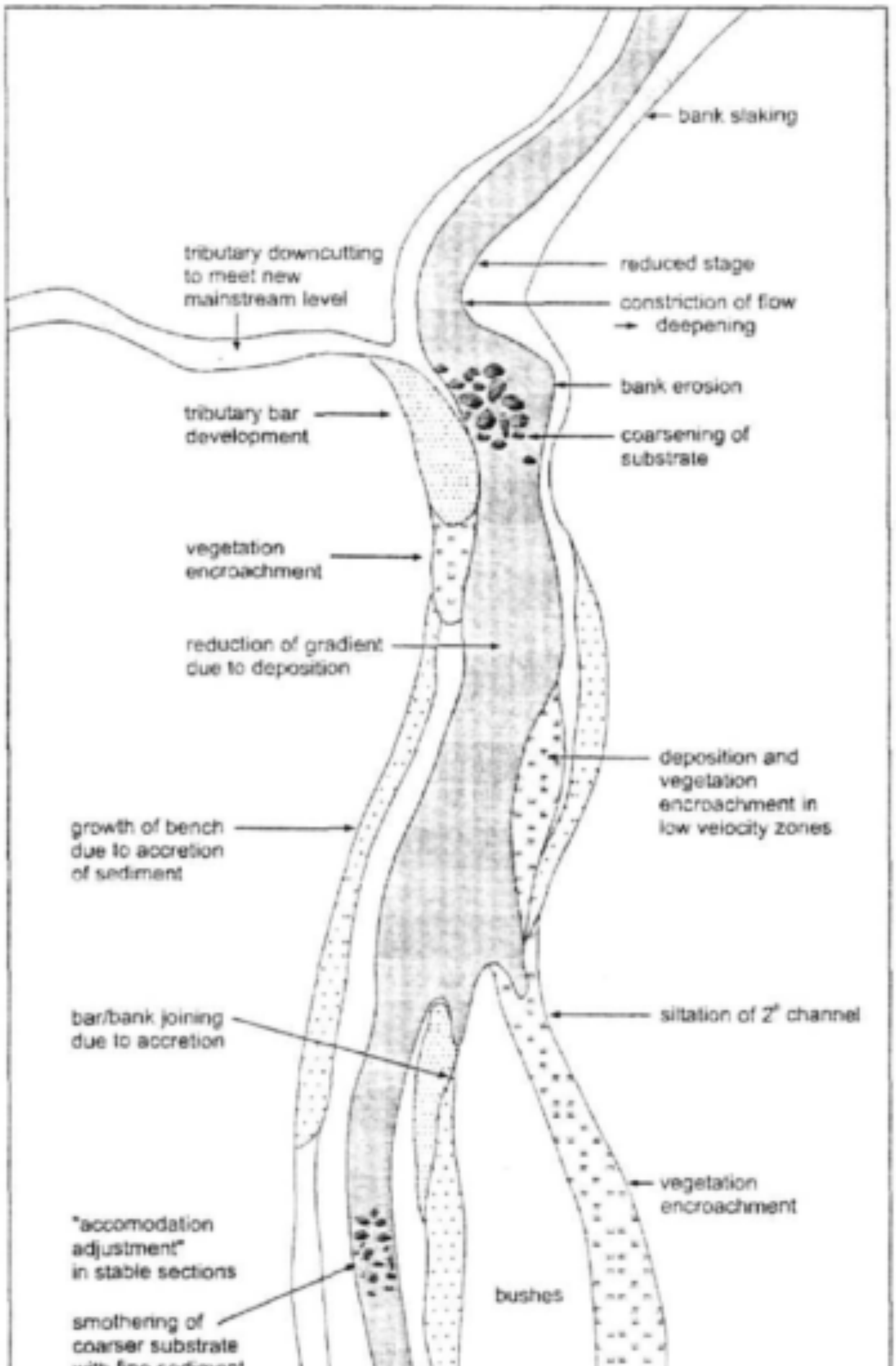

Figure 2.6: *Illustration of morphological change in an impounded river.*

A review of 77 papers from the international literature (Appendix 1) was used to document the various processes that can take place below a dam (Figure 2.6) and to develop a conceptual model of channel change (Figure 2.8). The model showed that there are many responses to river impoundment, which are varied and complex, both in time and space. Responses or secondary impacts depended on the nature and degree of the primary impact or process alteration and on the sediment and flow regime of the river. High flows were affected in all cases and low flows were affected in most cases. The simplest form of change was Petts' (1979) concept of 'accommodation' of the regulated flow within the existing channel form. More complex responses occurred where the channel perimeter was unstable, or where tributaries introduced fresh sediment loads. The river could adjust its long profile, cross-sectional area and substrate composition by aggradation or degradation. A 'working diagram' related to all the recorded responses and the conditions under which they occur, was constructed (Figure 2.8). It serves as a starting point for predicting change in particular reaches in an impounded river.

It is intended that these conceptual models may be used as basic tools which might contribute to a better understanding of our river systems, and ultimately to improved sustainable resource management

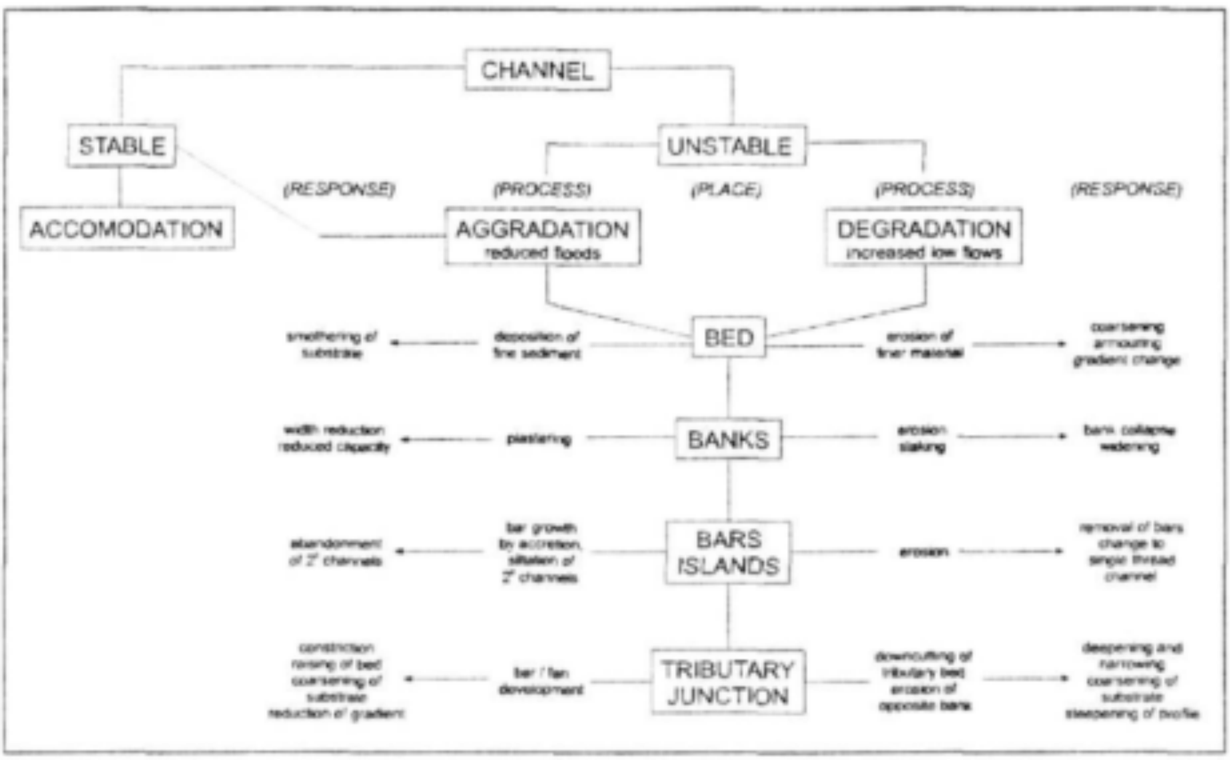

Figure 2.8: *Flow diagram for predicting morphological change.*

CHAPTER 3: INTERBASIN TRANSFER SCHEMES IN SOUTH AFRICA

In Chapter 3 our attention turns to the issue of interbasin transfers (IBTs). This chapter outlines the extent of IBTs in South Africa and points to the lack of attention given to their geomorphological impacts. The South African situation is mirrored by the global picture; there is an apparent lack of research world wide.

CHAPTER 4: GEOMORPHOLOGY AND RIPARIAN ECOSYSTEMS IN DISTURBED SYSTEMS - A THEORETICAL VIEW

Chapter 4 presents a review of literature on the geomorphological and vegetation processes operating in a fluvial system and assesses the likely impacts of an IBT on these processes. An interbasin transfer has a number of direct and indirect effects on the biogeomorphology of the receiving river channel. The primary impact is a change in the flow. A secondary impact is the change in sediment dynamics as material is eroded and redeposited within the system. Together changes in flow and changes in sediment dynamics result in an adjustment of the channel morphology or channel geometry. The newly created channel morphology in turn provide new habitat for riparian vegetation which is also effected by the increased water availability. Changes in riparian vegetation impart feedback effects on channel stability.

It is shown how, under natural conditions, channel form can be expected to change in a regular manner downstream. Width and depth should both show a progressive increase in depth downstream, while channel morphology should change from one dominated by erosional processes to one in which depositional forms become more prevalent. Vegetation can be expected to reflect this change in morphology, with an increased morphological heterogeneity being reflected in an increased species diversity. As vegetation becomes established it will tend to aid erosional or depositional processes depending on its characteristics and position in the channel and along the long profile.

The primary impact of an IBT is the increase in flow. This will be most significant in the reach immediately below the receiving point where the transferred flow is likely to dominate the hydrograph, especially in a semi-arid system. Baseflow levels throughout the system will be significantly increased and in the upper reaches of the river may approach natural flood levels. This distortion of the natural downstream flow pattern can be expected to impact on the downstream hydraulic geometry, the pattern of sediment supply and deposition and the morphological heterogeneity of riparian habitat.

CHAPTER 5: CASE STUDY OF TWO SOUTH AFRICAN RIVERS.

Research designed to test the assumptions set out in Chapter 4 is described in Chapter 5. The research was based on the Skoenmakers River in the semi-arid Karoo region of the Eastern Cape. This river is used as a transfer route for the Orange-Fish-Sundays River Interbasin Transfer Scheme. Water from the Orange River is conveyed by way of the Great Fish River before passing by canal to the top of the Skoenmakers. The Skoenmakers is then used to convey water into Lake Darlington where it is stored for use in the Sundays River Irrigation schemes and by the Nelson Mandela Metropole, which includes Port Elizabeth. The transfer has changed the hydrological regime of this once ephemeral stream to a much bigger perennial river. The effect of this change on the geomorphology and riparian vegetation was evaluated through a comparison with a non-regulated tributary of equivalent size, the Volkers River.

Qualitative, descriptive geomorphological data was gathered by means of field observations and this was then compared to the quantitative data collected by means of surveyed cross-sectional profiles at selected sites along the length of both the regulated Skoenmakers River and the non-regulated Volkers River. Riparian vegetation data was gathered by means of plot sampling along belt transects at each site. A qualitative assessment of the vegetation conditions was also made at each site and then added to the quantitative data from the plot sampling. At each site the different morphological units were identified along the cross-section and changes in the vegetation and sediment composition were recorded. Aerial photographs were used as additional sources of data and observations made from these were compared to data gathered in the field.

CHAPTER 6: RESULTS OF THE CASE STUDY

The flow regime of the regulated Skoenmakers River changed after 1978 from an ephemeral stream to a perennial river with a maximum average daily flow of four cubic metres per second. After 1985 the maximum average daily flow increased to 22 cubic metres per second. Thus a flood dominated ephemeral stream was converted into a base flow dominated perennial river.

The change in the hydrological regime of the Skoenmakers River had dramatic impacts on the physical and ecological characteristics of the river. It directly influenced the channel geometry, i.e. the long profile and the cross-sectional profile. The influence on the riparian vegetation's composition and spatial distribution was found to be either direct (eg. loss of species caused by inundation) or indirect (eg. loss of species due to loss of suitable regeneration sites).

The most prominent changes to the channel of the Skoenmakers River was the incision of the channel bed in the upper reaches to such a degree that the bedrock has been exposed (Figure 6.6). Other changes to the channel due to the IBT include an initially wider active channel zone (increased width), armouring of the bed due to the removal of finer sediment, more bed material further downstream due to sedimentation, and decreased lateral stability of the channel. A comparison of similar sites in the non-regulated Volkers River with sites in the middle reaches of the regulated Skoenmakers River showed the formation of shelves as the only major difference in this section of the regulated river (figure 6.7). Morphological units such as shelves and mid-channel bars was found to have a stabilising effect on the river channel's geometry. This effect on the stability of the channel can be direct through the enhancement of deposition of sediment or indirect by providing additional habitat for riparian vegetation growth and therefore an enhancement of the deposition of finer materials. High degrees of sediment deposition in the lower reaches of the regulated river led to a decrease in the average channel depth. The lower reaches of the regulated river were able to 'absorb' the impact of the IBT much better than the upper reaches (Figure 6.8).

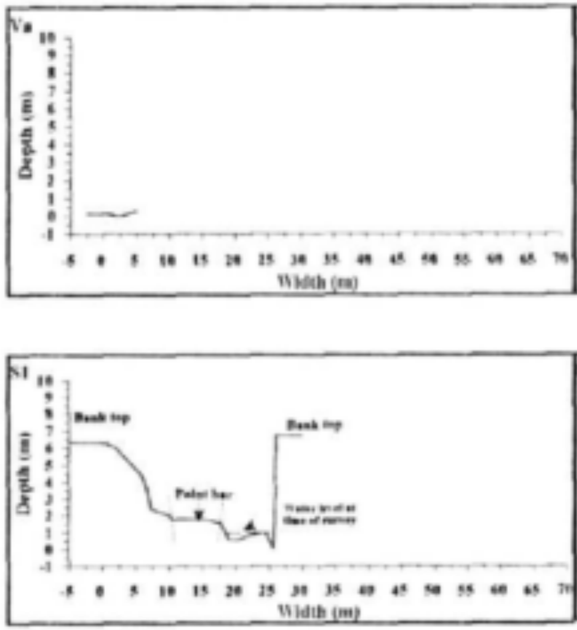

Figure 6.6: *Comparison of two cross-sectional profiles for the upper reaches of the Volkers (Va) and Skoenmakers River (S1) immediately below the point of inflow of the IBT.*

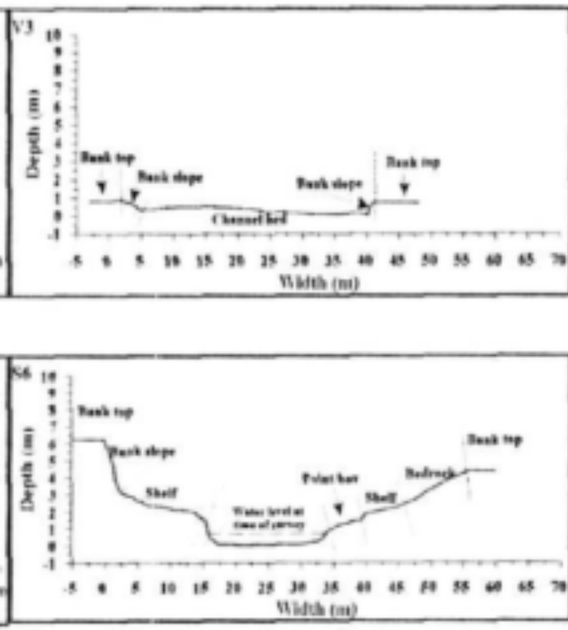

Figure 6.7: *Comparison of two cross-sectional profiles for the middle reaches of the Volkers (V3) and Skoenmakers (S6) approximately 25 km below the point of inflow of the IBT*

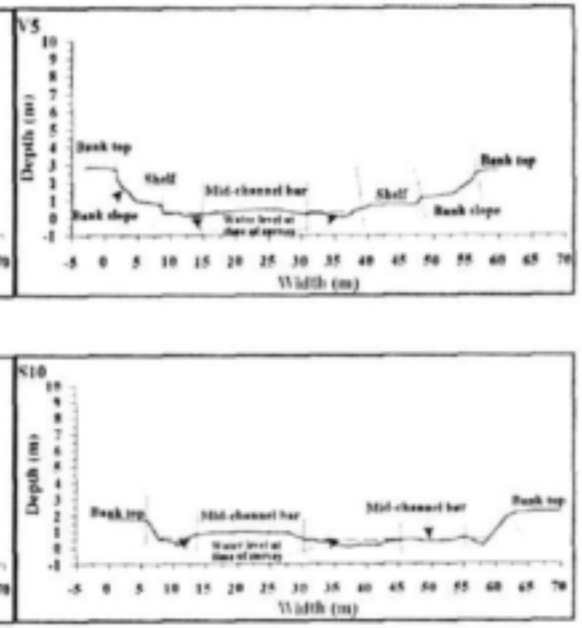

Figure 6.8: *Comparison of two cross-sectional profiles for the lower reaches of the Volkers (V5) and Skoenmakers (S10) approximately 40 km downstream for both rivers*

Erosion and deposition play a major role in the morphological diversity of the physical habitat which, in turn, was found to affect the diversity of the riparian vegetation. It was evident that an increase in the diversity of the physical habitat along the cross-sectional profile led to an increase in the species diversity of the riparian vegetation (Figure 6.10. The spatial distribution of the different riparian vegetation types (grass, reeds, sedges, etc.) was found to be influenced by the type of sediment present, the distance away from the channel and elevation above the water level. It was found that woody species prefer distances further away from the active channel and therefore also higher elevations above the water level. Sedge species were present at sites where a higher percentage of finer sediment was observed, especially where shelves have been formed. The presence or absence of sedge species could therefore be linked to site availability.

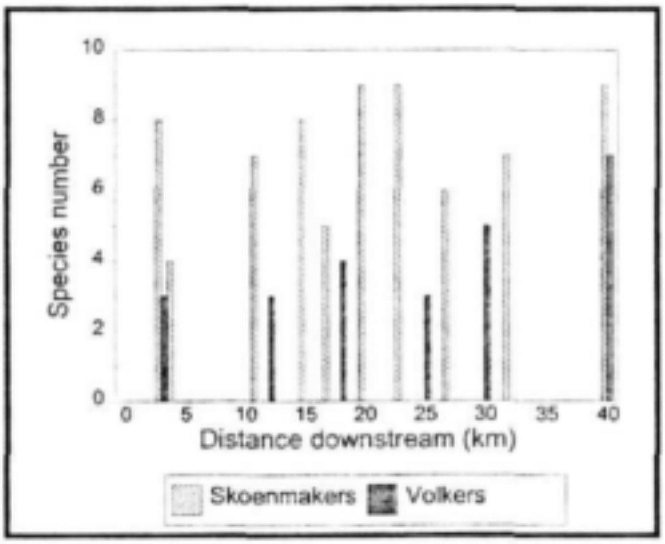

Figure 6.10: *Downstream change in the number of riparian vegetation species for the Volkers River and Skoenmakers River.*

The availability of suitable sites for regeneration and establishment of riparian vegetation species was strongly influenced by the pattern of erosion and deposition. Increased erosion led to a loss of habitat in the upper reaches of the regulated river but caused the introduction of more sediment into the river system downstream. Deposition of this additional sediment created new sites for the establishment of species such as grass and sedges. It was found that a strong link exists between the number of riparian vegetation species and the number of morphological units along the cross-sectional profile, and therefore the availability of sites.

The influence of the IBT on the Skoenmakers River in terms of the composition of the riparian vegetation was evident from the greater average number of species for the regulated river. This increase in the number of species was found to be related to the introduction of sedge species to the former ephemeral system as a result of the available water. A comparison of the importance percentages in terms of the different vegetation types, trees, grass and sedges (Figure 6.11),clearly indicated a lower value for woody species along the regulated Skoenmakers River in comparison to the non-regulated river. On the other hand, significantly higher

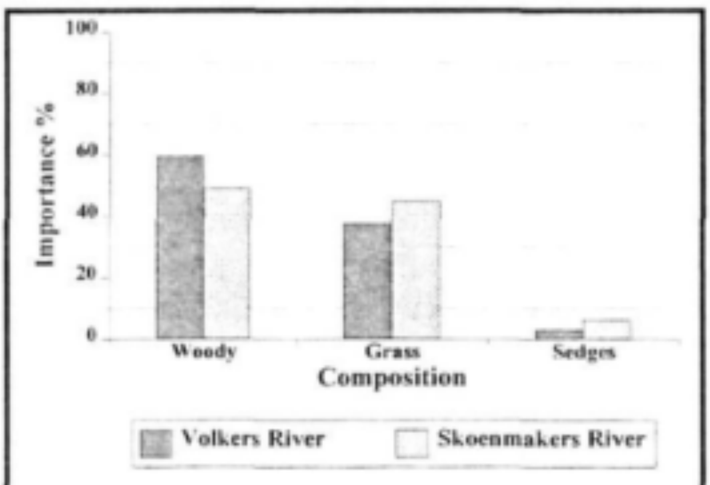

Figure 6.11: *Importance percentage for vegetation types in the Skoenmakers river.*

importance percentages were recorded for grass and sedge species along the regulated river when compared to the non-regulated Volkers River. Sedge species values more than doubled along the regulated river.

The effect of water availability was most evident for the woody species of the regulated river. This vegetation type has increased along the regulated river for the post-IBT period due to the availability of water on a regular basis to the otherwise dry stream.

CHAPTER 7: CONCLUDING REMARKS.

The final chapter in Volume 1 presents an overview of findings. Of interest is the concern raised over biodiversity, which generally increased as a result of the IBT. In the upper eroding reaches instability of both bed and banks resulted in loss of riparian vegetation without the creation of new stable habitat. In the middle to lower reaches, however, species diversity increased relative to the natural vegetation characteristic of the ephemeral Volkers River. This raises the question of whether maximum biodiversity is always the best measure of river health. If the ecological status is to be measured against the natural condition, the more diverse Skoonmakers system is clearly significantly modified in terms of hydrology, geomorphology and ecology as a result of the interbasin transfer. The implications of this change for the regional ecology are unknown.

VOLUME 2

CHAPTER 2: SOUTHERN AFRICAN FLUVIAL SYSTEMS

Chapter 2 presents a review of the current state of knowledge of the physical functioning of southern African fluvial systems. The review highlights that modern southern African fluvial system form is dependent on the physical template imposed by past geological, tectonic and climatic processes. This, together with a highly variable and unpredictable hydrological regime has resulted in many rivers being incised on to bedrock, with steep irregular longitudinal profiles and complex two-phase channels. While the origins of modern fluvial systems are better understood, modern fluvial system *process* studies are limited and fragmentary. The review further highlights the scarcity of information relating to the magnitude and frequency of channel forming discharge and bed material transport of southern African fluvial systems. This limits the ability of the geomorphologist to contribute meaningfully to the setting of the Ecological Reserve. It is argued that since southern African fluvial systems are subject to a highly variable and unpredictable hydrological regime, and are strongly influenced by bedrock control, that for effective river management to occur, there is an urgent need to develop appropriate local knowledge. This report attempts, in part, to develop that knowledge.

CHAPTER 3: MAGNITUDE AND FREQUENCY OF CHANNEL FORMING DISCHARGE

Chapter 3 presents a review of the magnitude-frequency debate. The debate essentially reflects the fact that there are theoretical problems with defining 'important' discharges in rivers and that this problem remains largely unresolved. Two sections are covered; the first section considers the magnitude-frequency debate, while the second section reviews environmental flows with specific reference to sediment-maintenance flushing flows. The first section highlights the fact that where *work* in rivers is defined as long-term sediment transport, moderate-magnitude, high-frequency events are considered the most *effective discharges* in that they transport the most sediment over a long period. The physical expression of this flow is often the *bankfull discharge*, also commonly termed *dominant discharge*. However, where *work* is defined as 'irreparable' modifications to the landscape, high-magnitude, low-frequency events are considered the *effective discharges*, as they are the only events that are capable of mobilising the entire bed, altering channel morphology and affecting channel change. Nested between these apparent opposite ends of the spectrum are those systems characterized by highly variable hydrological regimes with nested channel architectures that are adjusted to multi-scale discharges. The three sets of information required for a geomorphological assessment for IFRs (discussed earlier) are fundamentally linked to the magnitude-frequency debate. The second section of the chapter reviews environmental flows and concludes that despite the difficulties and limitations of environmental flow methodology, the holistic management of rivers requires an environmentally acceptable flow regime must be based on sound scientific principles. The chapter concludes that while it is clear that there is no singular relationship between event magnitude, frequency, duration and sediment flux or fluvial system change, the magnitude-frequency concept provides a useful tool around which the question of what flows are 'important' for fluvial system functioning can move forward. This is not a trivial point, for our understanding of fluvial system functioning is key to the way in which fluvial systems are managed.

CHAPTER 4: GEOMORPHOLOGICAL APPROACHES TO BED MATERIAL TRANSPORT

Chapter 4 provides a review on bed material transport. The chapter highlights the fact that knowledge of bed material transport is critical in understanding fluvial system functioning, as the movement of bed material acts as a regulator of a river's character, geometry, planform, cross-section and longitudinal profile. Furthermore, the review highlights the fact that bed material transport is a complex process that is difficult to model accurately, particularly where the riverbed consists of coarse heterogeneous material and/or where unsteady flow conditions are in operation. Basic terminology relating to bed material transport is explained, as are the difficulties and limitations of predicting initial entrainment and the movement of particles. Temporal variations in transport and supply are also considered. An overview and comparison of the equations available for predicting bed material transport, their limitations, constraints and potential application are also presented. It is concluded that very little progress has been made in understanding the processes related to bed material transport, and that as long as the physics of bed material transport remains incompletely understood, there is little reason to suggest that any of the available bed material transport equations will produce accurate results. The chapter concludes that despite this obvious shortcoming, when faced with practical problems such as recommending flows that will perform a specific sediment transport task, the application of highly simplified, imprecise models are often the only practical paths forward.

CHAPTER 5: THE STUDY AREA AND RESEARCH DESIGN

The South African National Water Act of 1998 requires river managers to apply Resource Directed Measures to the protection of water resources. Though these measures it has become necessary to define a (regulated) flow regime that will mimic the significant effects of the natural pre-impoundment flow. This assumes, however, that scientists/engineers are able to predict the range of flows that maintain the flood plain, macro-channel and active channel in a 'natural' or 'equilibrium state' for a specified spatial and temporal domain. From a geomorphological perspective, this requires identifying the magnitude and frequency of channel forming discharge and sediment-maintenance flushing flows for a particular river reach. Currently, there are no methods available to achieve this. Research described in this report attempted, in part, to fill this information gap.

The aim of this research was stated as:

> ***to determine the magnitude and frequency of channel forming discharge for selected southern African rivers.***

A number of objectives were set in order to achieve this aim.

Objective 1: ***To determine the relationship between channel form, bed material transport and flow discharge for selected rivers..***

Objective 2: ***To determine the magnitude and frequency of the natural bankfull discharge with respect to channel form for selected rivers.***

Objective 3: ***To develop a conceptual model of channel forming discharge for selected rivers.***

Chapter 5 presents a description of the study areas, the research design and structure of the research process. Three rivers were selected for study that are representative of different channel types in southern Africa. These channels reflect a range of systems from the relatively un-impacted, semi-confined cobble-bed Mkomazi River in Southern KwaZulu-Natal; to the highly impacted alluvial, single thread Mhlathuze River in Northern KwaZulu-Natal; to the semi-confined, bedrock controlled Olifants River in Mpumalanga. The study sites on each of these rivers were chosen to be representative of different channel types associated with particular macro-reaches. The sites were surveyed in a manner that would achieve the research objectives. The research design reflects two major foci: The Mkomazi River was selected as the main research system where the techniques to determine the magnitude and frequency of channel forming flow were developed.. The Mhlathuze and Olifants Rivers were application systems where these techniques are applied to the see whether they could be used to explain the response of a channel to flow regulation.

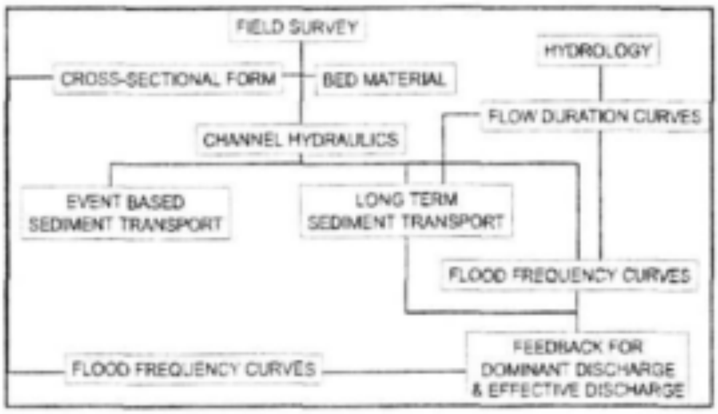

Figure 5.9: *Flow diagram indicating the structure of the research.*

The research process followed the structure depicted in Figure 5.9. Field surveys of cross-sectional data andbed material class for sites in the three different river systems were used to estimate long term bed material transport based on the hydrological record. Hydraulic variables determined from the cross-section data were used as input to bed load equations. Stage discharge rating curves together with long term flow duration curves were then used to determine the effective discharge for sediment transport.

Effective discharge was defined as the discharge class that has the greatest potential to transport sediment in the long term. This was estimated by combining flow duration curves with potential sediment transport estimated for predefined flow classes. Dominant discharge was defined as the flow value at which flows of this size or greater collectively transport 50 % of the long term sediment load.

Channel form features such as the bankfull level and in-channel benches were compared to flow variables such as flood peaks of a given recurrence interval, effective discharge and dominant discharge. The results of this analysis can guide interpretation of channel morphology in terms of geomorphologically effective flows.

This research was directed towards increasing our understanding of the importance of different flows for South African fluvial systems, thus contributing towards a better understanding of the discharges that are of 'significance' or 'importance' in selected South African rivers. This is of particular relevance in South Africa, where rivers are often controlled or semi-controlled by bedrock, have steep gradients with irregular long profiles, are often supply-limited and are subject to a highly variable hydrological regime. Little attention has been paid to these sorts of fluvial systems in the literature, and they are therefore poorly understood.

CHAPTER 6: HYDROLOGY

Chapter 6 describes the methods used to generate representative daily time series for each of the sites for the Mkomazi, Mhlathuze and Olifants Rivers. The daily time series are required for the bed material transport modelling (Chapter 8). The technique used is an adaptation of the one used to generate flow data for Ecological Reserve assessments (Hughes & Smakthin, 1996). The model uses an algorithm to patch and extend (if necessary) observed time series of daily streamflow. The technique is based on typical flow duration curves and on the assumption that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective flow duration curves. A two-step generation process is used: 1) the generation of source flow duration curve tables for source and target sites, and 2) the simulation of the time series using target flow duration curves for each site. The results of the modelling exercise are presented within the context of the historical flood records available for the Mkomazi and Mhlathuze Rivers. The modelled results indicate that the unregulated Mkomazi catchment generates the largest MAR of all three systems (1089 MCM), but the lowest CV (0.41). The daily time series for the Mkomazi system reflect natural (virgin) conditions. The impounded Mhlathuze River has a lower MAR (Virgin MAR 362 MCM; Present-day MAR 217 MCM) than the Mkomazi system, but has the highest CV of all three systems (0.93). Virgin and present-day flows were generated for the Mhlathuze system. Data for the Olifants system indicates a virgin MAR of 449 MCM and a CV of 0.70.

CHAPTER 7: CROSS-SECTIONAL DATA, BED MATERIAL AND HYDRAULICS

Chapter 7 presents the methods and results for the cross-sectional data analysis, bed material sampling and hydraulic computations. Sites for each of the three rivers were selected based on the representivity of channel types within the macro-reaches, the degree of disturbance and accessibility. A number of representative fixed-point cross-sections were surveyed at each site. Each of the cross-sections was rated and the modelled discharge extrapolated beyond the range of field measurements by estimating the 'friction slope-resistance'. Morphological features were identified in the field in a consistent manner. A minimum of 500 bed material samples were taken at each site and analysed using conventional laboratory techniques. These were later used in the bed material transport modelling exercise (Chapters 9 and 10). The study is therefore based on 13 sites and 27 cross-sections for the Mkomazi River, 4 sites and 12 cross-sections for the Mhlathuze River, and four sites and 26 cross-sections for the Olifants River.

CHAPTER8: BED MATERIAL TRANSPORT AND SEDIMENT-MAINTENANCE FLUSHING FLOW METHODS

Chapter 8 considers the methods used for the bed material transport calculations and the techniques employed in determining effective discharge and dominant discharge. The effective discharge is calculated using three selected bed material transport equations, together with the hydrology, cross-sections, bed material data and stage-discharge rating curves. The three bed material transport equations utilised include the Yang (1972), Ackers & White (1973) and Engelund & Hansen (1967) equations. These were chosen based on their suitability and good performance in a number of comparative tests. The dominant discharge was calculated using the Marlette & Walker (1968) equation. It is important to recognize that calculating the potential bed material load (PBML) and sediment-maintenance flushing flows depends on the magnitude, frequency and duration of flows that determine the hydraulic conditions necessary for transport, the bed material grain-size distribution, the type and spacing of the bed forms (if any exist) (form resistance), antecedent conditions and supply. Practically, it is difficult to account for all these factors, and hence it is necessary to make a number of assumptions in utilising this approach, these include:

- The bed material sampling programme for each site is representative of the supply of the material to the channel (hence PBML as opposed to bed load).
- Bed material sampling can be averaged for the whole site and used to represent each cross-section.
- The supply of material to each site is based on the existing bed material and its size distribution, and is available for transport at all discharges.
- Average conditions can be used.

Thus, the values that are generated are linked to individual cross-sections and represent bed material transport *potential* within the prediction limits of the equations for average conditions, and second, the technique does not account for sediment supply.These need to be considered in interpreting the results. It is argued, however, that given the lack of a suitable alternative, the approach provides a useful tool for determining channel forming discharge, but needs to be used with circumspection by a scientist/engineer who is aware of the limitations of the approach.

CHAPTER 9: RESULTS AND DISCUSSION – THE MKOMAZI RIVER

Chapter 9 presents the results obtained for the bed material transport analysis and the sediment maintenance flushing flow computations for the unregulated Mkomazi River. The results are discussed in the context of four research questions, these are:

- What are the channel morphology characteristics?
- What is the dominant discharge?
- What is the effective discharge?

- Is there any relationship between estimated bankfull discharge, dominant discharge and effective discharge?

Table 9.4: R-squared values for the relationships between flow variables and morphological features for the Mkomazi River (represents statistical significance at the 95% level).*

R^2	DD (Y)	DD (AW)	DD (EH)	Q_s (Y)	Q_s (AW)	Q_s (EH)	$Q_{1.5}$	$Q_{2.44}$	$Q_{p0.9}$	$Q_{p2.0}$
DD (Y)	-	0.39	**0.88***	**0.72**			**0.79***	**0.83***	**0.84***	**0.84***
DD (AW)		-	0.42		**0.77***		0.33	0.34	0.31	0.34
DD (EH)			-			**0.88***	**0.82***	**0.82***	**0.82***	**0.83***
Q_s				-	0.51	0.22	0.54	0.56	0.57	0.57
Q_s (AW)					-	0.30	0.55	0.55	0.54	0.54
Q_s (EH)						-	**0.71***	**0.71***	**0.72***	**0.72***
Q_b	0.06	0.001	0.09	0.005	0.002	0.17	0.04	0.05	0.06	0.06
B1	**0.73***	0.15	0.31	**0.82***	0.38	0.12	0.48	0.57	0.67	0.65
T1	0.01	0.07	0.01	0.02	0.20	0.01	0.16	0.13	0.10	0.10

DD (Y)	dominant discharge using the Yang equation
DD (AW)	dominant discharge using the Ackers & White equation
DD (EH)	dominant discharge using the Engelund & Hansen equation
Q_s (Y)	effective discharge using the Yang equation
Q_s (AW)	effective discharge using the Ackers & White equation
Q_s (EH)	effective discharge using the Engelund & Hansen equation
$Q_{p1.5}$	1.5 year return period flow on the annual series
$Q_{p2.44}$	2.44 year return period flow on the annual series
$Q_{p0.9}$	0.9 year return period on the partial duration series
$Q_{p2.0}$	2.0 year return period on the partial duration series
Q_b	estimated bankfull discharge
B1	bench
T1	low terrace

The results indicate that the Mkomazi River does not conform to conventional wisdom developed for temperate alluvial rivers, in that the channel is strongly controlled by local conditions such as bedrock, a variable hydrological regime and a coarse heterogeneous bed. There does not appear to be any relationship between the estimated bankfull discharge and the hydrological regime. However, there does appear to be some agreement between the 0.9 and 2.0-year return period on the partial duration series and the 'bench-full discharge'. Two sets of 'effective discharges' are significant: an effective discharge that transports the most bed material over a long period of time - this has been shown to be in the 5-0.1%

range on the 1-day daily flow duration curve (Figure 9.4) and, second, a 'reset discharge' - a flood event with a return period in the range of 20 years that has the energy to mobilise the entire bed thereby maintaining the channel. The channel architecture of the Mkomazi River is therefore a response to two sets of effective discharges: the active channel is controlled by the lower set of effective discharges, while the macro-channel and overall channel form is a response to the 'reset' discharge. It is argued that these two sets of effective discharges do not operate independently of each other: rather the effective discharge sets the template for the effectiveness of the 'reset' discharge.

CHAPTER 10: RESULTS AND DISCUSSION – THE MHLATHUZE AND OLIFANTS RIVERS

Chapter 10 presents the results obtained for the bed material transport analysis and the sediment maintenance flushing flow computations for the regulated Mhlathuze and Olifants Rivers. The discussion is presented in terms of four research questions, these are:

- Do the results obtained from the two regulated systems add to the understanding gained from the Mkomazi system? What is the impact of flow regulation on the relationships?
- Are the observed morphological conditions related to virgin flow conditions or the regulated present-day conditions?
- What lessons can be learnt for Instream Flow Requirement (IFR) assessments?
- Given the results obtained, what flows should be recommended and why?

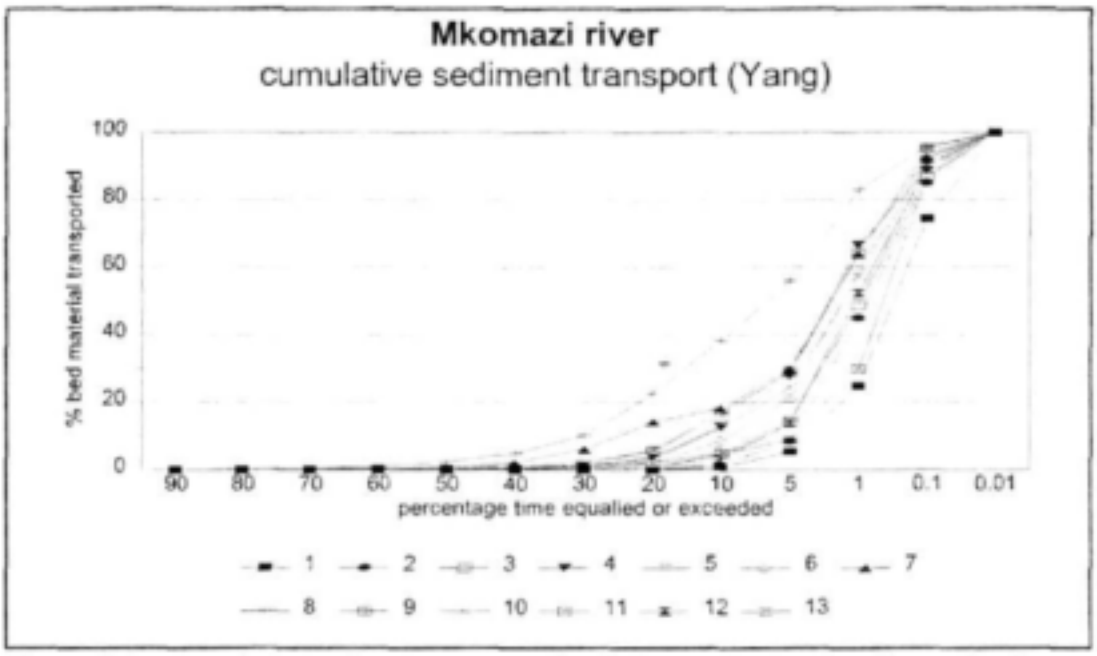

Figure 9.4: *Cumulative sediment transport for the Yang equation for all sites for the Mkomazi River.*

It was demonstrated that the channel morphology and PBML in the Mhlathuze River has been considerably altered by the regulated flow environment, with the present-day observed morphological relations related to present-day flow conditions. The Olifants River on the other hand shows a high degree of resilience to change, probably due to the strong bedrock control of the channel boundary and the coarse heterogeneous bed. It is probable that the Olifants system is supply-limited and that the coarse bed material is a reflection of this state. Given these results, it is likely that fluvial systems will respond very differently to a regulated flow environment. Both the Mhlathuze and Olifants systems display highly variable hydrological regimes under virgin flow conditions (CV of 0.93 and 0.70 for the Mhlathuze and Olifants Rivers respectively), and yet they respond very differently to the imposed change. The Mhlathuze shows major geometry and bed material transport capacity changes, while the Olifants indicates very little adjustment. It would appear that channel boundary conditions are of great significance in determining the impact of flow regulation. This must be taken into account when setting IFRs. It has been suggested that for the Mhlathuze, different flows should be recommended for the site immediately below the Goedertrouw Dam, and for those sites downstream of the major tributaries. Where tributary inputs of discharge and sediment occur, bed mobility conditions and degree of human impact need to be taken into consideration. It is argued that flows should be set close to the effective discharge to ensure that the amount of sediment entering a channel reach is equivalent to the amount of sediment exiting a reach (i.e. an equilibrium state). Two sets of effective discharges were recommended for the Olifants system: first, the effective discharge that would ensure that fine material, sand and gravel would be flushed through the system thereby preventing fine material entering the interstitial zone. Second, that high magnitude low frequency 'reset' flood events should be allowed to move through the system to ensure that bed is overturned occasionally, thereby maintaining the channel form.

CHAPTER 11: THE DEVELOPMENT OF MAPPING TECHNIQUES FOR THEASSESSMENT OF HYDRAULIC BIOTOPES

Habitat assessments in South African ecological reserve (Instream Flow Requirement) workshops are based on hydraulic analyses applied to one or two line transects across representative morphological units at representative sites. A hydraulic analysis is applied to each transect to derive the discharge related changes in wetted perimeter, maximum depth, the depth distribution across the profile, and mean velocity. The distribution of substrate size across the section can also be provided. The quantitative description of habitat at any one point on the transect is therefore limited to substrate and flow depth; estimates of point velocities are unavailable. In effect, the transect is treated as a lumped system, characterised by average values. This is a major limitation of the method as used at present. A second, possibly more serious limitation is that quantitative assessments are restricted to a single line transect for each representative morphological unit, no method having been developed to assess spatial changes in habitat across the unit as a whole. There is a clear need for a technique that can incorporate spatial changes in habitat as an integral part of reserve assessments. This chapter reports the results of a research project that set out to develop more effective ways to map hydraulic habitat.

Habitat is comprised of a number of components. Instream habitat depends on the flow hydraulics, substrate conditions, overhead cover, water temperature and water chemistry. The first two of these components can be related directly to the channel geomorphology and can be termed hydraulic habitat. Available hydraulic habitat can be described in terms of the wetted perimeter (the total availability of habitat), the flow depth and flow velocity, coupled to the material on the channel bed which forms the habitat substrate. Hydraulic habitat varies across the channel cross-section, forming distinct patches that can be related to the channel form and bed conditions. These patches have been termed hydraulic biotopes, defined by Wadeson (1994) as *a spatially distinct in-stream flow environment characterised by specific substratum and hydraulic attributes*. Hydraulic biotopes were used in this research to map hydraulic habitat at a range of low discharges for sites in the Mgeni and Tugela Rivers in KwaZulu-Natal.

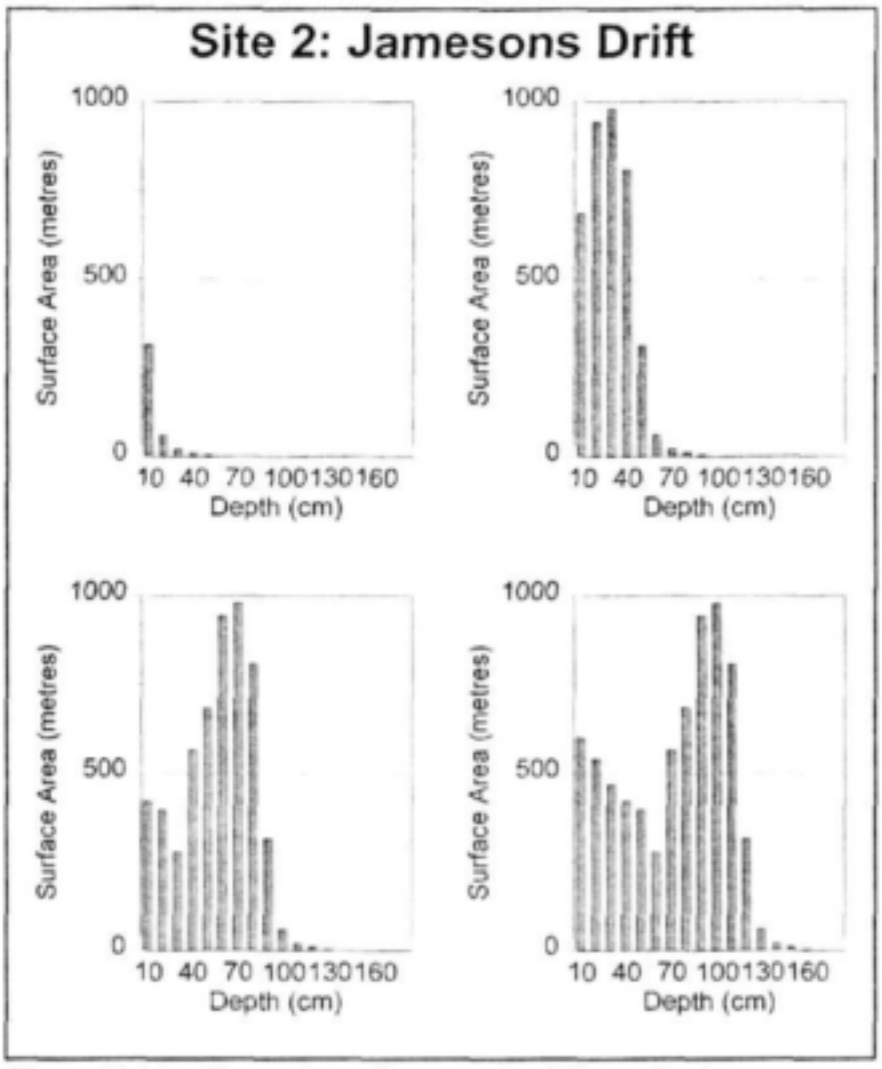

Figure 11.14: *Change in surface area for different depths as discharge increases. Site 2, Jamesons Drift, Tugela River, for discharges of 3, 10, 40 and 70 $m^3 s^{-1}$.*

Two techniques were explored. The first used fixed point photography. This successfully captured the mosaic of hydraulic biotopes at one discharge for a relatively small area of a specific study site. It was not easy to replicate the the photographs at different discharges, or to apply the method to an extensive channel area.

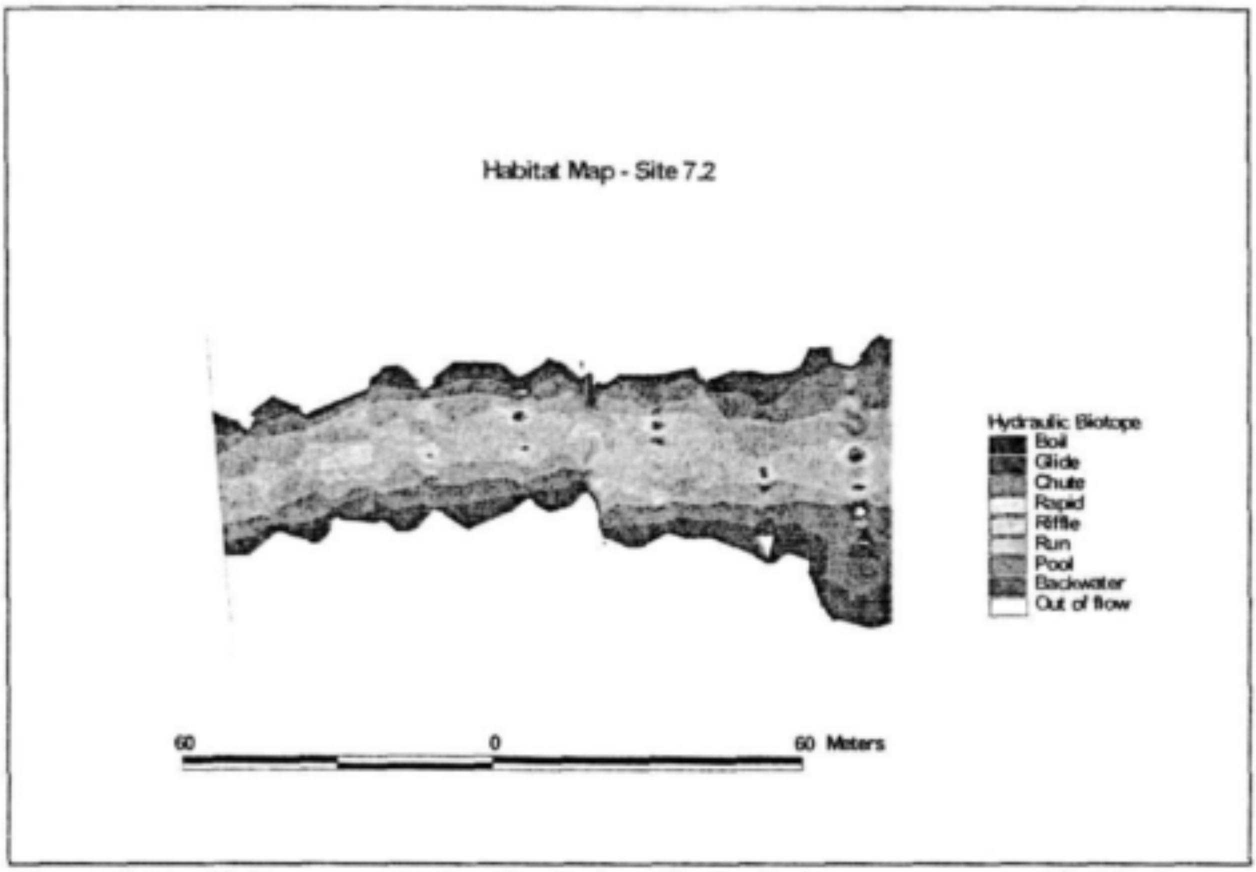

Figure 11.16: *Habitat maps showing distribution of hydraulic biotopes at one specified discharge*

The second method was based on a topographic survey of closely spaced line transects to establish the topography of the research site. The GIS package ArcView Spatial Analysis was used to create a 3-D topographic template. This was coupled with hydraulic modelling to establish the water depth over the mapped area for a range of discharges. A substrate map was created by noting changes in mapping sediment size along the transects. The kine surveys were transformed to a continuous surface using ArcView Spatial Analysis. In a similar way, hydraulic biotopes were mapped along the transect lines, then converted to a continuous map using ArcView Spatial Analysis. Repeated mapping of hydraulic biotopes along the fixed transect allowed discharge related changes in habitat to be monitored.

This method was shown to be effective in displaying the spatial pattern of flow types and flow depth. Of particular importance was the information provided on connectivity or fragmentation of certain habitats, for example as might be related to fish passage. The use of ArcView also enabled quantitative data on the proportions of different depth classes or habitat types to be assessed. The method has been used to good effect in Reserve determinations for the Tugela. It is recommended that the method be refined through further research and development.

CHAPTER 12: DISCUSSION, SYNTHESIS AND CONCLUSIONS

The final chapter presents a synthesis and the conclusion of the study. Implications of the research for river management in general, and setting the ecological reserve in particular, are discussed. The focus of this project has been to examine the relationship between flow regime, geomorphological process, channel form and related habitat. This relationship underlies the concept of the ecological reserve, defined as the quantity and quality of water required to protect an aquatic ecosystem in order to secure ecologically sustainable development and use of aquatic resources. In determining the reserve the timing of flow as well as its total quantity is important, and embedded in the notion of timing is the distribution of flow between floods and low flows. As geomorphologists, our attention is focussed on the floods as these are the flows that effect geomorphological change. In a Reserve determination the geomorphologist is given the responsibility of recommending flood flows for maintaining the required channel form, in terms of both overall channel dimensions and bed sediment conditions. It is therefore important to be able to evaluate the role of flood events and the possible implications of changing the flood regime on channel processes.

An important outcome of the research on the magnitude and frequency of channel forming flows was the proposed model of channel form - flow relationships. This model lies between the 'Leopold' alluvial model and the 'Structural' model of bedrock control. This model would argue that two sets of effective discharges aresignificant. First, a range of effective discharges in the 5% -0.1% or 5% - 0.01% flow duration class are responsible for the bulk of the bed material transport and largely determine the morphological adjustment of the active channel. Second, a 'reset' discharge, composed of the large floods that occur on average every 20 years or so, maintain the macro-channel and mobilise the entire bed, thus 'resetting' the system. These two categories of effective discharge will have different outcomes in bed rock controlled or semi-controlled systems and alluvial systems. It is suggested that because of the 'resetting' it is unlikely that the active channel will achieve a true equilibrium form, but that rather it is constantly being reconstructed after major events, hence the ubiquitous inset channel benches. The implications of this model for river management are discussed in this chapter.

Geomorphology determines the shape of the channel, and channel shape plus flow level determines aquatic habitat. Habitat is therefore both flow and morphology dependent. This relationship was embodied by Wadeson (1996) in the hydraulic biotope concept. Research carried out during the present project aimed to develop practical techniques by which hydraulic biotopes can be integrated into Reserve assessments as a means of assessing flow-related habitat availability.

Three major products have been developed during this research. The first is the documentation of the impacts of flow regulation through impoundment and interbasin transfer, based on international experience and a case study of a South African IBT. The second is a set of methods and techniques to identify the range of flows necessary to maintain channel form and equilibrium for selected southern African rivers. This in turn has lead to a better understanding of the range of flows that maintain channel form for southern African rivers and should assist in setting geomorphological flow requirements for the Reserve. The third is a set of protocols for describing and mapping flow related changes in hydraulic habitat. The application of these products by the research team to Reserve determinations has been an integral part of the research process.

While the research has gone a considerable way to developing concepts and techniques that can be applied to river management, specifically through the process of Reserve determination, there are many unanswered questions. Further research and developments could add both confidence and efficiency to their use.

While international research has pointed to a range of geomorphological impacts of flow regulation, to date there has been limited study of these impacts in South Africa. There appears to have been limited research on the geomorphological impacts of IBTs. There is clear scope to extend this work to monitor the impacts of new developments such as the transfer from the Mooi River into the Mgeni system. Observed impacts can be tested against the channel forming concepts developed in this report.

Research on the magnitude and frequency of channel forming discharges was carried out in three rivers draining the Great Escarpment of Mpumalanga Province and KwaZulu-Natal. There is a need extend the research to a wider geographical range. Application of the method to other rivers (such as rivers in the Western Cape or more arid systems in the Karoo) would generate further useful information.

A major limitation to the application of channel process models to river management is an inadequate understanding of bed material transport in rivers. There is a need to develop sediment models that can integrate the sediment supply from the catchment, the conveyance of sediment through the channel network and the reach scale transport processes. Moreover, if we are to understand the development of alluvial channel morphology, sediment deposition processes are as important as sediment transport. There is also a compelling need to validate the available sediment models with real data from local rivers. Attention needs to be paid to monitoring bedload movement through the use of devises such as bedload traps. A research programme focussing on bedload transport and channel change would add valuable incites into fluvial processes in South Africa.

One limitation of using the sediment transport model in Reserve workshops is the computational time required using the current operation which is based on manipulation of spreadsheet data. Developing a computer-based program to improve the efficiency and accessibility of the method is recommended.

There is considerable scope to extend the habitat mapping approach described in this report. What is the most efficient way of mapping hydraulic habitat? Can we develop models of habitat change for different channel morphologies? How can this information best be presented in a Reserve workshop? These are the questions that future research should address.

If geomorphology is to become an accepted part of river management its methods must be based on sound scientific principles validated through research in local environments. We also need methods of data manipulation and presentation that make that science relevant to the other workshop participants. Good science and good communication are the two most pressing challenges that practising geomorphologists must address if they are to make a significant contribution to the protection of water resources.

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Ms M Du Plessis and Ms G McGregor both graduated from Rhodes University in April 2000 with Master of Science degrees. Although Ms McGregor was not funded in any way by the WRC, contact with the project has been helpful in her research development.

Mr E Dollar graduated from Rhodes University in April 2001 witha PhD.

Honours students in the Department of Geography a Rhodes University participated in field trips to collect data as part of their teaching programmes.

The research described in this report was developed in association with active participation in Reserve determinations. The research outcomes have therefore already found application within the Reserve.

During the course of this project (1996 - 2000) the project team produced 16 related research papers or book chapters in journals, conference proceedings and text books, presented 14 conference papers at 9 conferences, 2 bibliographies and edited a series of bibliographies, contributed to 11 Reserve starter documents and other RDM documentation and produced 2 reports independent of the present one.

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GEOMORPHOLOGICAL RESEARCH FOR THE CONSERVATION AND MANAGEMENT OF SOUTHERN AFRICAN RIVERS

The Steering Committee responsible for this project consisted of the following persons:

Dr SA Mitchell	Water Research Commission (Chairman)
Mr DS vd Mervwe	Water Research Commission
Dr J King	University of Cape Town
Ms D Schael	University of Cape Town
Mr R Rowlston	Department of Water Affairs and Forestry
Prof C James	University of the Witswatersrand
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Dr J Boelhouwers	University of the Western Cape
Prof J O'Keeffe	University of Rhodes

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The Department of Water Affairs and Forestry provided numerous opportunities for data collection and testing methods during IFR exercises, while the Department of Water Affairs (Craddock) provided hydrological data on the Fish-Skoonmakers IBT

A number of people gave freely of their time to assist with the application of the models used in this research: Mrs Angelina Jordonava and Mr Andrew Birkhead of the University of the Witswatersrand assisted with hydraulic modelling, Mr Andrew Birkhead and Professor Chris James (also of the University of the Witswatersrand)with sediment transport modelling, Professor Dennis Hughes of Rhodes University with hydrological modelling and setting up spread sheets for sediment modelling

The farmers along the Skoonmakers and Mkomazi are thanked for allowing access to research sites for access to river

A number of ad hoc field assistants and clerical assistants assisted with field data collection and analysis: Ms M. Armstrong (office assistant), Ms A van der Stock & Ms N Motteux , Mr Michael Dollar, Pete Illgner (divers and sediment samplers in the Mkomazi), Geomorphology Honours class of 1998 (field assistants).

Assistance with editing the final report was given by Ms Rachel McDermott, Ms Gaelene Kramer and Ms Leanne Du Plessis.

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Section A: Introduction

Chapter 1: Introduction: geomorphology and water resource protection in South Africa

1.1 Geomorphology and water resource protection

The need to protect the river ecosystem as a component of the water resource base is being increasingly brought to the attention of water resource managers world wide. An essential component of this ecosystem is the river channel and its associated riparian zone, now recognized in South Africa through the National Water Act (36 of 1998) as constituting part of the water resource. The physical characteristics of the river channel and riparian zone are determined by geomorphological processes responsible for eroding the channel bed and banks and supplying, transporting and depositing the sediments which comprise many channel features. Geomorphologists worldwide, therefore, are increasingly being called upon to act in a professional capacity with respect to water resource protection and rehabilitation.

Geomorphologists have been actively researching channel processes and channel process-form relationships for at least half a century. Under the leadership of researchers such as Luna Leopold, Wolman and Stanley Schumm, fluvial geomorphology took off as a quantitative science in the 1950s and 1960s (Leopold *et al.* 1964). Over the ensuing fifty or so years research has focussed both on natural systems and those disturbed by human impact. As a result our understanding of fluvial processes and their relationship to channel form has increased by orders of magnitude. It is noteworthy, however, that much of the research reported in the international literature has been carried out either in the United States of America, Canada or the United Kingdom, with smaller contributions from Australia. The implications of this for our understanding of fluvial systems such as those occurring in South Africa is discussed at length in Chapter 2, Volume 2.

More recently, geomorphologists have applied their science to the broader scope of river management, and have become members of multidisciplinary teams involved for example in river condition or health assessments, rehabilitation or setting environmental flows for resource protection (Dollar, 2000). Two recent text books underline this trend: 'Applied Fluvial Geomorphology for River Engineering and Management' by Colin Thorne, Richard Hey and Malcolm Newson (Thorne *et al.*, 1997) and 'River Channel Restoration, Guiding Principles for Sustainable Projects' by Andrew Brookes and F.Douglas Shields Jr. (Brookes and Shields, 1996).

Rivers have suffered the affect of human activity since society first began to impact on catchment condition through land cover changes, to develop water resources for urban and agricultural use and to modify channel structures for flood mitigation and to improve navigation. The main impacts on channel structure (or morphology) of concern to geomorphologists tend to vary around the world depending on a country's geography and development history. In the United Kingdom, for example, the main cause of channel modification has been the enlargement and desilting of channels to increase flood capacity (Brookes, 1988). Flow regulation through dam building and interbasin transfer schemes is a global phenomenon, but the biggest dams are often associated with development projects and are therefore most prevalent in the developing areas. In Australia much effort has been put into de-snagging, the removal of woody debris from water courses to aid navigation and flood conveyance.

Throughout the world catchment activities have resulted in a change in materials brought into the channel, either in solution or as sediment. Whereas dissolved material has marked impacts on water quality, of more concern here are the coarser sediments derived from hillslope erosion which contribute to river morphology. Sediment yields are notably high in semi-arid areas where the natural ground cover offers little protection to rainfall impacts and in all areas where the natural cover has been depleted through cultivation or heavy grazing, especially in steeply sloping areas with erodible soils.

Table 1.1: *Major changes to rivers of Western Europe: bold font indicates those impacts that will have geomorphological significance in South Africa. After Petts and Amoros (1996).*

catchment land use changes
impoundments, weirs , locks
water abstraction
industrial, urban and agricultural pollution
engineering for navigation and flood control
channel network linkages decoupled following regulation
changes to riparian zone, effects on buffering capacity
development of flood plains for urban and industrial uses.

Table 1.1 lists the main causes of river modification noted for Western Europe by Petts and Amoros (1996). Those of geomorphological significance in South Africa are highlighted. In South Africa the main environmental issues of geomorphological concern relate to river regulation, reservoir construction and interbasin transfers, as engineers have sought to address the spatial and temporal mismatch between supply and demand that is characteristic of the country. Also important has been the widespread degradation of catchments, with consequent high sediment inputs into the river channels. Increased sediment loading has been shown to change the nature of the river channels (Heritage *et al*., 1995) and can create significant instability in the form of meander cutoffs (Dollar and Rowntree, 1995). River regulation may exacerbate the impacts of an increased sediment yield. Locally, channelization for flood mitigation has occurred, especially in urban areas and some flood plain agricultural areas, but on the whole South Africa's rivers have escaped large scale in-stream engineering schemes. The nation's rivers are not used for commercial navigation and recreational boating seldom results in intentional channel modification. Another major impact of concern is the degradation of vegetation in the riparian zone through grazing, firewood collection, clearing for flood mitigation and invasion by exotic species. Changes in the species composition and physical structure

of the riparian vegetation can have significant effect on channel processes and channel form (Rowntree, 1991; Rowntree and Dollar, 1999).

Dams have a major impact on downstream geomorphology through the interruption of both streamflow and sediment flux. The changing relationship between the long term transport capacity of the river and the sediment entering the channel below the dam results in a progressive change in channel form, often resulting in a narrowing of the channel (Petts, 1980). This in turn changes the type of habitats available to instream and riparian organisms. The negative impacts of dams on the downstream river ecosystems was formally recognized by the Department of Water Affairs in the 1980s in response to the negative impacts observed in the rivers of the Kruger National Park. In the early 1990s DWAF worked with teams of ecologists, hydrologists and geomorphologists to set in place procedures for assessing the nature of flow releases required to maintain downstream ecosystem in an acceptable state. The recommended flow regime became known as the Instream Flow Requirement (IFR), which specified the quantity of flow in terms of volume and timing. The National Water Act (36 of 1998) took this a step further by defining the Ecological Reserve as the quality and quantity of water required to protect an aquatic ecosystem in order to secure the ecologically sustainable development and use of the relevant water resource. Resource quality encompassed the quality of all aspects of a water resource which must be protected, including

- the quantity, timing, water level and assurance of instream flow (formerly the IFR);
- the water quality, including the physical, chemical and biological characteristics of the water;
- the character and condition of the instream and riparian habitat; and
- the characteristics, condition and distribution of the aquatic biota.

In the Act the definition of habitat includes the physical structure of a water resource and the associated vegetation, whether in relation to the watercourse itself (instream) or along the banks (riparian). Clearly, geomorphologists have an important role in advising on habitat alteration through changes to the physical structure of the channel and its riparian zone.

Determining the Reserve comes under a set of procedures known as the Resource Directed Measures for the Protection of Aquatic ecosystems. These measures focus on the water resource as an ecosystem and set clear objectives for resource quality which represent the desired level of protection for that resource. Catchment erosion problems and sediment yield fall outside the ambit of Resource Directed Measures, but should be considered under Source Directed Controls which deal with both point source and diffuse source pollution.

Since 1992 geomorphologists have played a significant role in developing the procedures adopted by the Department of Water Affairs and Forestry (DWAF) under their Resource Directed Measures (RDM) for the protection of water resources. Of particular relevance has been the development of the Building Block Methodology (BBM) for setting the water quantity component of the Reserve, or the Instream Flow Requirement (IFR) (King *et al*., 2000). The aim of the BBM is to recommend a skeletal flow regime which should maintain essential river processes and thus sustain the river ecosystem in an acceptable state. The flow regime is conceptualised as consisting of three 'building blocks': low flows, intermediate or flushing flows, high flows or flood events. The intermediate and high flows are of most concern to geomorphologists as these are the flows which maintain the structure of the channel bed and the overall form of the channel. Together they can be thought of as habitat maintaining flows as it is the channel form and bed conditions which ultimately determine the physical habitat available at any given flow, including the low flows. Thus the geomorphological characterisation of the channel aids the assessment of low flow requirements through its link to available habitat.

Although geomorphologists have been involved in IFR assessments since 1992, they have been severely hampered by a paucity of empirical research on channel processes in South African rivers. While developing home grown procedures for determining flows, it has been necessary to base assessments on theory developed from empirical studies in often very different environments. There is, therefore, a clear need for a critical review of international literature and for the development of process-form models which are more appropriate to local conditions.

1.2 Geomorphology and the river environment

The river environment is typified by flowing water within a defined channel which, under natural conditions, has been formed by past river flow. Flows within a channel vary from low, dry season flows (or even no flow in an ephemeral river) to high flood flows which over top the channel banks and inundate any flood plain or flood bench present (the riparian zone). The channel provides the physical boundary within which the water flows. The shape of the channel controls the hydraulics of the flow at any given discharge, whilst the channel perimeter provides the substrate within which benthic fauna live, and a rooting medium for vegetation. The size and shape of the channel also determines the frequency of flood plain inundation and recharge of the riparian zone. In turn the shape of the channel and the distribution of associated sediments is determined by the long term history of erosion and deposition, itself controlled by the historical pattern of river flow.

From a hydro-geomorphic perspective the most important components of the river environment are the flow hydraulics, the substrate of the river bed and the sedimentary bars and river banks which provide habitat for riparian vegetation. These components can all be related to the interaction between flow discharge, sediment load and channel morphology. Other important considerations are the physico-chemical variables such as water chemistry, water temperature and dissolved oxygen. These variables are considered to be outside the scope of the present study.

The river environment is characterised by constant change, related firstly to the flow hydrograph and secondly to morphological change. Under natural conditions it is rare for a river to experience steady flows (unchanging in time) as the river continuously responds to precipitation events over its catchment. During the wet season, storms over the catchment result in rapid fluctuations in flow as 'floods' pass through the channel. Even under dry season baseflow conditions there is a steady if imperceptible decline in flow rates. Morphological change takes place in response to these changing flows. High flows, above a certain threshold for the entrainment of the different sized particles in the bed and banks, are responsible for the erosion, transport and ultimate deposition of river sediment and hence for the morphology of the river channel. Alluvial channels, which are formed within 'modern' sediments, undergo continual change in response to sediment erosion and deposition. These changes are usually reversible so that erosion during one storm event can be restored by subsequent deposition. The location of erosion and deposition may shift, but within a reach the balance should be maintained in the long term. It is thus possible to conceptualize channel change within the context of dynamic equilibrium in which a quasi-constant channel form is maintained by the long term pattern of flow discharge. Only if the pattern of flow discharge or of sediment load changes in the long term is channel transformation (irreversible change at the reach scale) likely to take place. Such changes can take place as a result of macro-scale natural environmental change (e.g. climatic change) or may be due to engineering developments upstream or changes in the catchment which alter the long term flow and/or sediment regime.

The implications for river management are twofold. Firstly, managers and conservationists must be aware of the changing nature of the river environment and must be cognisant of the time scales over which geomorphological change takes place. It is important to distinguish cyclical change due to natural system disturbance from channel transformation due to anthropogenic impacts which have changed the long term system inputs. Secondly, the significance of different time scales depends on the spatial scale at which one is working. Together time and space scales determine the nature of process-response relationships and change the direction of cause and effect; they also provide a framework within which equilibrium concepts can be understood. The importance of time and space scales in geomorphology is reviewed below.

1.3 Time and space scales in geomorphology

1.3.1 Space scales

In their report to the Water Research Commission Rowntree and Wadeson (1999) stressed the importance of recognising different spatial scales within any river system. They presented a hierarchical framework for river classification which "provides a scale based link between the channel and the catchment so as to account for catchment dynamics and allows a spatial description of spatial variation in stream habitat." (Rowntree and Wadeson 1999 p. 22). This system was modelled on that of Frissell *et al.* (1986), while similar concepts have been adopted by Rosgen (1996) and Thompson (2001). The South African hierarchical framework consisted of six nested levels: the catchment, the zone, the stream segment, the reach, the morphological unit and the hydraulic biotope. Rowntree and Wadeson (1999) provided guidelines to the classification of morphological features at each of these levels. The hierarchy and associated classification systems have since been refined (Rowntree, 2001). The revised classification framework is outlined in Table 1.2.

***Table 1.2:** Definition of geomorphological classification levels*

Hierarchical unit	Description	Scale
Catchment	The catchment is the land surface which contributes water and sediment to any given stream network.	Can be applied to the whole river system, from source to mouth, or to a lower order catchment above a specified point of interest.
Longitudinal zone or Macro-reach	A zone is a sector of the river long profile which has a distinct valley form and valley slope. River zones fall within segments and are delineated according to macro-reaches.	Sectors of the river long profile.
Segment	A segment is a length of channel along which there is no significant change in the flow discharge or sediment load.	Segment boundaries will tend to be co-incident with major tributary junctions.
Reach	The unit of river length in which characteristic sources and sinks for sediments can be observed: as a result, the reach has a characteristic morphology : both geometry and form (Newson and Newson, 2000).	'00s of metres
Morphological Unit	The morphological units are the basic structures recognised by fluvial geomorphologists as comprising the channel morphology and may be either erosional or depositional features.	Morphological units occur at a scale of an order similar to that of the channel width.
Hydraulic biotope	Hydraulic biotopes are spatially distinct instream flow environments with characteristic hydraulic attributes.	They occur at a spatial scale of the order of 1 m^2 to 100 m^2 and are discharge dependent.

1.3.2 Time scales

Schumm and Lichty, two American geomorphologists working in the 1960s, produced a framework of time and space scales which provides a useful framework for understanding fluvial systems (Schumm and Lichty 1965). They presented a threefold subdivision of time into cyclical time, graded time and steady state time. Cyclical time can be equated to geological time periods over which long term landscape evolution takes place at the regional and catchment scale and can encompass models such as the Davisian cycle of erosion. Time, initial geology and climate are the independent variables, catchment and drainage network morphometry the dependent variables. Graded time is the timescale over which channel equilibrium occurs at the reach scale, with channel form being maintained by a balance between erosion and deposition within the reach over the long term (decades to centuries). At this time scale the independent variables are catchment scale variables, related to catchment hydrology and catchment sediment yield, while channel form is the dependent variable. Steady state time refers to the short term during which the system can be considered to be constant, with an equilibrium between the independent system variables of flow discharge and channel morphology and the dependent variables of flow hydraulics and sediment transport. This is the time scale at which primary data collection and direct observation of river characteristics takes place. It is also the time scale in which river ecologists tend to work.

It can be seen that the relationship between independent and dependent variables change between the different time scales. A modification of Schumm and Lichty's (1965) scheme is given in Figure 1.1. In this figure geological, geomorphological and ecological time are equivalent to cyclical, graded and steady state time of Schumm and Lichty (1965). The space scales are taken from the geomorphological hierarchy of Rowntree and Wadeson (1999). Figure 1.1 provides a useful framework for assessing the time dependency of cause and effect and for contextualizing the role of geomorphological studies in river management.

The geological timescale is clearly outside the time frame of river management, nonetheless it provides an important time scale for understanding modern river systems. Tectonic, climatic and environmental change have impacted on fluvial systems throughout geological time (cf. Arnell, 1992; Blum *et al.*, 1994; McCabe & Hay, 1995; Thomas & Thorp, 1995). South Africa's rivers reflect the geological history of the last 140 million years, since the break up of Gondwana at the end of the Jurassic. Peneplanation and retreat of the Great Escarpment during the Cretaceous and early Tertiary, followed by tectonic uplift in the Miocene (c.15Ma) and Pliocene (c.2Ma), created the modern river long profiles. Regional variations in geological events have given rise to major differences between eastern seaboard rivers of KwaZulu-Natal and their Western cape counterparts, whereas the Great Escarpment provides a divide between rivers of the interior and coastal rivers. Any attempt to develop a regional geomorphological classification of rivers should take account of the geological time scale. Scientists need to bring this long term evolution to the attention of river managers, as it is possible to misinterpret natural instability in fluvial systems as being a result of human impact (cf. Macklin & Lewin, 1992; Gilvear, 1994; Zhang, 1998), or to mis-diagnose cyclical changes as channel instability (cf. De Ploey, 1989; Moon *et al.*, 1997; Poesen & Hooke, 1997) or even to exaggerate human impact (cf. Grayson *et al.*, 1998). While the integrated management of catchments is implicitly contemporaneous, it should always be performed within a historical context (Davis *et al.*, 1999).

The geomorphological timescale is the timescale over which river processes result in an 'equilibrium' channel morphology at the reach scale in an alluvial channel. It is also the time scale over which channel response to engineering developments takes place. Channel adjustment takes place in response to changes in the flow and sediment regime. At the geomorphological timescale, changes in riparian and aquatic habitat occur due to changes in channel morphology. This is the timescale which provides the framework for the assessment of the geomorphological component of the Instream Flow Requirement (IFR). Although this is the time scale appropriate for the application of equilibrium concepts, is important to bear in mind that at any one point in time a channel may portray 'memory' of an extreme event in the past which caused major changes from which the channel is now recovering. Thus widespread deposition may represent recovery of an eroded system after a natural disturbance and should not necessarily be taken as a sign of system degradation.

Within the ecological timescale it is assumed that the channel morphology is stable, only flow discharge and sediment movement varies. Instream habitat (hydraulic habitat) at any given discharge is determined by the mosaic of hydraulic patterns induced on the flow by the channel morphology. Channel morphology also determines the frequency of overtopping of riparian components such as islands, lateral bars and the flood plain. The hydraulic habitat classification developed by Wadeson and Rowntree (1998) applies at the ecological time scale. Rowntree and Wadeson (1996) have shown how the observed mosaics of flow types and substrate classes within a particular channel morphology varies with flow discharge.

The ecological timescale provides the framework within which many data are collected and processes observed. It is therefore the timescale which is most readily conceptualised by researchers and managers alike and is the timescale which drives most decisions in an IFR.

Rhoads (1994) has argued that (p.588) "The most critical challenge confronting fluvial geomorphologists today is to devise strategies for integrating a diverse assortment of research that spans a broad range of spatial and temporal scales". This report addresses the application of geomorphological thinking to problems of water management at a range of time and space scales.

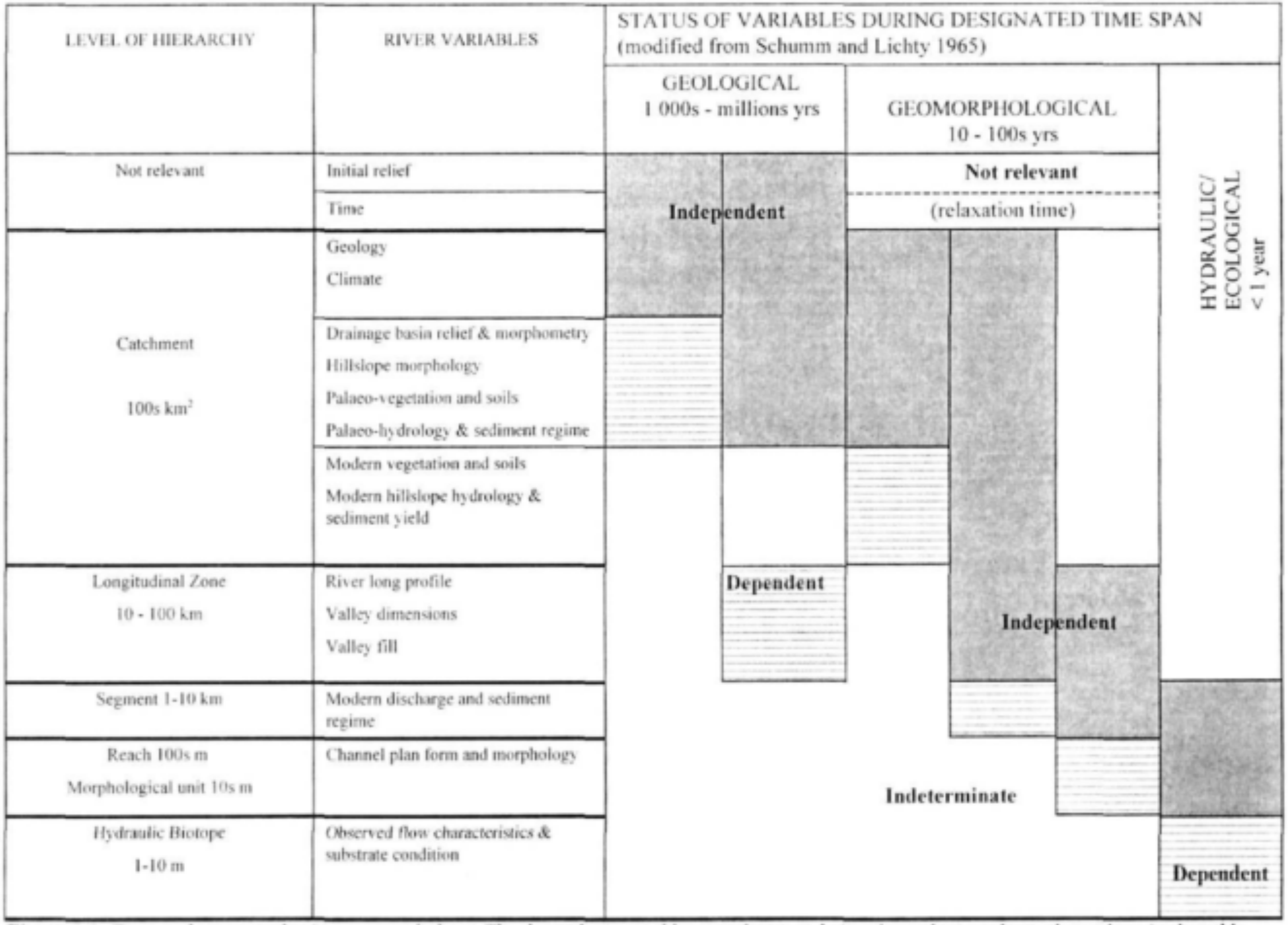

Figure 1.1: *Time and space scales in geomorphology. The dependent variables are shown as being dependent on those above them in the table.*

1.4 Aims, objectives and outline of the report

The geomorphological research presented in this report has a strong applied thrust. In particular it aims to develop geomorphological tools which should be seen as part of a multi-disciplinary approach to management aimed at the conservation of the ecological integrity of our river systems. Much of the research has been co-sponsored by the Water Research Commission (WRC), the National Research Foundation (NRF) and the Department of Water Affairs and Forestry (DWAF). Specific research objectives were set as follows:

- to refine the geomorphological component of the IFR methodology,
- to develop geomorphological indices and monitoring procedures to assess channel condition,
- to further assess the hydraulic biotope concept and its application to the assessment of habitat condition.

Geomorphological Indices were developed as part of a separate initiative funded by the Department of Water Affairs and Forestry. Separate reports have been published as part of the River Health Programme series: Rowntree and Ziervogel (1999); Rowntree and Wadeson (2000). This report presents the results of research aimed at refining the geomorphological component of the IFR methodology through both fundamental research into geomorphological processes and the development of the hydraulic biotope concept. The research is presented in two volumes. The first examines the geomorphological impact of water resource developments through impoundment behind dams and through interbasin transfers, two common activities in South Africa. These are both situations where an IFR (or the quantity aspects of the Reserve) would be required to mitigate the effects of the developments. Chapter 2 of Volume 1 presents a review of the international literature on impoundments studies undertaken by McGregor as part of her Masters thesis (McGregor, 2000). The main part of Volume 1 presents the work by Du Plessis on the impact of an interbasin transfer between the Fish River and Lake Darlington in the Eastern Cape. This is the first detailed study of the geomorphological impacts of an interbasin transfer scheme to be undertaken in South Africa. Indeed there are few if any similar studies reported in the international literature.

The second volume presents work which was undertaken with the specific objective of supporting the determination of the geomorphological flow requirement for the Environmental Reserve. Rowntree and Wadeson (1998) point out that the geomorphological contribution to the setting of IFRs has focussed on three groups of information requirements: the maintenance of channel form, the maintenance of substratum characteristics, and temporal availability of hydraulic habitat. The relationship of these three requirements to space and time scales is indicated in Table 1.3. The maintenance of channel form, the ultimate determinant of the in-stream flow environment, must consider processes that take place in the medium to long term (10 to 100 year period). Channel form is the long term response to movement of sediment through the river long profile and is the result of dynamic processes that take place within the geomorphological time scale and are manifested in the reach space scale. The maintenance of substratum characteristics involves, firstly, the seasonal flushing of fine materials from the surface matrix of the gravel-bed and, secondly, the over-turning and transport of the coarse matrix itself. These are essentially event driven processes which respond at the scale of the morphological unit. Seasonal inputs of sediment from the catchment are also important. Hydraulic habitat is determined by the response of the instantaneous discharge to a fixed channel morphology. Hydraulic habitat varies within the short term in response to the flow hydrograph and over small space scales determined by channel morphology and bed substratum.

Table 1.3: *A geomorphological framework for the assessment of Instream Flow Requirements: problems and information needs (after Rowntree & Wadeson, 1997).*

Problem	Time scale	Spatial scale	Information needs
Maintenance of channel form:			
Channel plan and cross-section adjustment:	Long-term (10-100 years)	Reach (100m)	Channel cross-sections, gradients, bed and bank resistance, sediment supply, natural flow regime
Maintenance of channel substratum characteristics:			
Seasonal flushing of substrate:	Short-term (single event - 5 years)	Morphological unit (10 -100m^2)	Substratum particle size distribution, cross-section hydraulic geometry, channel gradient, rate of sediment supply from upstream
Modification to substrate:	Medium term (2-20 years)		
Spatial and temporal availability of habitats:	Short-term (discharge specific - hours to months)	Hydraulic biotype and morphological unit (<1-10m^2)	Distribution of hydraulic biotypes; channel cross-sections, substratum type, flood plain morphology

Channel geomorphology is determined by the cumulative effects of events over geological, geomorphological and hydraulic time scales. Interpretation of channel form and recommendation of future flow regimes for managing form must take into account the environmental history. An in depth review of environmental change in South Africa as it relates to fluvial geomorphology is given in Chapter 2 of Volume 2.

A key concept underpinning geomorphological flow requirements to maintain channel form and channel substratum characteristics is that of magnitude and frequency. Setting the water quantity requirements for the Ecological Reserve is about recommending the flow regime to ensure that the resource quality is maintained. One component of the geomorphological flow requirement is the high flows or flood flows required to maintain channel form and bed conditions through the transport of sediment. The key question is 'what magnitude of flows are required to transport the incoming sediment without causing excessive erosion and channel enlargement and how often should they occur?'. The magnitude and frequency of channel forming flows has been an ongoing debate amongst geomorphologists. The application of this thinking to the Reserve determination is explored by Dollar in Chapters 3 to 10 of Volume 2.

The final section of Volume 2 addresses the relationship between magnitude and frequency of flows and available habitat within a stable channel. Wadeson developed the concept of the hydraulic biotope to describe discharge variant changes in hydraulic habitat within morphological units (Wadeson 1996; Rowntree and Wadeson 1999). The application of the hydraulic biotope concept to Reserve determination is taken further in the research presented in Chapter 11.

Section B: Geomorphological impacts of Impoundments

Section B is based on the thesis by Gillian K.McGregor: **"The geomorphological impacts of impoundments, with particular reference to tributary bar development on the Keiskamma River, Eastern Cape** " Unpublished MSc thesis, Rhodes University 2000.

Chapter 2: Downstream impacts of impoundments: a predictive model for South Africa

G.K. McGregor

2.1 Global water developments in perspective

Humankind has manipulated water in many ways, from the simple furrow-fed terrace agriculture of the Chinese and Indian cultures to the sophisticated hydro-electric power schemes of the modern Western world. In the ancient world great civilisations flourished on the fertile flood plains of major rivers. The Egyptian dynasties were sustained by the fertile floodplain of the Nile for centuries. The empire of Mesopotamia developed on the banks of the Tigris and the Euphrates where major irrigation works were undertaken in the 4th millennium BC (Hellier, 1990) and even today, despite the heavy utilisation of the river for many purposes by several nations, plans are afoot to further harness its potential. According to Hellier (1990), current water development plans on the Euphrates will reduce its 30 billion m^3 average annual flow by between 40 and 70% due to evaporation and abstraction.

In order to supply quantities of potable water to an increasing population, and to give some assurance of supply through the wet and dry season, it is necessary to store water. The world's oldest known dam was a masonry structure, 49 ft (16m) high, built in 2900BC on the Nile at Kosheish in Egypt. The Assyrians, Babylonians and Persians built many dams in the period 700-250BC for water supply and irrigation. One of their dams, built in present day Syria around 1300BC, is the oldest dam still in use (McCully, 1996).

According to Beaumont (1978), in Western Europe the greatest number of dams were built in the 19th century. 'Big' dam building is a feature of the 20th century. In North America, Europe, South East Asia and Japan, and in southern Africa there was intense big dam building activity before and after World War II. Most of the large dams in developing regions were built at a time when dam building was slowing down in first world countries. Originally many were built by colonial powers to assist development in those regions and to irrigate crops to provide the mother country with raw materials.

Beaumont (1978) found that in Africa and North America reservoirs trapped 20% of those areas' available runoff, while in Europe and Asia they captured 14 and 15% respectively. An assessment of regulated central European rivers by de Coursey (1975), cited in Petts (1979), showed a 20% reduction in the magnitude of the 50 year flood and a reduction of 25% for the mean annual flood due to reservoir construction. These figures serve to highlight the degree of control worldwide which humankind exerts over water resources. They point to the significant impact that dam building has had on the natural functioning of river systems, particularly in terms of control of downstream discharge.

2.2 An overview of South African dams

South Africa's water development history may be traced back to the 17th century, when the 2000m^3 Waegenaars Dam built by the Dutch East India Company supplied fresh water to ships calling at the Cape.

It is ironic that the original European settlement of this country can be said to have been for water supply, yet today a shortage of this resource is one of the most pressing problems facing the country and a major limiting factor to its economic development.

A register of dams with a wall height greater than 5m or a capacity of more than 50 000m^3 in South Africa is kept by the Department of Water Affairs and Forestry (DWAF). This data, available from the WR90 data set (Midgley *et al.* 1994) along with other hydrological information, has been used to provide an overview of South African dams. It was necessary to edit the data set to correct for a mismatch found between the dam locations and the attribute information attached to them. Only registered impoundments are considered in this data set and it does not take into account the many small farm dams and direct abstractions that occur in almost all catchments. In the former homeland areas, many dams were not registered as they were not controlled by DWAF.

At present reservoirs control 71% of the available runoff of South African rivers (derived from WR90 Digital data: Midgley *et al.*, 1994). There are few rivers that are not dammed by many reservoirs both large and small (Figure 2.1). Dam building really became a feature of the country in the first quarter of the twentieth century as agriculture developed, and the need for reliable irrigation supply arose. Figures 2.2 and 2.3 show the relationship between the number of dams built during the past century, measured against the total capacity of the dams. Five of the oldest 'large dams' in the country are situated in the Eastern Cape: Lake Mentz - 1922, Lake Arthur - 1924, Grassridge - 1924, Van Rynevelds Pass - 1925, Kammanassie -1926. The first three, located in the arid Karoo region, have been beset by sedimentation problems, as predicted by the director of the Cape Irrigation Board in 1919, and have had their walls raised to compensate for the loss of supply (Van Veelen & Stoffberg, 1987). The first noticeable large capacity dam building period was in 1935 when Clanwilliam, Loskop and the first Vaal Dam were constructed. The 1970-1985 period is distinctive for the high capacities of individual dams built in that period. Four large dams: Bloemhof, Gariep, Pongola, and Spioenkop were built between 1970 and 1975. The Gariep Dam on the Orange River, which has a capacity of 5958 x10^{6}m^3 at full supply level and covers an area of 347km^2, is the largest in the country. The dam was completed in 1971 and overflowed for the first time in March 1972. Another four large capacity dams: Grootdraai, Woodstock, Heyshope and Gt. Brandvlei were built in the period 1980-1985. The period thereafter is characterised by the construction of many smaller capacity dams whose cumulative capacity is great, as can be seen in Figure 2.2. and 2.3.

This is not an indication of stabilised demand, but rather an indication that all suitable sites have been utilised. Certainly the most ambitious project to date must be the current Lesotho Highlands Water scheme, which aims to divert 2200 x10^{6}m^3/annum to the Vaal River basin.

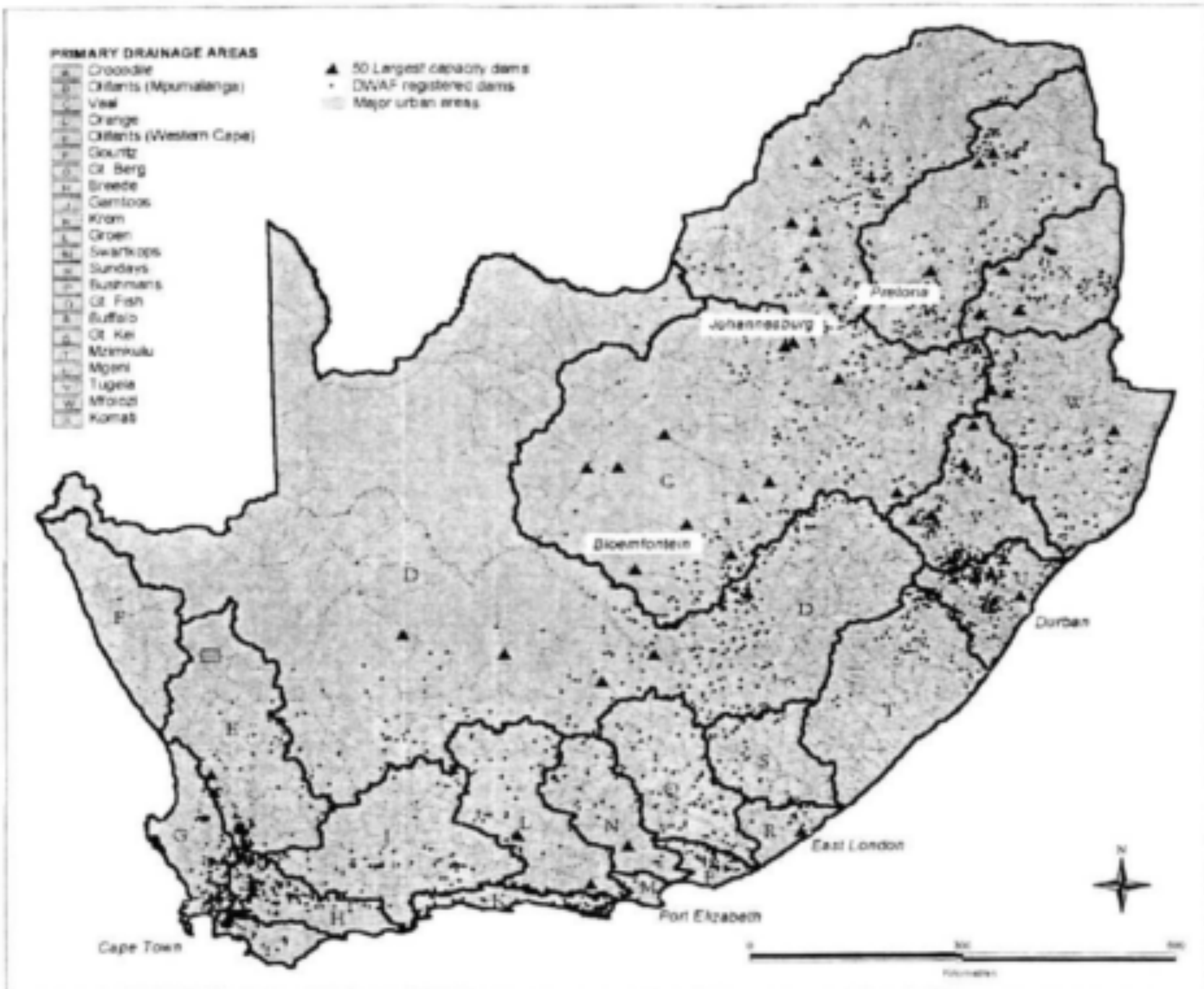

Figure 2.1: *South Africa's water resources: primary drainage regions, river network, largest capacity dams, registered dams and urban areas.*

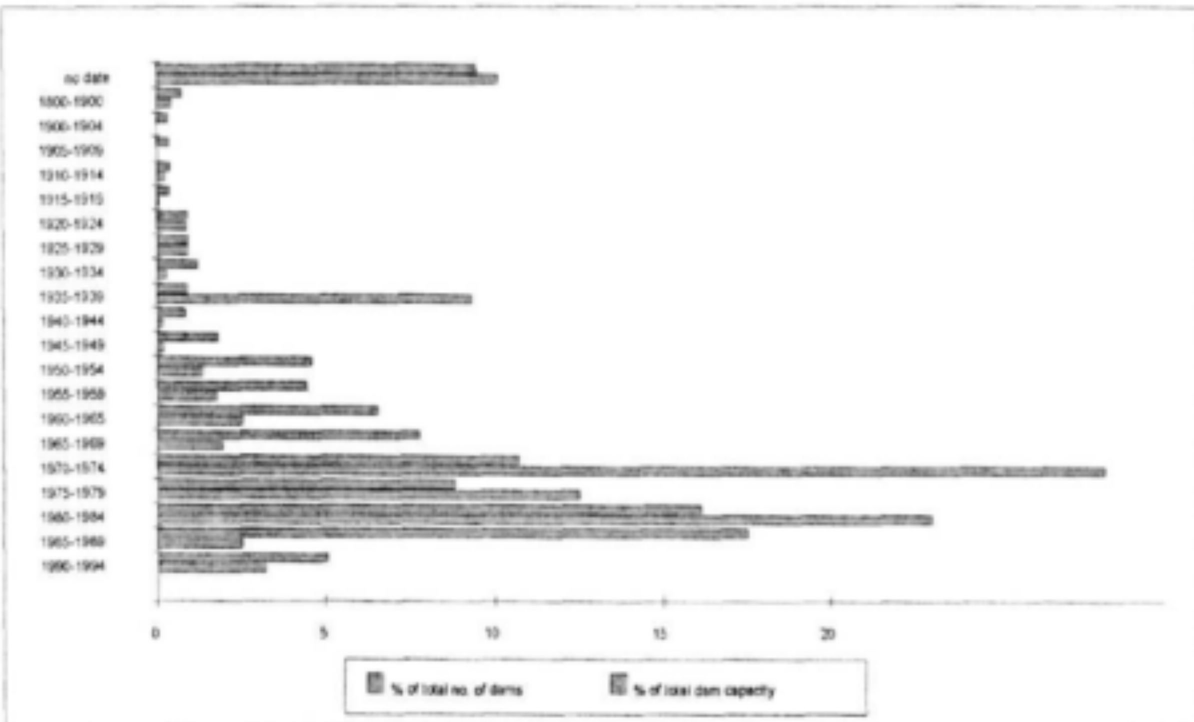

Figure 2.2: *Graph showing proportion of total impoundment capacity vs. number of dams built in succesive 5 year periods from 1800 to 1994.*

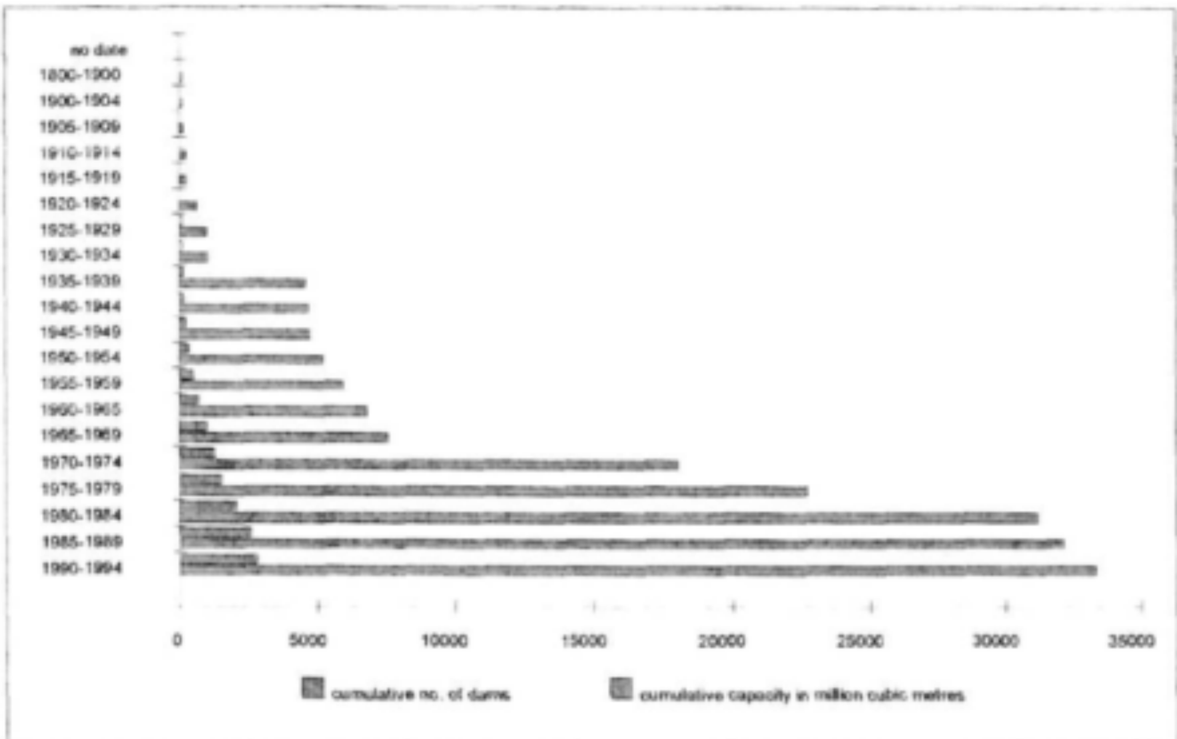

Figure 2.3: *Cumulative capacities and cumulative numbers of dams built in five-year periods from 1800 to 1994.*

Figure 2.4, which maps the distribution of dam building by time period, also points to some interesting trends: the pre-1900 distribution appears to be quite scattered, with dam building occurring evenly across the country as new areas were settled. Thereafter, dam construction was more concentrated in developing regions. The distribution of dams built in the 1930s, located in the semi-arid to arid interior, is probably a reflection of government job creation during the depression, in the form of public works projects. A similar pattern is seen in the 1950s with heavy government subsidy of irrigation schemes for 'poor' farmers in the arid interior, on land that was often unsuitable for intensive agriculture.

Figure 2.5 shows the proportion of the mean annual runoff controlled by impoundments by primary drainage regions. Drainage regions D and C (the Orange and Vaal respectively) are developed well beyond their annual runoff capacities. The semi-arid nature of large areas of these catchments adds to the significance of this development. The Lesotho highlands, representing only 7,5 % of the total catchment area of the Orange River, generates 65 % of its mean annual runoff (MAR). The ecological impact of this degree of control must be great. The impoundment capacity of the catchments of the Limpopo tributaries in Northern Province is close to that of the mean annual runoff. Elsewhere in the country the impoundment capacity by primary catchment tends to be between 60 to 80 % of the MAR. Only in the Western Cape does the figure tend to be significantly lower.

At present South Africa's major dams (the 550 DWAF controlled structures) have the capacity to hold 71 % of the country's runoff. To ensure a reliable supply and to allow for the variability of the hydrologic regime of this country, our dams are built at great economic cost because of the high storage capacities required on our rivers (Alexander, 1985). To cope with assuring supply in the face of such variability, dams are often designed to trap several times the mean annual runoff. The high sediment production rates in most catchments due to the semi-arid environment and poor land management make dam sedimentation rates a concern in 'assuring supply'. Fuggle & Rabie (1992) estimate that the average loss in capacity of South African dams is just under 10 % per decade. According to Rooseboom (1992), South African reservoirs have a sediment trap efficiency of 99 % and any dam which impounds more than 5 % of the MAR will have sedimentation problems. Given that few of our dams impound less than this, it is not surprising that sedimentation is a major issue.

The high sediment trap efficiency and the high proportion of MAR that is impounded in many reservoirs disrupts both the sediment and water regimes of the river. South African dams have been designed to counteract the variability of a naturally variable system. In so doing, natural channel processes are modified, leading to a change in channel geomorphology. In order to better understand the kind of impacts which have/may result, the impacts of impoundments as observed on rivers worldwide are reviewed below. This review forms the basis of a conceptual model that can guide geomorphological recommendations in Instream Flow Requirement workshops.

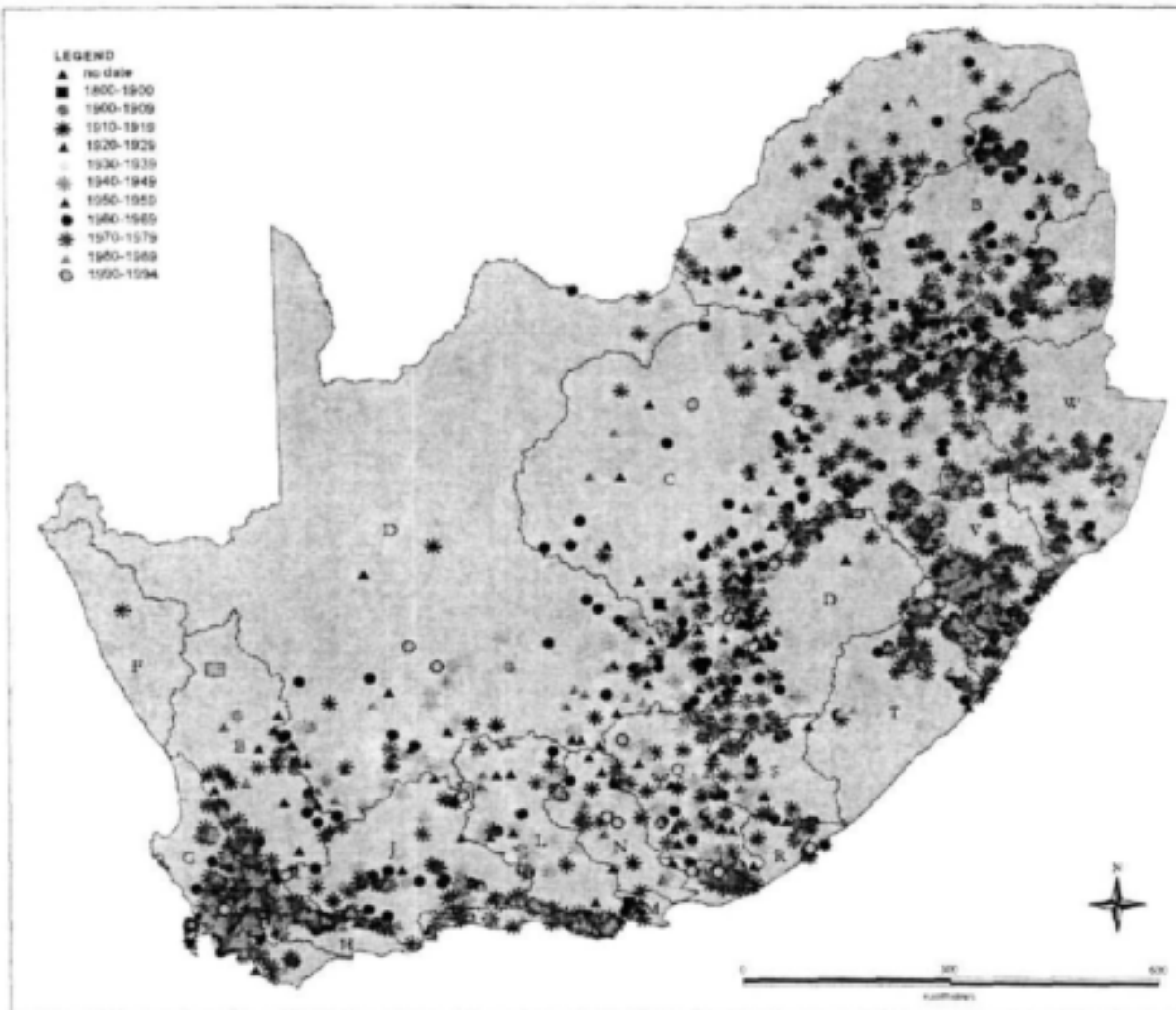

Figure 2.4: *Distribution of dams built in South Africa in ten year time periods.*

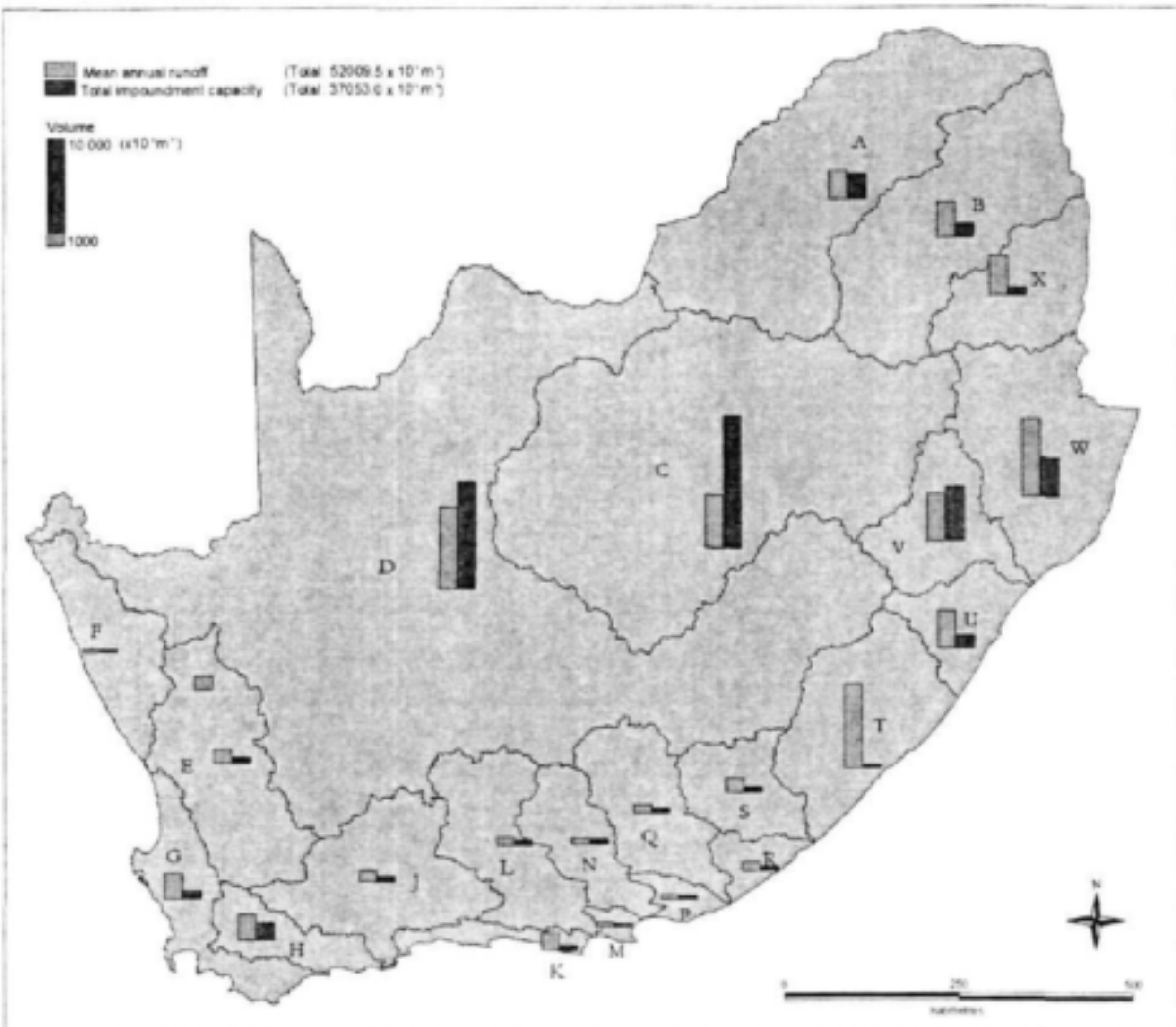

Figure 2.5: *Total impoundment capacity vs primary mean annual runoff per catchment.*

2.3 *Review of the impact of impoundments*

2.3.1 The impact of impoundment on river channel morphology

By impounding a river, a regulated state is enforced on a natural system, upsetting the natural regime of a river and its associated biota which are adapted to surviving under a particular set of conditions. The primary impact is in the control of water releases to the downstream system and the reduction, or complete removal of the sediment load from the system. Depending on the degree of control, the impact may be large or small. River regulation is a common option for water resource management in most countries whether it is by storage for hydro-electric power generation, irrigation and domestic use or flood control.

The impact of river regulation on geomorphology has long been recognised internationally. As early as 1890, channel morphology changes below reservoirs were observed in the UK (Lane, 1890, cited in Buma & Day, 1977). From a South African perspective this recognition has been delayed as economics drove the demand for water resource development and environmental issues tended to be sidelined by a powerful controlling DWAF, in response to a politically powerful agricultural community. From an overview of literature it is obvious that the impact of river regulation on a stream is substantial, covering a broad spectrum of disciplines and environments, although the dominant fields are ecology and engineering (Buma & Day, 1977; Chien, 1985; Erskine, 1985; Gill, 1973; Gordon *et al*., 1996; Graf, 1980; Park, 1977; Petts, 1979; Williams & Wolman, 1984). In South Africa, studies have concentrated on the ecological impacts, mainly via water quality assessment (Byren & Davies, 1989; Gale, 1992; Palmer & O'Keeffe, 1990), vertebrate studies (Cambray, 1984; Coke, 1970) and invertebrate population sampling (Chutter, 1969; Harrison & Elsworth, 1958, Palmer, 1991;). With the exception of a chapter in Davies *et al.* (1993), Rowntree & Dollar (1996) and some comment in Davies & Day (1997), an assessment of the geomorphological impact of river regulation is lacking in the South African literature.

The most extensive published work on the impact of impoundments on rivers has been carried out by Petts in Britain. His work provides a good starting point for this discussion as he provides a useful theoretical framework within which to consider other case studies on the impact of impoundment.

2.3.2 Geomorphological impacts of impoundments according to Petts (1984)

Petts' work is based on his 1979 doctoral thesis. The results of the 14 case studies he carried out are given in Appendix 1. Petts (1984) classifies the human impact on the environment into three orders of impact:

1. a first order impact entails a process alteration, or a direct effect on some natural activity;
2. a second order impact involves changes of form, ecological or geomorphological in response to the process alteration, striving for a new equilibrium (1-100 years);
3. a third order impact involves readjustment of the system - a feedback effect from the first order impact, which may take hundreds of years.

Petts (1984) used a range of techniques to study 14 impounded rivers in Britain, with relatively homogenous catchments ranging in area from 3.5 to 127 km^2, and time spans of five to 85 years to study the first and second order impacts of dam building. The first order geomorphological impacts of dam building are a change in magnitude and frequency of flood events and reduced sediment load. Second order geomorphological (and ecological) impacts are varied and complex in space and in time. A series of interlinked responses: erosion, deposition and aggradation, happened simultaneously, but to varying degrees in different places. Stream capacity generally increased immediately below the dam due to a net balance of erosion, then reduced within a short distance as sediment was deposited, tending towards normal further downstream as the unregulated area increased. Based on the various case studies, Petts was able to establish that once the unregulated contributing catchment area below the dam reached 40 % of the regulated catchment area, the geomorphological impact of the impoundment would be insignificant. At tributary junctions responses were complicated by injection of sediment and water. Reduction of width by deposition was found to be the main means of contraction in actively meandering sections, while simple accommodation of the reduced flow in the existing channel was the response in stable channel sections. Depending on sediment/discharge relationships, width and depth reduction was also achieved by the deposition of sediments on the bed, or in the form of channel side benches. The rate of change was linked closely to the availability of sediment and water: in the absence of competent discharges, the existing channel would simply accommodate reduced flows. Only a large event would then be sufficient to initiate change. In the case of large reservoirs, there may be a significant time lag between impoundment and channel response.

The third order impacts stemming from second order impacts (change in channel morphology and ecology), will reflect in changes to the communities of living organisms in the system. Fish and invertebrate habitats are intimately associated with the hydrological, sedimentological and morphological characters of river channels. Many are opportunistic breeders relying on stimuli from the river to trigger new life cycles. Changes in flood patterns, width, depth and bed particle size distribution, which control velocity and flow actions, will affect organisms which are sensitive to these kinds of variables.

According to Petts (1984) many of the environmental problems that have resulted from dams have been due to a failure to recognise second and third order impacts, and the time span over which they act. River systems consist of numerous inter-related hydrological, sedimentological, morphological and biological components and the response to impoundment is complex because each of these factors comes in to play.

2.3.3 Distribution and relevance of impoundment studies

A detailed literature review of studies on the geomorphological impact of impoundments was conducted to gather the information used in the compilation of the following sections. Summaries of all these studies are given in Appendix 1.

Most of these are concentrated in the UK, largely due to the efforts of Petts. The USA also has a good scattering of research and Australia is fairly well represented. There is a noticeable lack of geomorphological studies in the developing world, despite the notoriously negative impacts of large dams in these areas. The environmental, social and economic impacts are vast, and as such have been well documented, but there has been a lack of research on the geomorphological changes in these systems; the developers had a poor perception of the geomorphological ramifications of their efforts. The negative impacts of impoundment are particularly detrimental to people in less developed communities who are directly reliant on natural resources. The following two examples from South Africa and Egypt illustrate the dependence of local populations on the geomorphological functioning of a river system.

On the Pongola River, Northern Zululand, the Tonga culture has evolved around the fertile floodplain. The alluvial terraces provided good agricultural soils for a variety of subsistence crops; the perennial pans, sustained by the annual flood provided hatcheries for a variety of fish species and a source of food for local inhabitants who trapped them with traditional baskets; reeds from the pans and river's edge and trees from the riparian zone provided building materials. Damming of the river at Pongolapoort in 1979 significantly altered the flood regime of the river and affected the structure and functioning of this complex and sensitive floodplain environment. In the absence of the annual flood, the diversity of the riparian zone has been reduced; the once extensive reed beds are degraded and fish yields in the pans are poor. Plans for irrigated commercial rice farming have been singularly unsuccessful due to unsuitable soils. DWAF officials at the Pongolapoort dam have attempted to address the situation by altering the dam operational rules to simulate a more natural flow regime.

The sediment load of the Nile has been as significant in the history of the Egyptian people as the river itself. The alluvial soils of the floodplain provided good arable lands. The annual flood with its high sediment load provided a natural fertilizer loaded with nitrogen rich bacteria while the many small floods allowed the operation of flood fed furrow irrigation systems. The alluvial deposits also provided brick-making materials which were replenished each year by the annual flood.

The Nile was first dammed in 1902 by the Aswan Low Dam to allow irrigation of extensive cotton lands, providing raw material for British cotton mills. In 1969, the High Aswan Dam was built to extend irrigated agriculture. By 1993, the Egyptian government claimed that they had 'reclaimed' 690 000 hectares from the desert and put it under irrigation. In reality, the actual area of irrigated land had not changed much: degradation and problems with salinity had rendered hectares of land useless for agriculture. Some previously productive areas had been urbanised, while the brickmaking industry had begun quarrying former farmlands, in the absence of the annual flood to replenish their silt/clay sources. Traditional flood-fed furrow systems no longer operated due to a reduction in the water level (degrading bed) and reduction of small floods. The annual flood with its fertile silt load containing the essential nitrogen rich bacteria was reduced by the dam and the floodplain is steadily eroding (McCully, 1996).

2.4 *Impoundment: an overview of the impacts*

It is evident that river response to impoundment is varied and complex - in magnitude and in time. An impoundment will affect the lotic environment and its inhabitants, as well as the riparian zone and the floodplain. The communities influenced will be both botanical and zoological, varying in size from the macro-invertebrates which inhabit the spaces between substrate particles, to the large trees of the riparian zone. It is the physical channel environment which provides these creatures with a habitat, and it is the morphological response of a river to impoundment as described in all the previously mentioned studies which underlies all other responses.

A dam in a river changes the normal flow pattern of the stream. Two generalisations can be made about the impact of impoundment: the flow will be altered and the sediment load will be changed. This may be exaggerated depending on the purpose of the dam and its operational procedures. Flood storage dams drastically reduce the variability of a system. Their impact on sediment transport is as dramatic as their impact on flow. Dams operated for irrigation tend to reduce high flows in the wet season and increase dry season flows. Hydro-power dams dramatically disrupt the diurnal and seasonal flows and introduce short-term variability to the system.

The volume and timing of water passing to the downstream river will depend on the function of the dam. On average, the same volume of water may pass downstream, but its release pattern will be artificially controlled. If much water is abstracted, the volume and magnitude of water releases will be reduced if not stopped. While some dams allow for sluicing out of sediments, the volume released can never be great as that entering the dam.

Identifying and quantifying the geomorphological first order impacts of impoundment is relatively straightforward if there are stream gauging records for the pre-impoundment period. Discharge data at least can give a good indication of the extent of change in the river's flow and its timing. Alternatively, study of a similar unimpacted catchment in close proximity can provide a valuable control and case for comparison. If sediment data is available, the normal sediment suspended load of the river can be compared with the sediment load of post-dam discharges.

Identifying morphological changes - the secondary impacts - is not a simple task. Until recently, it has not been standard procedure to make pre-impoundment assessments of the channel (at least not in South Africa). Because of the time involved (immediate to hundreds of years) and the difficulty of isolating changes due to impoundment, impacts are not simple to quantify. The downstream change is complex because of the many feedback mechanisms which operate in a natural system, and will vary in time and space. The secondary impacts which can be identified as the physical channel adaptations, will depend on the physical characteristics of the downstream channel. The response of the downstream channel will depend on the nature of the channel prior to impoundment: the composition of its substrate, the stability of its banks, the nature of its long profile/gradient. Change in bedrock channels will be insignificant, while change in sandbed, or mixed substrate channels may be significant. The impact of the dam will

***Table 2.1:** Summary of the primary impacts of impoundments according to studies reviewed.*

STE - sediment trap efficiency; **MAR** - mean annual river flow; **d/s** - downstream; **MAF** - mean annual flood; **Study no.** refers to appendix case study number; **Q** - discharge in m^3s^{-1}

Study no.	*Country and author*	*River and reservoir*	*Primary impact on sediment*	*Primary impact on water*
41	**Argentina** Navarro & Pujal, 1994	Piedra del Aguila, Limay	no figures	100year flood of 6000 m^3s^{-1} reduced to 2800m^3s^{-1}
33	**Australia** Benn & Erskine, 1994	Windermere, Cudgegong	STE 95% plus	truncation of high flows >3x10^6l d^{-1}; increase in low flows < 30x10^6ld^{-1} 10% duration reduced from 260 x 10^6l d^{-1} to 130 x 10^6l d^{-1}; 80% duration increased from 6 x 10^6l d^{-1} to 21 x 10^6l d^{-1}
32	**Australia** Erskine, 1985	Glenbawn, Hunter	STE 98-98.5% mean daily susp.load - 659.9 to 6.6 tonnes	truncation of flows >8 x $10^6m^3d^{-1}$; reduced frequency of flows >7 x $10^6m^3d^{-1}$; increased low flows
34	**Australia** Jacobs *et al.*, 1994	Dartmouth, Mitta-Mitta	no figures	unseasonal high flows; reduction of floods
35		Hume, Murray	no figures	reversal of seasonal flow; total volume 9% more due to IBT.
31	**Australia** Sherrard & Erskine, 1991	Mangrove Creek, Mangrove Creek	STE 100%	post dam flows reduced by 70%; largest pre-dam flood - 348x10^8 ld^{-1}, post dam 171x10^7 Mld^{-1}; 1.08 return on pre dam scale; 54-66% reduction for larger floods at Mangrove Mountain; largest flood - return interval of 1.21 yrs.
7	**Australia** Walker, 1985	Murray Darling; *several*	no figures	average monthly low flows increased from 100 m^3s^{-1} to approx 300 m^3s^{-1} ; high flows of 6-800 m^3s^{-1} , reduced by 1-200 m^3s^{-1} ; medium flows reduced by 1-150 m^3s^{-1}
37	**Canada** Buma & Day, 1977	Deer Creek, Deer Creek	no figures	no figures
46	**Canada** Church, 1995	WAC Bennet, Peace	not an issue	peak flows reduced, mean annual flow the same; MAF reduced by 68% below dam; 42% at delta
47		Kemano IBT	no change	mean natural flow = 44m^3s^{-1}; augmented flows = 100-150m^3s^1
48	**Canada** Kellerhals & Gill, 1973 Bray & Kellerhals, 1979	WAC Bennett, Peace	nearly sediment free water	annual peaks: 3500-9000 m^3s^{-1} lows:150-250 m^3s^{-1} ; regulated range:500-2000 m^3s^{-1}
27	**China** Chien, 1985	Sanmenxia, Yellow	100km d/s: at 1000-2000 m^3s^{-1} load reduced by 64%; at 3000 m^3s^{-1} load reduced by 82%	12400 m^3s^{-1} flood reduced to 4870 m^3s^{-1} (60%); medium flow duration (1000-3000 m^3s^{-1}) increased from 120-204 days

Study no.	*Country and author*	*River and reservoir*	*Primary impact on sediment*	*Primary impact on water*
28		Gaungting, Yong-dng	operated to flush sediment out in moderate size flows	3700 m^3s^{-1} flood reduced to 800 m^3s^{-1}
29		Danjiankou, Hanjiang	6km d/s: average sediment concentration reduced from 2.92 to 0.03 kgm^3; sediment transport capacity reduced by 41%	6km d/s: average peak discharge reduced from 16600 to 78400m^3s^{-1}; average low season discharge increased from 328 to 714 m^3s^{-1}
30	**China** Qiwei *et al.*, 1982	Danjiankou Hanjiang	annual sediment transport capacity reduced by 41%	annual high flow reduced from 4087 m^3s^{-1} to 3041m^3s^{-1}; for 100km d/s - flow velocity is 70-80% of pre-dam velocity
9, 39 & 38	**Egypt** Hammad, 1977 Shalaby, 1986 Kinaway *et al.*, 1973.	High Aswan Dam, Nile	STE 99.5%; pre-dam suspended load - 125mil.tons/yr; post-dam, 965km d/s suspended sediment load of 6mil.tons/yr	flood season flow reduced from 7-900 $10^6m^3d^{-1}$ to < 225 x $10^6m^3d^{-1}$; flow range of 720-13000 x $10^6m^3d^{-1}$ reduced to 930-2600 x $10^6m^3d^{-1}$; mean annual release to the Mediterranean of 40km^3 reduced to 2-3km^3
26	**Korea** Woo & Yu, 1994	Keum, Daechong	no figures	traps 60% (1.49 x 10^6 m^3) of the MAR
43	**Lithuania** Assarin *et al.*, 1994	Kaunas HPP, Neman	no figures	MAR = 9.2 x 10^9m^3 dam capacity: 0.46 x 10^9m^3 (5%)
77	**Mocambique** Davies, 1996	Cahora Bassa, Zambezi	no figures	floods greatly reduced
76	**Norway** Fergus, 1997	Fortun HPP, Fortun	no figures	post regulation discharge: 35% of natural discharge; mean annual discharge reduced from 20 m^3s^{-1} to 7 m^3s^{-1}; MAF reduced from 140m^3s^{-1} to 86 m^3s^{-1}
45	***Pakistan*** Tariq, 1994	*Indus, Tarbela*	*STE 97%*	traps 15% *of the MAR of 79 billion* m^3
42	**Poland** Assarin *et al.*, 1994	Zimlyanskaya, Don	no figures	MAR = 22 x 10^9m^3 dam capacity: 23.8 x 10^9m^3 (108%)
40	**Poland** Hrabowski *et al.*, 1994	Debe, Narew	no figures	no figure
18	**UK** Gregory & Park, 1974	Clatworthy, Tone	no figures	1.5yr flood and 2.33yr floods reduced to 40% of pre-dam Q.
14	**UK** Higgs & Petts, 1988	Clywedog, Severn	no figure	MAF reduced at 3 stations: 192 to142m^3s^{-1} ; 269 to 200m^3s^{-1}; 273- to 249m^3s^{-1} low flows: 22% higher than the natural Q_{95}.; MAF reduced by 30%; median flow reduced by 50%

Study no.	Country and author	River and reservoir	Primary impact on sediment	Primary impact on water
12	**UK** Petts, 1984	Nant-y-moch Afon Rheidol	no figure	flows greatly reduced - 3 spillages since 1963
17	**UK** Petts & Thoms, 1986	Chew Valley, Chew	no figures	greatly reduced floods; 1968 - 100yr flood, no spillage
6	**UK** Petts & Thoms, 1987	Kielder, NorthTyne	no figures	peak flows reduced by 30-50%; highest pre-dam flow >250m^3s^{-1}; Q = 175 m^3s^{-1} exceeded 4 times in 1966; regulated releases: irrigation flows = 1.32m^3s^{-1} in summer, 0.66m^3 s^{-1} in winter; supplemented by hydro-electric releases of 15m^3s^{-1}
25	**UK** Richards & Greenhalgh, 1984	Sea Cut, Derwent	no figures	bankfull reduced from 11.5-14.2m^3s^{-1} to 8.3m^3s^{-1}
10	**USA** Andrews, 1986	Flaming Gorge, Green	105 miles d/s: mean annual sediment discharge decreased by 54% from 6.92 x 10^6 tons to 3.21 x 10^6 tons	pre and post dam flows at 3 stations in ft^3s^{-1} 7450 → 2750 20500 → 11500 26500 → 20500
49	**USA** Dolan *et al.*, 1974	Glen Canyon, Colorado	median sediment concentration reduced from 1250 to 350ppm	median discharge: 8200 ft^3s^{-1} reduced to 12800ft^3s^{-1}; MAF: 86000ft^3s^{-1} reduced to 28000ft^3s^{-} ; 10yr flood: 122000ft^3s^{-} reduced to 40000ft^3s^{-1}
53	**USA** Graf, 1984	Flaming Gorge, Green	no figures	maximum release capabilities: 170m^3s^{-1} compared to pre-dam maximum flood of 510m^3s^{-1}
13	**USA** Hadley & Eschner, 1982	Platte, *Several*	no figures	increased low flows, reduced floods
50	**USA** Kearsley, Schmidt & Warren, 1994	Glen Canyon, Colorado	reduced from 6x10^{10}kg to 8.3 x 10^7kg	annual peak discharge: 2180m^3s^{-1} reduced to 940m^3s^{-1}
51 & 52	**USA** Turner & Karpiscak, 1980	Glen Canyon, Colorado	26km d/s: reduced median sediment concentration from 1500 to 7ppm	average annual maximum flows reduced from 2486m^3s^{-1} to 803m^3s^{-1}; median discharge increased; average diurnal fluctuation from a few centimetres to several metres
44	**Vietnam** Assarin *et al.*, 1994	Hoa Binh HPP, Da	no figures	MAR = 57.2 x 10^9m^3 dam capacity: 9.5 x 10^9m^3 (16.6%)

Table 2.2: *Summary of the primary impacts of impoundments from Williams & Wolman (1984).*

d/s - downstream; Study no. - refers to appendix case study number; **Q** - discharge in m^3s^{-1}; **mgg** - megagrams

Study no.	*River and reservoir*	*Primary impact on sediment*	*dist. d/s of dam*	*Average daily Q*		*Annual peak Q*		d_{65}	
				pre	*post*	*pre*	*post*	*pre*	*post*
54	Glen Canyon, Colorado	150km d/s: mean annual suspended sediment load reduced from 126mil.mgg/yr to 17mil.mgg/yr (87%)	26	480	320	2200	800	100	31
55	Hoover, Colorado	180km d/s: mean annual suspended sediment load reduced from 120-400 mil.mgg/yr to 5-30 mil.mgg/yr	180	520	400	2200	640	120	145
56	Davis, Colorado		72	400	340	640	550	145	140
57	Parker, Colorado		6.4	230	340	850	640	125	140
58	Jemez Canyon, Jemez		1.3	1.5	1.5	160	39	0.006	0.0
59	John Martin, Arkansas	water emptied annually, most sediment sluiced out with it; trap efficiency ranges from 0-99%	34	7.3	4.8	560	190	0.05	0.07
60	Fort Peck, Missouri		100	200	280	770	690	70	40
61	Fort Randall, Missouri		11	880	680	6300	1500	195	155
2	Garrison, Missouri	121km d/s: mean annual suspended sediment load reduced from 48.6mil.mgg/yr to 5.3mil.mgg/yr	120	600	660	3900	1100	140	250
63	Gavins point, Missouri	8km d/s: mean annual suspended sediment load reduced to 1% of pre-dam value (from 121 to 1.5 mil.mgg/yr); 1147km d/s mean annual suspended sediment load reduced to 30% of pre-dam value	8	930	740	5200	1200	250	220
64	Medicine Creek, Medicine Creek		15	2.7	-	530	-	0.8	-
65	Milburn, Middle Loup	operated to flush out sediment periodically	19	23	22	58	53	16.5	16.5

Study no.	*River and reservoir*	*Primary impact on sediment*	*dist. d/s of dam*	*Average daily Q*		*Annual peak Q*		d_{85}	
				pre	*post*	*pre*	*post*	*pre*	*post*
66	Red Rock, Des Moines		19	140	200	1200	800	7.6	13
67	Kanopolis, Smoky Hill		1.3	8.7	9.9	320	135	0.5	0.5
68	Milford, Republican		2.7	23	24	290	150	4.5	1.2
69	Fort Supply, Wolf Creek				1.7	240	35	.006	0.01
70	Canton, N. Canadian	99.5% trap efficiency; suspended sediment concentration takes 120-500km to recover	0.8	7.7	4.7	280	44	0	0.03
71	Eufalfa, Canadian		13	175	130	3600	740	3.1	1.6
72	Denison, Red	99.22% sediment trap efficiency; 150km d/s: at a known discharge sediment concentration is 20-55% of that recorded for the same discharge before the dam was built		185	120	3000	950	7.1	3.2
73	Town Bluff, Neches		93	60	54	660	270	19.0	12
74	Bufford, Chattahoochee		4	60	54	660	270	19	12

Table 2.3: *Summary of secondary impacts of impoundments according to studies reviewed.*

Category	Impact	Authors
cross section change	channel position change	Erskine, 1985; Williams & Wolman, 1984; Chien, 1985; Buma & Day, 1977; Petts, 1979.
	bank slaking	Petts & Pratts, 1983; Navarro & Pujal, 1994; Walker, 1985; Jacobs, 1994; Dolan *et al.*, 1974; Williams & Wolman, 1984; Sherrard & Erskine, 1991.
	bank erosion	Navarro & Pujal, 1994; Walker, 1985; Jacobs, 1994; Chien, 1985; Buma & Day, 1977; Dolan *et al.*,1974; Turner & Karpiscak,1980; Petts & Pratts,1983; Fergus, 1997; Petts & Thoms, 1987; Williams & Wolman, 1984; Kearsley *et al.*, 1994.
	bank aggradation	Sherrard & Erskine, 1991; Richards & Greenhalgh, 1984; Buma & Day, 1977; Benn & Erskine, 1994; Gregory & Park, 1974; Petts & Pratts, 1983; Petts, 1979; Fergus, 1997; Petts, 1984.
	bed aggradation	Woo & Yu, 1994; Kellerhals & Gill, 1973; Assarin *et al.*, 1994; Hammad, 1972; Hadley & Eschner, 1982; Walker, 1985; Jacobs, 1994; Sherrard & Erskine, 1991; Petts, 1984; Qiwei *et al.*, 1982; Chien, 1985; Petts & Thoms, 1986; Buma & Day, 1977; Benn & Erskine, 1994; Bray & Kellerhals, 1979; Petts & Pratts, 1983; Petts, 1979; Kellerhals & Gill, 1973.
	bed degradation	Erskine, 1985; Hrabowski *et al.*, 1994; Woo & Yu, 1994; Walker, 1985; Jacobs, 1994; Sherrard & Erskine, 1991; Qiwei *et al.*, 1982; Chien, 1985; Buma & Day, 1977; Turner & Karpiscak,1980; Kinaway *et al.*, 1973; Shalaby, 1986; Assarin, *et al.*, 1994; Petts & Pratts, 1983; Petts, 1979; Fergus, 1997; Williams & Wolman, 1984.
	channel contraction	Hadley & Eschner, 1982; Navarro & Pujal, 1994; Sherrard & Erskine, 1991; Petts & Thoms, 1987; Petts, 1984 ; Gregory & Park, 1974; Petts & Thoms, 1986; Benn & Erskine, 1994; Petts, 1979.
	bar erosion	Turner & Karpiscak, 1980; Fergus, 1997; Kearsley *et al.*, 1994.
	bar development	Kellerhals & Gill, 1973; Hadley & Eschner, 1982; Chien, 1985; Richards & Greenhalgh. 1984; Petts, 1979.
	bar/bank joining	Sherrard & Erskine, 1991; Petts,1984; Hadley & Eschner, 1982; Chien, 1985.
	silting/abandonment of 2° channels	Hadley & Eschner, 1982; Chien, 1985; Navarro & Pujal, 1994; Fergus, 1997; Davies, 1996.
	accommodation	Erskine, 1985; Kellerhals & Gill, 1973; Benn & Erskine, 1994; Petts, 1979; Fergus, 1997.
long profile change	gradient change	Kellerhals & Gill, 1973; Petts, 1984; Graf, 1980; Petts, 1979; Hrabowski *et al.*, 1994; Fergus, 1997.
	channel pattern change	Hadley & Eschner, 1982; Navarro & Pujal, 1994; Chien, 1985.

Category	Impact	Authors
substrate change	coarsening/armouring	Erskine, 1985; Woo & Yu, 1994; Hammad, 1972; Assarin, *et al*., 1994; Tariq, 1994; Chien, 1985; Turner & Karpiscak, 1980; Dolan *et al*., 1974; Kinaway *et al*., 1973; Petts, 1979; Williams & Wolman, 1984.
	change in composition	Petts & Thoms, 1987 ; Richards & Greenhalgh, 1984 ; Petts 1984; Petts & Thoms, 1986; Hadley & Eschner, 1982; Chien, 1985; Qiwei *et al*., 1982; Williams & Wolman, 1984; Benn & Erskine, 1994; Graf, 1980; Kearsley *et al*., 1994.
tributary zone change	downcutting	Kellerhals & Gill, 1973.
	bar development and stabilisation	Sherrard & Erskine, 1991; Kellerhals & Gill, 1973; Petts & Thoms, 1987; Petts, 1984 ; Graf, 1980; Petts & Thoms, 1986; Petts, 1979; Benn & Erskine, 1994.
	delta growth	Kellerhals & Gill, 1973; Bray & Kellerhals, 1979; Petts, 1979 .
	coarsening of substrate	Benn & Erskine, 1994; Erskine, 1985; Graf, 1980; Petts & Thoms, 1986; Sherrard & Erskine, 1991.

decrease in a downstream direction, in relation to an increase in the contributing unregulated catchment area. The sediment and water balance will gradually be restored. This all takes place over time: a few years to hundreds of years.

Summarised versions of the original studies consulted are contained in Appendix 1. The primary and secondary geomorphological impacts of dams have been summarised by description, tabulation, and illustration in the next section.

1. Tables 2.1 and 2.2 are a summary of primary impact findings from all the studies.
2. Table 2.3 is a summary of all the possible secondary morphological changes described by the authors, Figure 2.6 is an illustration of these changes.
3. The conceptual model illustrated in Figure 2.7, which covers first, second and third order impacts, is derived from the results of all these studies.
4. Table 2.4 relates flow regime to channel type and the likely change.
5. Figure 2.9 is a working flow diagram for predicting morphological change.

The changes in the discussion which follows have been organised according to the following idea: a channel will adapt to a new flow pattern to facilitate the optimal transport of water and sediment. A channel can change its dimensions by adjusting its width, depth, position, long profile and substrate composition as it tends towards a state of equilibrium with its new flow and sediment regime.

2.4.1 Change in cross-sectional area

Bed degradation: this is well documented in engineering literature because it is the first and most easily identifiable impact occurring immediately below the dam. It is also significant because it can affect the stability of the dam structure and must therefore be catered for in the dam's design. It happens initially immediately below the reservoir outfall, where the sediment-free releases have a high capacity to erode and transport sediment. Its extent will depend on the availability of sediment and the nature of the substrate. The water can only erode sediment with movement thresholds within the capacity of the flow. Erosion of the bed and banks will occur until an equilibrium state is reached by armouring; exposure of a resistant substrate, or through reduced velocity in response to reduced gradient. The erosional front will progress gradually downstream until a state of equilibrium has been reached. This condition is most pronounced in alluvial sand bed rivers, greatly reduced in more stable gravel bed or channels and non-existent in resistant bedrock channels. Bed degradation has been observed on the Keiskamma River below Sandile Dam (McGregor, 2000), on the Mhlatuz River below Goedertrouw Dam and on the Fish River below Grassridge Dam.

Bank erosion: this will occur where banks are not cohesive, or where reduced flows undercut the banks because of their lower position in the channel. Bank erosion is also associated with pulse type releases typically associated with hydro-electric power generation. High velocity discharges have the capacity to erode the river banks, particularly where the bank materials are not cohesive.

Aggradation: the eroded material from upstream will be deposited when the transport capacity of the flow drops below a threshold. As the channel gradient reduces, flow velocities are reduced, and deposition occurs on the channel bed and banks. The velocity gradient in a channel is such that the fastest flows occupy the thalweg, with areas where there is friction or a high roughness having lower flow velocities. Anywhere where the velocity drops below the settling threshold of the sediment load, deposition will occur. A minor obstruction in a channel may cause a depositional zone, leading in time to the development of a bar. On the channel sides, where the water is shallow and velocities low due to friction, sediment will be deposited to form benches. Fine sediment may adhere to the banks by plastering. In this way the bank encroaches into the channel which is no longer capable of moving the sediment out, and the channel tends to deepen and narrow. The bedload will be deposited first, while finer material may stay in suspension as long as the flow has the capacity to transport it. In the absence of destabilizing high flows, vegetation is able to establish itself, and further stabilised depositional features (see Plate 2.1). The channel cross-sectional area is reduced in width and/or depth from its natural dimensions, to carry a much reduced flow. The stream occupies a micro-channel within the existing channel, with a bench which marks the new bankfull level. Aggradation on the stream bed can be a problem where the stream no longer has the energy to move its load onto the floodplain and instead the load is deposited in the stream, causing the channel bed to rise.

Channel pattern change: as flow velocities change and the long profile changes, the channel may change from a braided to a single thread channel. In the case of a multi thread channel, flow seldom divides evenly around a deposit, with the result that one channel is more active than the other (Schumm & Lichty, 1963). In the absence of high flows to activate and flush secondary channels, these channels may become silted up as the flows which pass through them are likely to be depositional rather then erosive. The main channel is likely to deepen and narrow, leading to the reinforcement of a single thread stream. The accumulation of silt and the absence of scouring flows provides suitable conditions for vegetation establishment. Linder (1952), cited in Schumm & Lichty (1963), has shown in laboratory experiments that the fork with the smaller discharge carries the highest bedload concentration, thereby making the smaller channel the most likely site of deposition. Vegetation converts once temporary bars to permanent channel features and eventually the secondary channels may accrete to such a degree that they bridge the islands/bars they once separated. In this way a multiple channel stream becomes a single thread stream, with water following the channel of least resistance. The change in channel pattern is not easy to 'certify' because it takes time, and may be an intermediate stage in adjustment (Chien, 1985). This type of change has been observed on the Zambezi River, below Kariba Dam by Davies, 1996 (pers. comm) where temporary islands created by braiding have become permanent features, and on the Keiskamma downstream of the Sandile Dam in the vicinity of the Amatola tributary (McGregor, 2000).

Accommodation: possibly the simplest reaction to a changed flow regime is the 'accommodation adjustment' described by Petts (1979). Regulated flows are below the thresholds of change, so the flow simply occupies a lower position in the existing channel, for that particular reach. This would happen where the channel boundary is too stable to allow any change, as in a bed rock channel, a homogenous gravel channel, or a cohesive alluvial channel. The reduced flow is simply accommodated within the existing channel form and has sufficient power to transport available sediment through the reach.

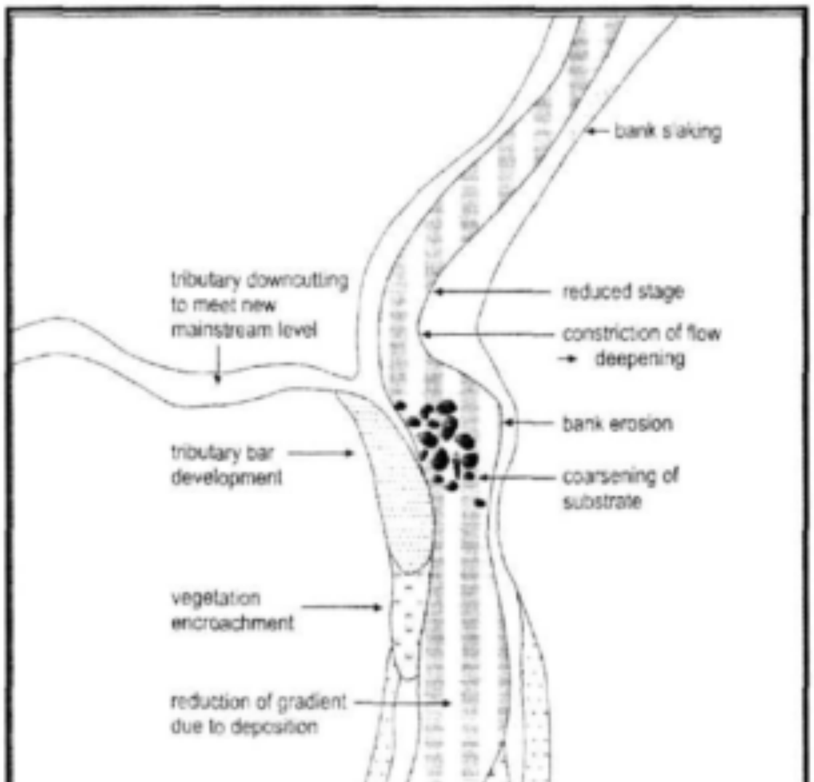

Figure 2.6: *Illustration of morphological change in an impounded river.*

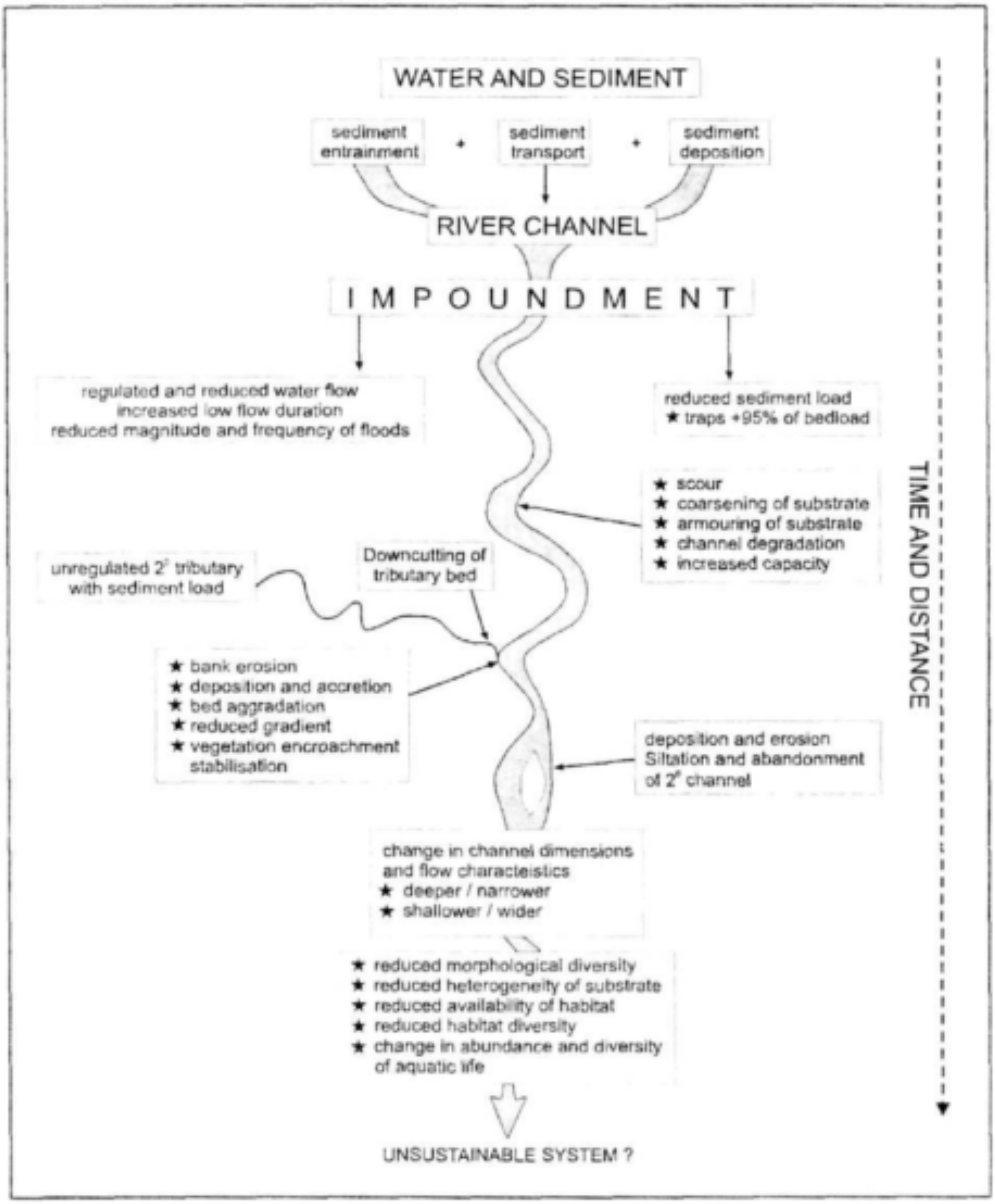

Figure 2.7: *Conceptual model of the geomorphological impacts of impoundments.*

2.4.2 Change in long profile

Gradient change: the long profile of the river will adjust depending on whether the stream is eroding or aggrading. For any significant profile change to take place a tremendous quantity of material would have to be eroded. It seems that in many cases bed coarsening/armouring causes a reduction in velocity that reduces transport capacity sufficiently to limit degradation and prevent a change in slope. Sand bed rivers are particularly susceptible to downcutting and profile change although armouring of the bed does take place, thereby checking it. However, where coarse calibre sediment is introduced by tributaries, and is allowed to stabilise in the absence of high flows, the stream will at some stage respond by increasing its gradient locally in the form of a rapid/riffle. Under low velocity conditions and in the absence of erosive high flows, a stream with a high sediment load will gradually reduce its profile through aggradation because it is dominated by depositional processes. The process of deposition will eventually cause a localised increased gradient which will create conditions of sufficient velocity to move material through the reach. The siltation of a side channel on the Keiskamma River, 100m below the Amatola junction, is probably the result of reduced post impoundment flows (McGregor, 2000).

2.4.3 Substrate change

Coarsening and armouring: the water which is released from an impoundment is free of sediment, having dropped its load in the low velocity environment of the dam. It thus has a high capacity to erode downstream of the dam. Depending on the velocity of the water, it will selectively erode particles, removing those sediments with a low entrainment threshold first. Because of the reduced discharge, the flow will be unable to move the coarser fraction of the channel substrate. The result is a protective armoured layer of coarse sediment with a high threshold of movement. The increased roughness reduces velocities, further reducing the transport capacity of the flow. Only very large flows will be able to disrupt the surface. This forces the erosional front to move downstream to where it is able to do work, owing to the presence of finer sediments. The long term result is a coarsening of the substrate in a downstream direction, until the process is interrupted by an incoming tributary with a natural sediment load and unregulated discharge. This self protection mechanism also prevents any significant alteration of the long profile/bed slope. This process occurs across a range of substrates, and will almost certainly occur below any impoundment. An example of substrate armouring is shown in Plate 2.2.

Change in substrate composition: increased flows may downcut the channel bottom until a resistant surface is encountered, in the form of bedrock or coarser sediments. Where unregulated tributaries enter the mainstream, their coarse sediment load will dominate that reach if the main stream lacks the power to move the deposited material. Under reduced flow conditions with low velocities, deposition of finer sediments may take place over a stable bed. This is commonly associated with accommodation adjustment.

2.4.4 Tributary Junctions

Bar development and stabilisation: tributaries typically have steeper gradients than the mainstream, and therefore have the capacity to carry larger sized sediment. The status of the tributary must be considered with regard to its discharge and sediment production. The volume of water it introduces into the mainstream will be a function of its physical characteristics - geology, soils, landuse, catchment area, gradient, drainage density. The greater discharge in the main channel would normally compensate for the lower gradient, thus giving it the capacity to move incoming sediment. Under regulated conditions, the mainstream lacks the energy to move the deposits, so they accumulate in the form of a delta or bars which become stable features. As they accrete, they may protrude above the water, allowing further stabilisation by plant colonisation, encouraging further deposition. Eventually they may adjoin the bank. The tributary will dominate the processes in that reach. Coincident with this process is erosion of the opposite bank as the flow is directed and constricted by the tributary bar. This type of bar development has been described by McGregor, 2000. It has also been observed on the Buffalo River, downstream of Bridledrift and Laing Dams.

Petts (1984) and Petts & Thoms (1986) have studied tributary bar formation in great detail. Their findings show that the sediment is spread out in the reach in various forms: benches, bars, and channel bottom deposits, sorted according to sediment size fractions. Together these features constrict the channel flow, and raise the level of the bed. The volume of sediment in the features amounts to the volume eroded in the tributary catchment. At the bottom end of a tributary-dominated reach the channel adjusts its profile, with a rapid gradient increase. In the extremely arid environment of the Green River in Utah, Graf (1980) identified large scale tributary deposits in the mainstream. These accumulations of landslide debris, consisting of large boulders, are immovable in the regulated stream, and they cause the formation of rapids. As the feature stabilises by the accumulation of other material, a gradient change occurs.

Downcutting: under regulated conditions the mainstream will be out of phase with unregulated tributaries, so a high flow in a tributary will not necessarily coincide with a high mainstream stage. When this occurs, the tributary will erode its bed to meet the reduced mainstream stage.

Plate 2.1: *Vegetation encroachment and channel narrowing below the Kouga Dam, Eastern Cape*

Plate 2.2: *Coarse armoured substrate.*

Table 2.4: *Typical geomorphological responses to a regulated flow regime.*

REACH DESCRIPTION	*REDUCED FLOW*	*INCREASED LOW FLOW*	*ABSENCE OF HIGH FLOWS*
bedrock/stable bed	accommodation, sedimentation	accommodation, armouring	sedimentation
multiple thread/ anastomosing/ anabranching	change to single thread; closure of 2° channel	deepening of main branch	closure of 2° channel; vegetation encroachment
non-cohesive banks		erosion; slaking	aggradation and deposition
stable banks	accommodation	deepening of channel; erosion of in-channel features	
single thread	accommodation; deposition on perimeter	deepening of thalweg, or widening; increased sinuosity	dominated by aggradation
non-cohesive banks	accommodation	bank erosion; widening; reduced depth	aggradation in channel
stable banks	accommodation	deepening of channel	aggradation
braided	change to single thread	erosion of bars/islands	stabilisation of bars; multiple to single thread
tributary junction	downcutting; deposition and aggradation;	armouring; coarsening of substrate	bar/delta formation opposite bank erosion; raising of bed; gradient reduction or localised steepening

2.5 Predicting change

This chapter has presented an overview of the processes and responses in a fluvial system which give rise to particular channel morphologies. Together with a review of the known geomorphological impacts of impoundments, a picture begins to emerge of the type of physical conditions under which particular morphological changes will occur. Using this understanding, together with a knowledge of the primary impact of an impoundment (the nature of the regulated flows), it is possible to begin to predict the nature of geomorphological change in a river downstream of an impoundment.

Figure 2.8 is a flow diagram which can be used as a preliminary guide to predicting geomorphological change below an impoundment. The first division is simple: the downstream channels respond according to their state of stability. The processes which follow can be divided into three groups:

- accommodation which occurs in a stable channel under reduced flow conditions is the simplest, with no further responses;
- aggradation which occurs under reduced flow conditions;
- and degradation which occurs under increased low flow conditions or reduced sediment input.

The variety of responses and the places at which they can occur are then listed. Furthermore, the channel response will be determined by the type of channel (mixed bed, bedrock, alluvial) as detailed below.

Mixed bed channels: Change will be most complex due to the variety of impacts. Initially there will be degradation until an armoured layer is formed. Armouring may promote bank erosion while protecting the bed. Roughness will certainly increase, thereby further reducing velocities. If the channel boundary is sufficiently immobile, accommodation of the reduced flow in a 'micro-channel' within the old channel will occur. Features such as rapids composed of large boulders may become permanent stable features, in the absence of large enough flows to disturb them. Where aggradation occurs in sections of an anabranching stream, the side channels will become silted up in the absence of sufficient flows to move the sediment, and will cease to function. In- channel bars would favour deposition and increase in size, forcing the channel into a more sinuous, meandering pattern. Vegetation would have the opportunity to establish itself under the low flow conditions, and there would be a progression from pioneer to secondary type species, with deeper roots which would bind and stabilise the substrate further. This would further increase roughness and encourage further deposition, promoting the process of stabilisation, and reducing the diversity of the system. All of these factors would combine to reduce the velocity further.

A bed rock channel, or a stable boulder/cobble bed will simply accommodate the new flow without making any morphological adjustment. Incoming sediment may be deposited on the channel bottom in the absence of competent flows to move it.

In an *alluvial channel with non-cohesive banks, and a stable bed* - there is likely to be widening of the channel, caused by bank erosion or slaking. Deposition is likely to follow with the formation of new in-channel features. A sand bed channel will erode until armouring develops, a resistant substrate is uncovered, or until gradient is reduced sufficiently to decrease velocity and stop the erosion process. It is likely to be followed by deposition further downstream.

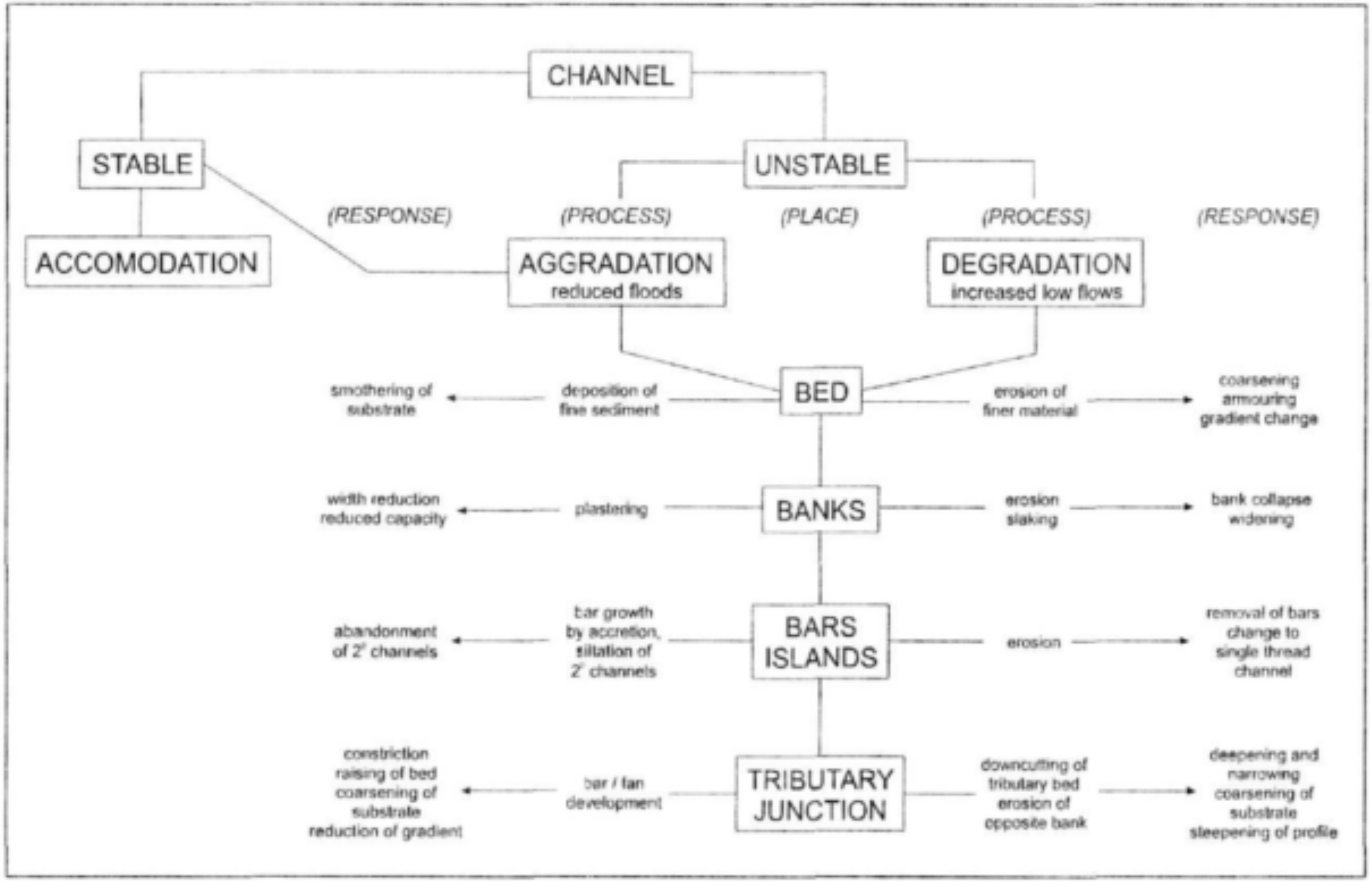

Figure 2.8: *Flow diagram for predicting morphological change.*

2.6 *Application of the model in South Africa*

The conceptual model described above can be used to predict the direction of geomorphological change in an impounded fluvial system. It is not intended to quantify that change or to make predictions of the time span over which change will take place. The model can be used to identify the channel reaches downstream of an impoundment where morphological change is likely to take place and those situations in which impacts are likely to be exacerbated.

Channel reaches that are likely to show the greatest impacts are listed below. These reaches would provide good 'indicator' sites which could be used as an index of the impact that an impoundment is having on a system. By monitoring these sites it might be possible to rectify the situation through different operational procedures at the dam.

- reaches which are braided or anabranching can change to single thread if conditions are altered sufficiently
- reaches with a low gradient where deposition dominates can accrete to such an extent that they become elevated above the level of the floodplain
- tributary junctions where tributaries have a high sediment load are likely to be problematic with a high rate of aggradation; coarsening of substrate and opposite bank erosion
- secondary channels which only function at higher flows are susceptible to closure
- coarse substrate reaches with high sediment input from the catchment will be susceptible to sedimentation in the absence of sufficient flow
- areas of aggradation which require periodic flushing to destabilise them

In addition there are certain circumstances under which the impact of an impoundment is likely to be exacerbated, which are listed below.

- high sediment production in the catchments of the tributaries
- semi-arid environment where the main channel is often out of phase with the tributaries
- semi-arid environment where the runoff controlled by the dam is a high proportion of the whole systems flow
- semi-arid environment where tributary contribution downstream is negligible
- unstable bed and banks
- operational procedures that produce a flow regime that is very different to the natural regime
- high abstraction rates which reduce the total volume of flow.

2.7 Conclusion

The models and ideas presented in this chapter are derived from available literature on the impact of impoundments on river geomorphology. They provide a general base from which to begin an assessment of the geomorphological impacts of impoundment in any system. As outlined above, the geomorphological response to river regulation is both complex and varied in time and space. The extent of the impact will be a function of the capacity of the dam in terms of the proportion of the mean annual runoff which it impounds, the variability of the hydrological regime and the nature of the geomorphology of the downstream and channel and catchments.

It is difficult to quantify and accurately predict changes. However, through an understanding of the processes which control channel geomorphology and a knowledge of the known potential impacts, and the conditions under which they occur, it is possible to identify channel reaches which might be susceptible to change under impounded conditions. In order to apply this knowledge in the South African context, the characteristic variability of South African river systems on the spatial and temporal scales, in terms of hydrology and geomorphology must always be taken into account.

Section C: Geomorphological Impacts of interbasin transfer schemes

This section is based on the thesis by A J Du Plessis **"The response of the two interrelated river components, geomorphology and riparian vegetation, to interbasin water transfers in the Orange-Fish-Sundays River Interbasin Transfer Scheme"**, unpublished Msc thesis, Rhodes University, 2000.

Chapter 3: Interbasin transfer schemes in South Africa

3.1 Introduction

An Interbasin Transfer (IBT) can be seen as a mass transfer of water between geographically distinct river basins that has been developed to overcome water supply problems within a country (Petitjean & Davies,1988). In South Africa IBTs have become a widespread means of meeting the geographical mismatch between supply and demand. Such transfers of water will result in an increased flow discharge within the recipient channel and therefore impact directly on the river morphology and ecosystem function. This section of the report presents the results of a study that investigated the impact of an interbasin transfer on the channel morphology and riparian vegetation of the Skoenmakers River in the Eastern Cape. These two components of the river ecosystem are considered to be interdependent and therefore form the focus of this study.

The complex interaction between variables controlling channel morphology are evident from Figure 3.1. Within a given catchment, two sets of variables are recognised as significant. Catchment variables such as climate, topography, vegetation cover and soil type determine the hydraulic and sediment regime of a river while at the reach scale variables such as bed and bank sediment characteristics and riparian vegetation determine channel stability and control the channel form (or morphology) (Rowntree,1991). An interbasin transfer impacts directly on catchment controls by significantly increasing the river flow and disrupting the natural catchment related downstream increase in discharge. At the same time, an interbasin transfer acts directly on riparian vegetation by altering water availability. The altered flow pattern in turn affects the erosion and deposition patterns within the channel, which are translated into changes in channel form. Habitats for riparian vegetation are destroyed through erosion while deposition creates new habitats elsewhere. As the review of literature will demonstrate, vegetation has been shown to exert a significant control on channel processes and channel form. In time a new channel form should develop which balances the hydraulic forces of the regulated flow regime with the controls on morphology resulting from an adapted riparian vegetation community. It is this complex response in the form of interrelationships between the IBT, the channel form and vegetation that is explored in this study.

Over 120 types of IBTs exist worldwide. These can be categorized in terms of the type and size of the donor and recipient river systems, transfer routes, direction and length of the transfer, the rate of transfer delivery and the temporal scale of delivery (constant, pulsed, seasonal, and so on). The donor is usually an impounded river or stream or one having a diversion weir downstream of the drawoff point. The recipient is usually a river or stream but may also be an impoundment. Several types of transfer routes exist, for example *pipes*, open or closed *canals*, *natural water courses* and *aquifers* (Snaddon & Davies, 1997). The operational criteria of an IBT refers to the timing and the type of the release as well as the volume and rate of the water transfer. The most common type of release is in the form of an outlet tunnel, pipeline or canal. The timing of the water release can be of great significance to both the physical and

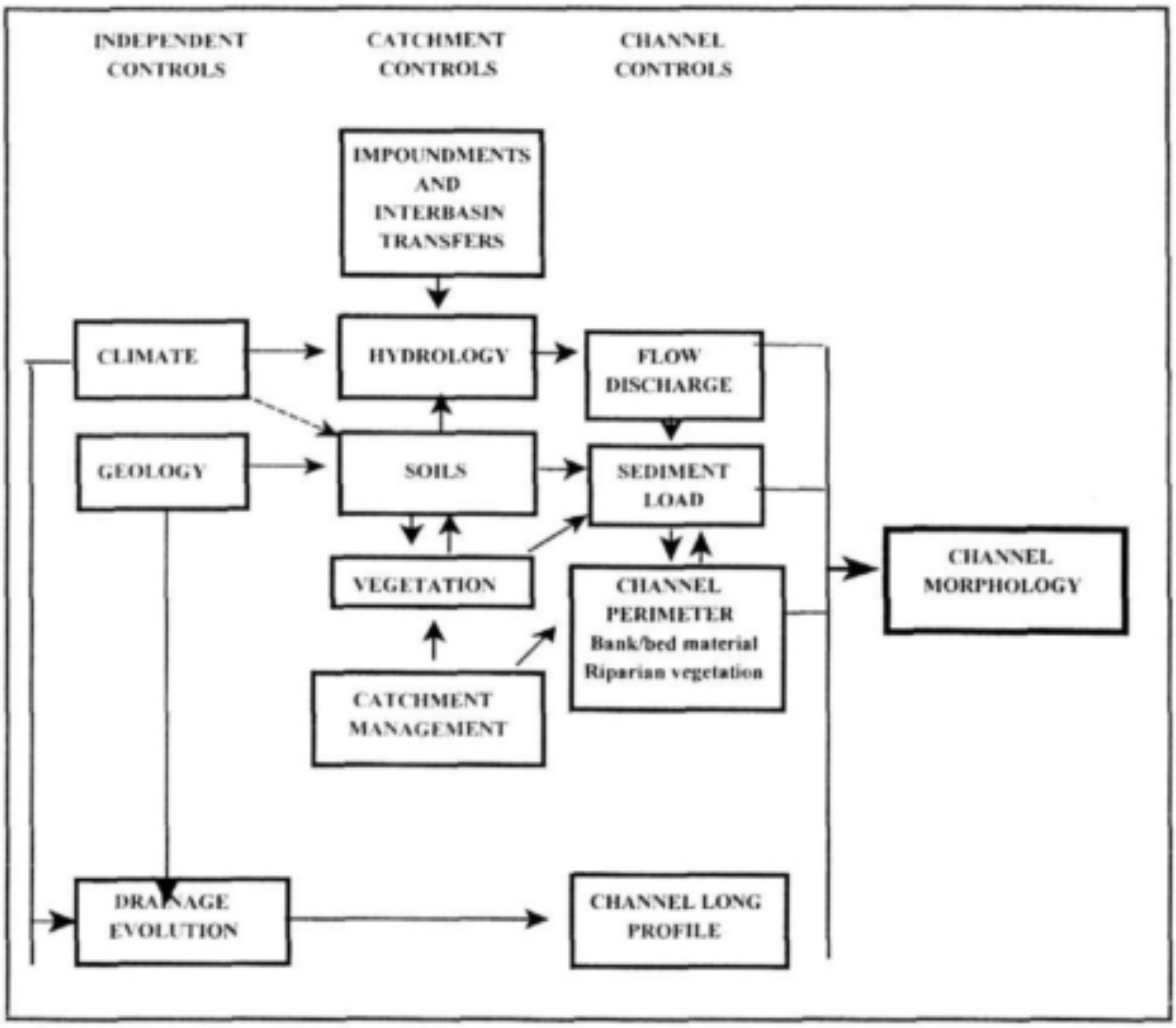

Figure 3.1: *Control mechanisms of river morphology (Rowntree & Dollar, 1996:33).*

biological environments downstream. Aspects such as riparian vegetation are expected to be greatly influenced by the seasonality of the water releases.

It is evident that several decades ago the irregular distribution of population, the extreme variability in rainfall and the generally high evaporation rates across South Africa caused engineers to turn their attention to the development of redistribution networks such as IBTs to account for the inequalities. Most of the large urban centres in South Africa, therefore, rely to a great extent on water supplies from well beyond their borders. For example, Gauteng Province (in the catchments of the Crocodile, Olifants and Vaal Rivers) is being augmented by several river basins including the Tugela, Orange, Usutu, Komati, Olifants and Buffles Rivers. Further shortages due to the high water demand are met by supply from rivers not only within the country's borders, but also from neighbouring Lesotho. The extent of IBTs in South Africa and their ecological impacts have been reviewed by Snaddon *et al.* (1999). Their review highlights the lack of geomorphological research into IBT impacts, not only in South Africa but also at a global scale. Likewise there have been few studies of the impact of IBTs on riparian vegetation. The geomorphological implications of IBTs in South Africa are reviewed below. Reference is made to the small number of local studies of channel geomorphology in recipient streams.

3.2 Existing and planned IBTs in South Africa

Table 3.1 represents a summary of all the IBTs currently operating and/or being planned in South Africa. Some of the influences on the physical and ecological environments of a selection of IBTs are discussed in more detail below.

(a) Orange River Project (ORP)

In terms of the water quantity and flow patterns, the primary influence of the Orange-Fish-Sundays IBT has been a 500 to 800 % increase in the flow of the upper section of the Great Fish River which has been transformed from a seasonal to perennial river. Snaddon *et al* (1999) report the results of research on the impacts of this IBT on water quality, fish species and invertebrate populations, but nothing on the impacts on either the riparian vegetation or the channel geomorphology. A study was carried out by Collett (1996) who noted incision of the receiving tributary for some distance below the inlet point accompanied by prolific reed growth which stabilised the banks.

(b) Riviersonderend-Berg-Eerste River IBT

A dramatic change in the discharge regime of the recipient system of the upper Berg River has occurred with the seasonal water transfers from the Riviersonderend into the upper catchment of the Berg River during the dry summer months to supply irrigation farmers downstream.. Snaddon *et al.* (1999) report an 830-4500% increased flow during the low-flow months. Hydraulic changes such as an increase in the depth and width of the stream are associated with the months of water transfer. No assessment of the geomorphological impacts has been carried out. Although there has been a significant increase in summer flows, the inflow point is into a relatively high order channel and the increase in flow along the regulated section is small relative to the winter floods flows that are most effective in driving geomorphological processes

(c) Mooi-Mgeni River IBT

Water is due to be transferred to the Mpofana River (tributary of the Mgeni River) from the Mooi River. Unconfined channels flowing through a wide or restricted floodplain have been identified in sections of this river and it can be predicted that these sections will be most susceptible to erosion.

As a result of a preliminary investigation into the potential geomorphological impacts (Heritage, 1995), the designed transfer was reduced from 10 m^3s^{-1} to 4.5 m^3s^{-1}. Even under this reduced flow the receiving stream will be at (or close to) bankfull for a significant distance below the transfer outlet. Increased erosion, channel straightening and incision, as well as meander cutoffs are all predicted as the likely response in the unconsolidated alluvial sediment (silts and sands) which make up the flood plain. Although the transfer is not yet in operation, some pumping has been carried out for pump testing, warranties, and so on and definite impacts are already visible (Wadeson, *pers. comm.*).

(d) Lesotho Highlands Water Project (LHWP)

The LHWP was initially designed to divert 2.2 x 10 m^3y^{-1} from the headwaters of the Orange River into the Ash-Liebenbergsvlei tributary of the Vaal River in the Free State. After completion of this scheme, it is anticipated that more than 75 % of the flow in the Vaal River could be imported from other catchments (Snaddon *et al.*, 1999). The transferred water will be used primarily for industrial and domestic consumption in South Africa and as a source of hydro-electric power for Lesotho.

A substantial reduction in the flow and changes to the natural flow regime of the donor Malibamatso River are the major consequences of Phase I (See Table 3.1). Due to settling out of the finer sediments in the Katse Dam, the downstream reaches of the Malibamatso River will receive sediment-free water, which will, in turn, lead to erosion, streambed armouring and downstream transportation of sediment. The recipient Axil River will also undergo changes in terms of the flow, temperature and sediment regimes. If the transfer volume reaches the expected 70 m^3s^{-1}, an extraordinary increase of up to the 20-year-flood discharge of the river will be reached. Geomorphological consequences for the Axil River also include erosion and armouring of the streambed.

It is evident that the alterations to the physical and ecological characteristics of the rivers affected by the LHWP will be considerable and that these river systems will remain unstable for an extended period of time. Field observations made after the first test releases in 1997 already showed signs of erosion of the sandy banks.

(e) Tugela-Vaal IBT

The Tugela-Vaal Scheme was one of the first IBTs designed in South Africa. It was designed to augment supplies in the Vaal River via a diversion from the Tugela River in the east from where water is pumped over the Drakensberg. In 1983 the scheme was expanded to provide a greater assurance of water supply to the industrial heartland of South Africa, Gauteng, with an increase in the transfer rate up to 20 m^3s^{-1}.

Early 'environmental impact assessments' only identified effects linked to the construction works, land to be inundated and powerlines that would blemish the natural beauty of the area. No assessment of the effects of the IBT on either the donor or recipient rivers and their biological communities was made. Rehabilitation of the affected areas was limited to revegetation of the construction sites (Snaddon, *et al.*, 1999).

(f) Amatole Transfer Scheme

The Amatole Transfer Scheme is designed to distribute water from the Kabusi Dam (on the Kabusi River) to the Nahoon and Buffalo systems via two first order channels. Rowntree (in Hughes, 1994) observed geomorphological changes downstream of the release point from the Wriggleswade canal into a first order tributary of the Nahoon River. Substantial bank erosion was observed during an experimental release of 3 m^3s^{-1}. Bed incision was limited due to the presence of bedrock. More recently, impact assessments of the receiving stream of the Yellowwoods River in the Buffalo system point to major impacts on channel stability were the planned releases to go ahead (personal observation).

The above are only a few examples of the impacts an IBT can have on the geomorphology and riparian system of both the recipient and donor river and/or stream. It is clear, therefore, that assessment of the river system as a whole is necessary to understand these impacts and, where possible, minimise or avoid pressure on the natural system. It is sobering to realise that despite the large number of major IBTs operating in southern Africa (see figure 3.2 and table 3.1), holistic environmental impact assessments have only recently been implemented. It was evident through a review of existing literature on IBTs in South Africa that little or no assessment of the impact of these IBTs on the geomorphology and riparian vegetation has been made. It is hoped that the research presented here will contribute to our understanding of geomorphology processes, channel form and associated riparian vegetation in receiving channels of an IBT.

Figure 3.2: *Map of major IBTs in southern Africa: 1, Tugela-Vaal Scheme; 2, Orange River Project; 3, Usutu Scheme; 4, Komati Scheme; 5, Usutu-Vaal Scheme; 6, Riviersonderend-Berg-Eerste Scheme; 7, Eastern National Water Carrier, Namibia; 8, Palmiet River Scheme; 9, Amatole Scheme; 10, Mzimkulu-Mkomaas-Illovo Scheme; 11, Lesotho Highlands Water Development Project, Lesotho; 12, Mooi-Mgeni Scheme; 13, Zambezi Aquaduct (Snaddon et al., in press).*

Table 3.1: *Summary of all the existing and planned IBTs in South Africa (Snaddon et al., 1999).*

Scheme	Phase	Cost ® million)	Volume of transfer ($x10^6$ m^3 cumulative)	Donor system(s)	Recipient system(s)
Usutu Vaal River Government Water Scheme Emergency Scheme	I II 	- - 83.6 -	160 260 -	Vaal Vaal Assegaai (Usutu) Assegaai (Usutu)	Trichardtspruit (Olifants) Steenkoolspruit (Olifants) Little Vaal/Vaal Ngwempisi Spruit (Usutu)
Grootdraai Dam Emergency Aumentation Scheme (1983)	-	-	-	Vaal	Vaal
Usutu River Government Water Scheme	5 phases	-	103	Usutu Mpamaspruit (Usutu) Ngwempisi Spruit (Usutu) Bonnie Brook (Usutu)	Mpamaspruit (Usutu) (Hydro-electric power station) Mpamaspruit (Usutu) Usutu
Komati-Usutu River link system Government Water Scheme	-	-	131	Komati	Olifants
Slang River Government Water Scheme	-	-	-	Slang (Buffels)	Perdewaterspruit (Vaal)
Tugela-Vaal Scheme	I IIa IIb	- 566 -	160347631	Thukela Thukela Thukela	Nuwejaarsspruit (Vaal) Nuwejaarsspruit (Vaal) Nuwejaarsspruit (Vaal)
Orange River Project	- -	- -	35426	Orange Great Fish to Little Fish	Teebusspruit (Great Fish River) Sundays
Riviersonderend-Berg River Project	I & II III	- -	103130	Riviersonderend (Breede) Riviersonderend (Breede)	Berg Eerste

Scheme	Phase	Cost (R million)	Volume of transfer ($x10^6$ m^3 cumulative)	Donor system(s)	Recipient system(s)
Mooi-Mgeni Scheme Mearns Emergency Pumping Scheme	-	-	36614	Mooi (Tugela)	Mpofana (Mgeni)
Amatole Scheme	-	225	36	Toise & Kubusi	Yellowwoods & Nahoon
Lesotho Highlands Water Project	Ia Ib Further phases	- - 25 000	533 851 2 207	Malibamatso Matsoku (Malibamatso) / Senqunyane Senqunyane (Orange) Senqu	Nqoe (Caledon)/Ash (Vaal) Malibamatso/Ash (Vaal) Axil (Vaal)
Palmiet River Scheme	I II	676 -	29127	Palmiet Palmiet	Steenbras Steenbras
Mooi-Mgeni Scheme	Ia Ib II	- - -	3 m^3/s 4-10 m^3/s 6 m^3/s	Mooi (Tugela) Mooi (Tugela) Mooi (Tugela)	Mpofana (Mgeni) Mpofana (Mgeni) Mpofana (Mgeni)
Mzimkulu-Mkomaas-Illovo Scheme	I II	680 -	375 -	Mkomaas Mzimkulu	Mgeni & Illovo Mkomaas
Sabie River Government Water Scheme	I II	270 -	25 -	Marite Sand	Sand Sand/Klein Sand
The Zambezi Aqueduct	-	6 000	2 500 - 4 000	Zambezi	Botswana & Vaal
Thukela-Mhlatuze Transfer	-	260	-	Thukela	Mhlatuze

Chapter 4: Geomorphology and riparian ecosystems in disturbed systems - a theoretical review

4.1 *Introduction*

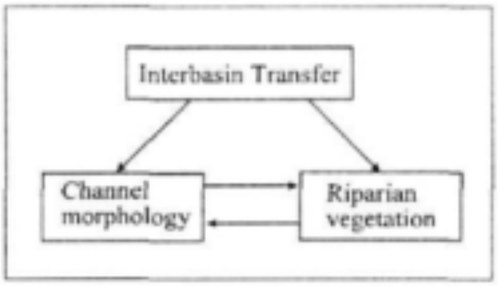

Figure 4.1: *Complex response of a channel to an interbasin transfer.*

An interbasin transfer has a number of direct and indirect effects on the biogeomorphology of the receiving river channel. The primary impact is a change in the flow. A secondary impact is the change in sediment dynamics as material is eroded and redeposited within the system. Together changes in flow and changes in sediment dynamics result in an adjustment of the channel morphology or channel geometry. The newly created channel morphology in turn provide new habitat for riparian vegetation which is also effected by the increased water availability. Changes in riparian vegetation impart feedback effects on channel stability. These interrelationships are conceptualized in Figure 4.1. This chapter presents a review of literature on the geomorphological and vegetation processes operating in a fluvial system and assesses the likely impacts of an IBT on these processes.

4.2 *Controls on channel morphology*

According to Rowntree & Dollar (1996) channel form is controlled by four interrelated groups of variables:

I. The long profile which determines distribution of gravitational energy along a channel;
II. River flow that provides kinetic energy for erosion and transportation of sediment;
III. Sediment which contributes to channel composition through deposition;
IV. Resistance of channel banks to erosion.

These four groups of variables are reviewed below. Possible impacts of interbasin tranfer schemes are assessed.

4.2.1 The long profile

The river long profile is an expression of the change in gradient down the length of the river channel and therefore represents the downstream change in potential energy. The long profile can be divided into reaches, each representing a stretch of river with a uniform gradient. The length of reaches depends on its position within the stream network as well as the heterogeneity of local control variables (Rowntree & Wadeson, 1999). The common progression of a long profile is as follows: steep gradient for the upper reaches, decreasing downstream until a very gentle gradient is achieved in lower reaches. The resulting profile is usually concave upwards with a division of the river into upper, middle and lower reaches (Mangelsdorf *et al.*, 1990).

According to Schumm (1977), the upper, middle and lower reaches can each be linked to the degree of erosion and deposition. Although these two morphogenic processes can be active along the whole river course, Schumm subdivided river courses into three zones, depending on the dominant force active (Mangelsdorf *et al.*, 1990):

- Zone 1: Production => Upper reaches;
- Zone 2: Transfer => Middle reaches;
- Zone 3: Deposition => Area of the mouth.

These reaches are also reflected in the sorting of bed material. According to Rowntree & Dollar (1996), gradient related sorting processes carry the finer particles downstream and therefore the upper reaches will be characterised by coarse material such as boulders and gravel. Lower reaches will carry more sand and silt. The channel morphology will in turn respond to these changes in sediment calibre (see Section 4.2.3).

The characteristic long profile of a river channel will determine the impact of an IBT on erosion and deposition processes along the length of the channel. As discussed below, the increased flow relative to natural conditions at the receiving point will exacerbate the potential for erosion and sediment production. Lower down the system the channel may be better able to accommodate the increased flow, but it will also have to accommodate the increased sediment load from upstream.

4.2.2 Flow as a geomorphological variable

Flow variations in time and space

Streamflow is often considered to be the primary driving force for channel processes as it is responsible for eroding, transporting and depositing channel sediments. The channel geometry is therefore believed to be closely related to the imposed flow regime. Flow variations in both time and space need to be taken into account.

At any one point along the channel network the natural flow varies between no flow, low flows characteristic of baseflow conditions and intermittent high flows associated with storm events. The flow regime can be analyzed in terms of the flow hydrograph - a continuous time-series, a flow duration curve which expresses the cumulative frequency of flows within given ranges, or a flood frequency curve which depicts the frequency at which floods of a given magnitude or greater occur (cf Gordon *et al.* 1996).

In a semi-arid stream the flow tends to be characterized by long periods of no flow or very low flow interrupted by short lived flood events. Floods large enough to overtop the channel banks occur infrequently, perhaps every two to five years. Baseflows, which are normally maintained by groundwater, are short lived and form an insignificant component of the flow hydrograph. (Knighton & Nanson, 1997).

The different flow components have different significance to channel processes. During the flood stage deformation of the river bed occurs while during the base flow stage riparian vegetation growth period and deposition of fine sediments are initiated (Tsujimoto *et al.* 1996). Flood stages or peak flows are needed for the rearrangement of the substratum (through scour), and to reconnect floodplain habitats with the channel and therefore to restore the habitat heterogeneity. Sustained base flow fluctuations are also needed to restore biodiversity and production within the shallow water habitats.

The streamflow hydrograph also changes downstream along the river channel. Total flow volumes increase as the contributing catchment area increases, whilst flood hydrographs become more attenuated. In semi-arid areas downstream increases in discharge are less pronounced than in humid areas because rainfall is more localized. The pattern of downstream adjustments of the channel geometry to these increases in flow is known as the downstream hydraulic geometry (see below).

High flows are far more effective in performing geomorphological work as it these high flows that are competent to entrain and transport sediment. In un-regulated streams it is therefore the floods that exert most control on channel form. The concept of a 'dominant' or channel forming discharge is explored further in Volume 2 Chapter 3, but conventional geomorphological theory states that it is the more frequent floods that are most effective in controlling channel form. In humid areas these floods occur on average about once a year, less frequently in semi-arid areas. In unconfined alluvial rivers with a well developed flood plain, the channel forming flood is also the bankfull flood, that is the flood that just reaches the top of the bank without inundating the floodplain.

Channel forming discharges in semi-arid areas do not relate to the annual flood but to some lower frequency event (Rowntree & Dollar, 1996). The channels of these areas take longer to recover from extreme events and the effects of floods are therefore preserved for a long time, especially where vegetation is sparse (Knighton & Nanson, 1997). This is mainly due to a lack of flows of intermediate magnitude which reconstruct the channel (Rowntree & Dollar, 1996).

An IBT has a significant effect on both temporal and spatial changes in the flow hydrograph. The main effect is to increase the volume of flows with a high percentage accedence, normally considered to be the baseflows, sometimes to levels equivalent to that naturally achieved only during smaller flood events. The duration of flows with a magnitude sufficient to entrain and transport bed and bank sediment may, therefore, be greatly increased. The frequency of natural floods will not be effected, but the volume (and therefore height) of flooding will be increased by an amount equal to the level of the transfer volume.

The hydrological impact of an IBT varies down the length of the channel system, with the impact being greatest at the receiving point, where the natural flows and channel size are the smallest. As the transferred water moves down the system, its volume relative to the natural flow volume becomes smaller and the channel size increases. The impact of an IBT on the river system depends, therefore, at which point on the channel network the transfer takes place. If the water is transferred into a steep, first order headwater stream the increased flow volume and concomitant erosive power can be enormous, resulting in large scale channel adjustment through bank erosion and or channel incision with associated sediment production. Increased sediment loads are carried downstream and provide material for constructing alluvial channel forms in downstream areas. If the water transfer takes place lower down the river system, the higher order channel will be better able to accommodate the higher flows and impacts throughout the system will be less.

Downstream hydraulic geometry

A natural channel accommodates the downstream increases in flow through adjustment to its width, depth and flow velocity. The relationship between changes in these three variables is termed the downstream hydraulic geometry (Leopold & Maddock,1953). This concept assumes that discharge (Q) is the dominant independent variable and that the dependent channel form variables are related to it as power functions:

$$w = aQ^b \quad \textit{(Equation 4.1)}$$

$$d = cQ^f \quad \textit{(Equation 4.2)}$$

$$v = kQ^m \quad \textit{(Equation 4.3)}$$

With w = width, d = depth, v = mean velocity,

From the continuity equation:

$$Q = w{*}d{*}v = aQ^b{*}cQ^f{*}kQ^m \quad \textit{(Equation 4.4)}$$

it follows that

$$b+f+m = 1 \quad \textit{(Equation 4.5)}$$

The expression b+f+m should always equal unity so that a change in the width exponent (b) will be compensated for by a change in depth (f) and velocity (m) exponents. Common values for these exponents are b = 0.5, f = 0.36 and m = 0.1 (Knighton, 1998). Thus the downstream increase in width is slightly greater than that for depth, resulting in an increase in the form ratio, the ratio of width to depth. Velocity increases slightly in the downstream direction. Research in semi-arid areas points to a rapid increase in width up to a contributing catchment area of 50 km^2 (Reid and Frostick, 1997). Thereafter the width is maintained at a more or less constant value, possibly due to transmission losses into the bed of the channel.

It is evident from these empirical equations that downstream hydraulic geometry reflects the way in which channel form changes as discharge increases in the downstream direction. It must be related to a specific discharge frequency, usually the 1.5 year recurrence interval or mean annual flood which should be approximately equivalent to the bank full or channel forming discharge (Rowntree & Wadeson, 1999).

Although discharge is considered to be the primary independent variable controlling channel form, other variables are also important. For example increased stream gradient usually increases stream power with a concomitant increase in channel width, a decrease in channel depth and an increase in channel roughness (Hupp, 1988). Wider channels (and therefore higher width-depth ratios) are also associated with an increase in both the size and mass of the bed material load. Low width-depth ratios are associated with factors promoting bank stability such as an increase in the percentage of fine material and the presence of woody vegetation (see Section 4.2.4).

An IBT will change the natural downstream hydraulic geometry. At the top of the system the transferred flows may be far greater than or equivalent to the mean annual flood and will therefore dominate channel processes, but as distance downstream increases the contribution of the natural flood regime to channel processes will increase until a point may be reached where it becomes the geomorphologically dominant flow component.

4.2.3 Sediment

The size and mass of sediment have important implications for channel form. If the channel morphology is to be maintained, the channel gradient and dimensions must be such that flood events generate sufficient stream power, but no more, to transport the sediment delivered from upstream. If sediment delivery exceeds the streams capacity to transport it, sediment will be deposited either on the banks or in the form of sedimentary bars. If the inverse is true, the channel will erode its bed and banks. In either case the channel morphology will adjust itself towards a more stable configuration.

The relationship between channel morphology and sediment transport capacity depends on the caliber of the sediment being transported. For fine sediment carried in suspension, transport capacity is inversely proportional to the width-depth ratio. Thus deeper flows, having a higher mean profile velocity, are more effective at transporting the suspended material. In the case of coarse material carried along the bed, a wider steeper channel is more efficient as there is a larger surface area across which to convey the material and shear forces at the bed are more important than the velocity above the bed.

In considering sediment dynamics within a channel it is important not only to consider the capacity of the channel to transport sediment, but also the mass of sediment delivered to the channel at any point along the river system. It was noted in Section 4.2.1 that the sediment production from the catchment tends to be highest in the steeper headwater regions (or from steep tributaries entering the main channel further downstream), whilst the middle reaches act to convey the sediment to sites of deposition downstream. Where an IBT is introduced into a system, the potential to erode the channel in the upstream reaches becomes significant so that the natural pattern becomes intensified. The reach immediately downstream of the receiving point is likely to become a major sediment source, augmented by tributary inputs downstream. In a semi-arid environment, in which tributaries flow infrequently, channel banks that are eroded as a result of the IBT will become the dominant sediment source.

4.2.4 Resistance of banks to erosion

The shape of the channel is largely a function of the stability of the channel banks and their ability to resist the erosive forces of the flow. Bank erosion can occur either by the detachment of individual particles or through mass erosion by slumping. The strength of the bank is determined by factors which effect cohesion between grains, soil drainage, and the amount of surface protection afforded, for example, by vegetation.

Cohesion is afforded by the presence of silt and clay or by a dense mat of plant roots. Banks eroded into bedrock have very high cohesion. Cohesive banks tend to fail through slumping whereas a lack of cohesion tends to encourage grain by grain detachment. Stratification can increase instability as detachment of grains in uncohesive beds leads to undermining and collapse of cohesive beds. Alternatively, the preferential erosion of non-cohesive layers which overly cohesive material can also lead to generation of shelves (Thorne, 1990) which provide a particular habitat for vegetation.

Bank accretion is the opposite of erosion and it occurs when the bank is stable and sediment input to the basal area is greater than sediment output downstream (Thorne, 1990). Point bars represent such deposits and, together with shelves, play a very important role in stabilising the river channel and promoting the growth of marginal vegetation.

Vegetation plays an important role in imparting stability to the channel banks. The interrelationships between vegetation and channel form are explored further below (section 4.7). Because of the variable nature of vegetation, the relationships between vegetation and channel form are difficult to quantify, but in general it has been shown that a good vegetation cover increases bank stability and that in many cases the presence of woody vegetation is associated with a reduction in the width-depth ratio as higher banks can be maintained (Rowntree, 1991; Rowntree and Dollar, 1996).

4.3 Channel morphology

Channel response to controlling factors such as discharge and sediment load depends on the channel type. According to Rowntree & Dollar (1996) there are two broad channel types, bedrock and alluvial channels. Bedrock channels are so-called 'controlled channels' as their form is determined primarily by bedrock controls rather than river flow. Alluvial channels on the other hand are formed within the sediment that is being transported by the river, for example gravel, sand or silt, and their form is primarily controlled by the river flow. Mixed channels are composed of alternating alluvial and bedrock sections such that alluvial features develop upstream of bedrock controls.

Alluvial channels form through the interaction of flowing water and a mobile boundary. Alluvial rivers, therefore, can continually change their form and position as a consequence of hydraulic forces acting on their beds and banks (Hails, 1977). Erosion of the bed and banks is counterbalanced by deposition of sediment in the form of bars. For example, in unconfined channels free to move across their flood plains, curved river channels shift laterally by erosion of the concave (outer) bank and deposition of point bars at the convex (inner) banks (Hickin & Nanson, 1984). A classification of bar types and morphological units of an alluvial river is given in Figure 4.2 and Table 4.1 (Rowntree & Wadeson, 1999). These different bars and other morphological units provide important habitat for riparian vegetation and therefore provide important descriptors of channel form.

The arrangement of morphological units within the channel can be described in terms of the channel cross-section (Figure 4.2) which describes the topographic variation across the channel. The cross-section is a useful means of relating morphological units to different flow levels and vegetation zones within the channel (Rowntree, 1991).

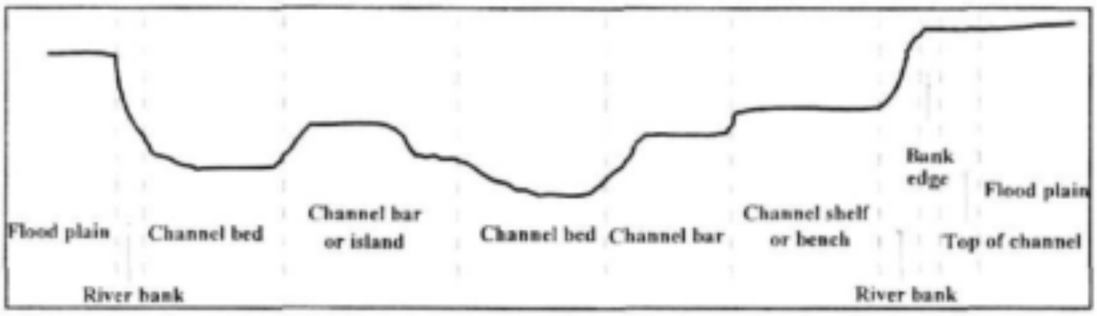

Figure 4.2: *Classification of the bar types and morphological units of alluvial river channels (Rowntree & Wadeson, 1999:44).*

Table 4.1: *Classification of the morphological units (After Rowntree & Wadeson, 1999:45).*

Morphological unit	Description
pool	A topographical low point in an alluvial channel caused by scour; characterised by relatively finer bed material.
backwater	Morphologically detached side channel which is connected at the lower end to the main flow.
rip channel	High flow distributary channel on the inside of point bars or lateral bars; may form a backwater at low flows.
lateral bar or channel side bar	Accumulation of sediment attached to the channel margins, often alternating from one side to the other so as to induce a sinuous thalweg channel.
point bar	A bar formed on the inside of meander bends in association with pools. Lateral growth into the channel is associated with erosion on the opposite bank and migration of meander loops across the flood plain.
transverse or diagonal bar	The bar forms across the entire channel at an angle to the main flow direction.
riffle	A transverse bar formed of gravel or cobble, commonly separating pools upstream and downstream.
rapid	Steep transverse bar formed from boulders.
step	Step-like features formed by large clasts (cobble and boulder) organised into discrete channel spanning accumulations; steep gradient.
channel junction bar	Forms immediately downstream of a tributary junction due to the input of coarse material into a lower gradient channel.
lee bar	Accumulation of sediment in the lee of a flow obstruction.
mid-channel bar	Single bars formed within the middle of the channel, with strong flow on either side.
braid bar	Multiple mid-channel bars forming a complex system of diverging and converging thalweg channels.
bench or shelf	Narrow terrace-like features formed at the edge of active channel abutting on to the macro-channel bank.
islands	Mid-channel bars which have become stabilised due to vegetation growth and which are submerged at high flows due to flooding.

4.4 Riparian Vegetation

4.4.1 Geomorphological effects of vegetation

"The role of riparian vegetation is considerably understated in fluvial geomorphology and certain kinds of vegetation-related fluvial processes are virtually overlooked, or poorly understood at best" (Hickin, 1984:112). The influence of vegetation on channel form can be difficult to quantify because of the varied aspects of vegetation that have to be taken into account such as species composition, growth form, age and density of the stand and so on (Thorne, 1990; Viles 1990). Moreover, not only does vegetation effect channel processes, but the resulting morphology determines the available habitat for riparian vegetation. In an unstable system such as one impacted by an IBT, both channel adjustment and plant succession are dynamic, interdependent processes. Unraveling them is no easy task.

Channel form and the lateral stability of a river may be influenced significantly by the binding properties of vegetation growing on and near the river banks. Bank drainage can be an indirect effect of riparian vegetation on bank stability. Due to increased water use and root induced permeability, vegetated banks are drier, better drained and therefore more stable than unvegetated banks. Well vegetated banks will be associated with lower width-depth ratios than poorly vegetated banks (Hickin, 1984). Riparian vegetation increased channel depth by approximately 63% and decreased width approximately 55% on average in gravel rivers in Colorado (Ikeda & Izumi, 1990).

Different types of vegetation also effect bank stability and channel form, mainly due to the difference in disturbance of flow by vegetation above ground as well as variations in shear strength resulting from different root systems (Gregory & Gurnell, 1988). Vegetation disrupts the flow of water in two distinct ways (Gray & McDonald, 1989); firstly, bank vegetation induces local deposition on banks by reduction of the near-bank velocities, therefore decreasing shear stress on banks and promoting sediment deposition on the channel shelf (Rowntree, 1991). Secondly, vegetation in the form of single, isolated trees enhances scour around the trunk and therefore accelerates local bank erosion. Mature trees can also add to bank loading, thus inducing slumping (Rowntree, 1991).

Much research has focussed on the influence of vegetation on channel roughness (Cowan, 1956; Petryk & Bosmajian, 1975; Powell, 1978; Engman, 1986; Gregory & Gurnell; 1988; Thorne, 1990 and Illgner, 1991). The roughness contribution of vegetation depends on interaction between water depth and flow velocity and height, flexibility and density of the vegetation. Dense vegetation (increased roughness) can reduce channel capacity during floods, leading to more frequent over bank flows (Rowntree and Dollar, 1999).

An ongoing question exists as to the effect of trees compared to grass, and the distinction between grassy and woody vegetation. Researchers agree that a good grass cover tends to protect banks against erosion and encourages deposition of sediment. Trees on the other hand leads to the development of deeper, narrower channels (Keller & Swanson, 1979; Murgatroyd & Ternan, 1983; Gregory & Gurnell, 1988; Viles, 1990; Van Coller, 1992; Rowntree & Dollar, 1996; Trimble, 1997). According to Van Coller

(1992), an increase in woody vegetation cover may have major stabilizing effects on channel bars and islands and can therefore be seen as an important component influencing future morphology. All riparian vegetation aids the development of channel bars and islands due to flow resistance and sediment trapping.

Vegetation communities are not static and therefore changes in vegetation often lead to spectacular changes in erosion rates and distribution and thus, ultimately, to the geometry of the channel. Cycles of build-up and erosion may occur as vegetation communities grow and are then killed off by an excess of sediment, leading to the development of distinctive landforms. Riparian vegetation thus plays a major role within the fluvial system. To assess this role, it is important to understand the sensitive nature of the riparian ecosystems and associated processes.

4.4.2 Riparian ecosystems

The riparian zone can be seen as the aquatic-terrestrial ecotone. At the macro-scale riparian ecosystems are powerful organizers of the structural and functional characteristics of streams, as riparian vegetation can often override or modify the basic geomorphological and hydraulic constraints (Cummins 1992). It is evident, therefore, that riparian ecosystems are both a product and formative agent of channel geomorphology.

Riparian ecosystems are organised within specific drainage patterns and are effectively interspersed within the landscape despite a small total area. They act as filters between adjacent landscape elements, and therefore also act as buffers against environmental change. Riparian ecosystems can also be seen as the most important natural corridors for flows of energy, matter and species through the landscape (Nilsson & Jansson, 1995). Nilsson & Jansson (1995:55) made the statement that "riparian ecosystems are central elements in many landscapes". Riparian ecosystems act as hotspots of species richness and are therefore key elements in the regulation and maintenance of landscape biodiversity. According to Kondolf *et al.*(1987), riparian ecosystems support more species diversity, higher population densities and greater plant and animal biomass than any other habitat

Riparian ecosystems are most sensitive to human influences and potentially are the most threatened ecosystems due to their exposure to natural and human related disturbances (Haslam, 1978; Rowntree, 1991; Naiman *et al.*, 1992 and Nilsson *et al.*, 1997). Nilsson *et al.* (1991) stated that riparian ecosystems can be used as indicator systems in assessing the effects of water regulation on the river margin. Riparian ecosystems in arid and semi-arid regions are under continuous pressure from water development activities such as IBTs (Stormberg, 1993). A study of the response of riparian vegetation to an IBT is therefore essential to add to the understanding of the diverse river system as a whole.

The distribution of riparian vegetation along a river system depends on a number of factors: the site preference of different vegetation communities, water availability, site availability and invasion by exotic riparian species. The diversity of species and communities along a river depends largely on the diversity of channel morphology which itself varies down the length of the river in response to the geomorphological processes operating. The different factors determining the species and community distributions in the riparian zone are reviewed below.

4.4.3 Site preferences

Plant communities are defined as a collection of plants showing a definite association with each other (Kent & Coker, 1992). This association implies that certain species are found to grow more frequently in certain locations and environments than would be expected by chance. The reason for this preference of a specific site depends on the specific requirements in terms of environmental factors, for example water, drainage and soil nutrients (see Figure 4.3). Species will be absent from locations or sites where optimum thresholds in terms of the environmental factors are exceeded. These sites are called the *zone of intolerance* (Kent and Coker, 1992;Figure 4.3).

The removal of existing vegetation and/or sediment, as well as deposition of sediment and vegetation on existing sites, is determined by the disturbance of flooding. Examples of vegetation sites created in such a way include exposed patches of bedrock and the cracks in between rocks and alluvial sediment

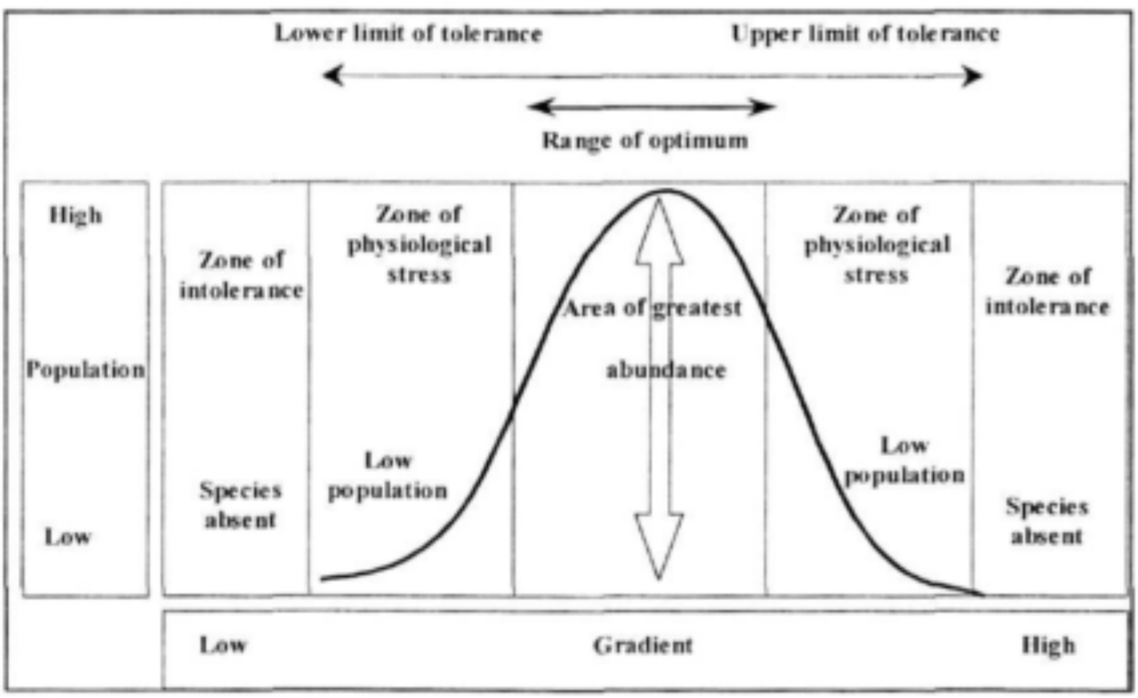

Figure 4.3: *The Gaussian or normal curve of plant species response to a single environmental factor (Kent & Coker, 1992:14).*

depositions. These are important regeneration sites with the variety in texture and organic matter content as the most important variables.

Erosion and sedimentation result in a variety of fluvial landforms with different surface substrata and there is a close correlation between type of fluvial landform and vegetation distribution patterns (Van Coller, 1992). The statement above is supported by research by a number of other authors indicating that the distinct site preferences of bank vegetation can be linked to the morphological change of the channel (and *vice versa*), as well as the sediment dynamics within the channel (Gregory & Gurnell, 1988; Thomas, 1988; Viles, 1988; Hupp, 1990; Simon & Hupp, 1990; Thorne, 1990; Trimble, 1990; Rowntree, 1991 and Collett, 1996) and water availability.

Different sets of hydrogeomorphic processes form the floodplain and the channel shelf, with different suites of characteristic vegetation (Hupp, 1988). Small reed infested bars tend to trap sediment, thereby increasing the height above the water and therefore their chance of survival. A more favourable habitat in terms of sediment is provided for the new community of plants through this process (Illgner, 1991). In ephemeral channels of semi-arid areas, woody species often colonise channel bed and bars. Channel shelves serve as habitat for herbaceous vegetation and riparian shrubs (Rowntree, 1991). It is therefore evident that the availability of these habitats plays an important role in the establishment of vegetation and its structure along river channels.

4.4.4 Site availability

The process of plant succession along rivers is usually initiated on new alluvium deposited during flood-stages. New space for the deposited sediment has to come from the destruction of older sections of the bank or floodplain. This constant replacement of older soil-vegetation complexes by new successional units results in a specific structure of riparian vegetation (Gill, 1973).

The removal of existing vegetation and/or sediment, as well as deposition of sediment and vegetation on existing sites, is determined by the disturbance of flooding. Examples of vegetation sites created in such a way include exposed patches of bedrock and the cracks in between rocks and alluvial sediment depositions. These are important regeneration sites with the variety in texture and organic matter content as the most important variables.

4.4.5 Water availability

The most important factors influencing the riparian water balance in any river section are the magnitude and timing of surface inundation and bank storage. The latter will depend largely on the cross-section morphology and the depth and porosity of the soil (Rogers & Van der Zel, 1989).

Riparian species have higher transpiration rates than terrestrial species and therefore require a permanent supply of water for at least part of the year (Van Coller & Rogers, 1996). Some riparian zones, especially in semi-arid areas, experience short seasonal floods and long dry seasons when water availability is low, at least for shallow-rooted plants. Water availability can be seen as the primary factor limiting riparian vegetation abundance in semi-arid regions. Small changes in discharge and riparian water availability lead to measurable changes in riparian vegetation abundance (Stormberg, 1993). An IBT will have an over-riding effect on water availability.

4.4.6 Exotic riparian vegetation species

A review of South African literature on vegetation-morphological relationships shows the potential impacts of alien vegetation on river morphology as one of the major concerns (Rowntree, 1991; Collett, 1996). Alien species have the tendency to invade disturbed areas along rivers because of the fact that it is easier for these species to establish in the new conditions. IBTs represent such a disturbance in the riparian zone and therefore it enhances alien invasions (Collett, 1996). Naturally unstable geomorphic units such as river bends are particularly susceptible to invasion. Perennial availability of moisture also plays a major role in establishment of exotics (Rowntree, 1991).

4.4.7 Morphological diversity

The numbers of both communities and species of riparian vegetation depend largely upon the diversity of the habitat and the degree of disturbance and therefore is a reflection of the diversity of channel morphology (Hellawell, 1988; Nilsson *et al*, 1989; Hughes, 1990). Morphology varies at two scales, within a site (across the channel section) and in the downstream dimension. According to Hughes (1990), species diversity is highest in the mid reaches of a river because of the fact that these reaches exhibit the highest environmental heterogeneity. Hughes(1990) recognised, however, that species composition is also a function of other environmental variables including the disturbance regime; disturbance therefore decreases the predictability of species composition from site attributes, a finding confirmed by Nilsson *et al.* (1989). They found that total species richness increased with substrate heterogeneity and was at maximum at intermediate levels of disturbance.

Downstream changes in habitat characteristics and associated zonation of vegetation can be explained by the changes in the morphological diversity resulting from water flow (quantity), channel width, channel depth, gradient and substrate (sediment). The sediment can be seen as one of the most important physical variables controlling plant distribution downstream (Haslam, 1978). Both the rates and types of sediment deposition have been shown to be important. Many riparian species are restricted to a narrow range of sediment types that allow successful seed germination (Hupp, 1988). Most bottomland sediment available for seedling establishment is alluvial, thus hydraulic sorting of sediment sizes and the rate of bed, bar or bank accretion are important geomorphic processes influencing vegetation distribution.

Patterns of riparian species distribution are strongly associated with the geomorphic balance between erosion and deposition (Simon & Hupp, 1990). Deep-rooted plants can withstand erosive forces and therefore these species are found more commonly in the upper reaches where erosion represents the dominant morphogenic force. In contrast, plants usually associated with deposition are represented by shallow-rooted species with a varying rooting level (that is, roots that will grow with the accumulating sediment). Thus the upper reaches will be associated with woody vegetation, whilst grass and reed species tend to be dominant in the lower reaches where deposition in the form of channel bars is prevalent (Van Coller, 1992).

Van Coller (1992) pointed out that species distribution is not controlled directly by the physical landforms themselves, but rather by the fluvial and hydrological processes associated with these landforms. Three gradients were identified to explain species distribution along streams:

(i) *Longitudinal gradient:*

Physical variables and hydro geomorphic processes change in a downstream direction and can be explained by the longitudinal gradient.

(ii) *Vertical* and (iii) *Horizontal gradients:*

A small change in elevation above (vertical gradient) or horizontal distance away from (lateral gradient) the active channel results in definite changes in flooding frequency, water table fluctuations, fluvial landform, as well as soil and sediment type.

According to Van Coller & Rogers (1996), the vertical, lateral and longitudinal gradients, combined with patchy geomorphological settings, lead to an extremely diverse and dynamic environment that influences species distribution patterns. Vegetation units or types[1] are also closely related to differences in degree of bedrock control and type of morphological unit. These relationships between the riparian vegetation and the physical environment result in specific site preferences for specific vegetation types as outlined in Section 4.4.

4.5 Overview

The potential impacts of an IBT on the geomorphology and riparian zone of the receiving stream have been assessed from a consideration of basic geomorphology with specific reference to published research on the interdependent relationship between vegetation and channel geomorphology. It has been shown how, under natural conditions, channel form can be expected to change in a regular manner downstream. Width and depth should both show a progressive increase in depth downstream, while channel morphology should change from one dominated by erosional processes to one in which depositional forms become more prevalent. Vegetation can be expected to reflect this change in morphology, with an increased morphological heterogeneity being reflected in an increased species diversity. As vegetation becomes established it will tend to aid erosional or depositional processes depending on its characteristics and position in the channel and along the long profile.

The primary impact of an IBT is the increase in flow. This will be most significant in the reach immediately below the receiving point where the transferred flow is likely to dominate the hydrograph, especially in a semi-arid system. Baseflow levels throughout the system will be significantly increased and in the upper reaches of the river may approach natural flood levels. This distortion of the natural downstream flow pattern can be expected to impact on the downstream hydraulic geometry, the pattern of sediment supply and deposition and the morphological heterogeneity of riparian habitat.

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[1]Vegetation type can be defined as a collection of common species which possesses a similar vegetation structure (vertical profile) and share the same set of ecological processes (Low & Rebelo, 1996:2).

Chapter 5: Case study of two South African rivers

5.1 Aim and objectives

Complex interrelationships exist between riparian vegetation and the morphology of a river in a natural or non-regulated river system. In South Africa, where more and more river systems are becoming impacted by anthropogenic disturbances such as IBTs, the question arises as to what would happen to these interrelationships within a regulated river system? The aim of this study is therefore to develop a better understanding of the response of river morphology and riparian vegetation to the influence of an IBT, specifically the Skoenmakers River. In order to accomplish this, the research focussed on the following objectives:

- To emphasize the importance of ecological factors such as riparian vegetation within a fluvial geomorphological context;
- To indicate the specific interrelationships that exist between river morphology and riparian vegetation;
- To determine the processes within both geomorphology and riparian vegetation that will change as a result of the IBT; and
- To indicate the response of the morphology and riparian vegetation to the IBT.

5.2 Study area

Impacts of an IBT on channel processes in the receiving stream can be assessed in two ways. The first is to survey the channel form and related attributes before and after the development of the IBT, the second is to compare two systems, a natural system with an impacted system. The first method has the advantage that changes can be related directly to the IBT, but depends on the availability of pre IBT data. The second method has the disadvantage that no two systems are directly comparable and differences may not be attributable to the IBT, but has the advantage that it does not rely on pre IBT data. In the case of the Skoenmakers River, no channel surveys of the pre IBT condition were available so comparisons were made with the adjacent tributary, the Volkers river.

The two rivers, the regulated Skoenmakers and the unregulated Volkers, form part of the Sundays River catchment (approximately 21 250km^2) which drains a large area of the semi-arid Karoo region of the Eastern Cape (Figure 5.1). They are similar with respect to catchment size, rainfall, geology and general catchment characteristics. Their natural hydrology and sediment yield should therefore be comparable. The Volkers River (subcatchment area of approximately 290km^2 and main channel length of approximately 50km) is a typical ephemeral, gravelbed river, as found in semi-arid regions of the Eastern Cape, and has its source within the Zuurberg mountain range near Kirkwood. The regulated Skoenmakers River has a subcatchment area of approximately 270km^2 (See Figure 5.2) and a main channel length of approximately 48km. It forms part of the Orange-Fish-Sundays River IBT which involves water transfers from both the Orange River and its tributary, the Caledon River, to the Great Fish and Sundays Rivers.

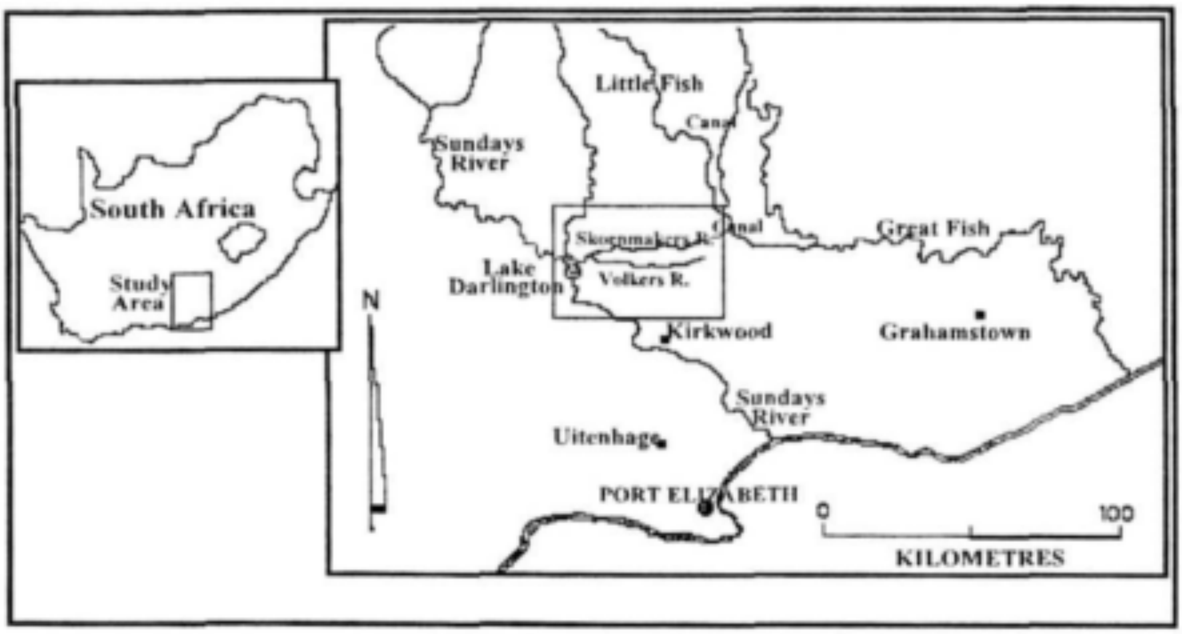


Figure 5.1: *Location of the study area within the context of the Orange-Fish-Sundays River Interbasin Transfer.*

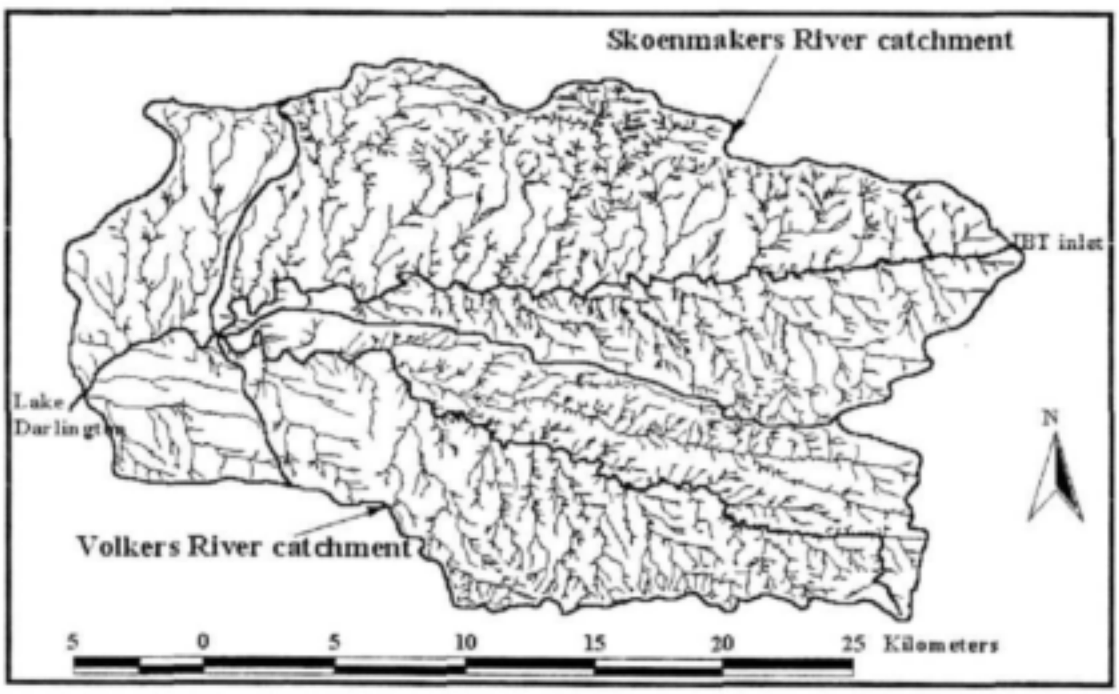


Figure 5.2: *Subcatchments for the Skoenmakers and Volkers Rivers.*

The transfer point is into a first order channel near the watershed. Under natural conditions the Skoenmakers River was an ephemeral stream (similar to the Volkers River), but the transfer of water from the Orange River since the late 1970s and early 1980s has converted it into a perennial river.

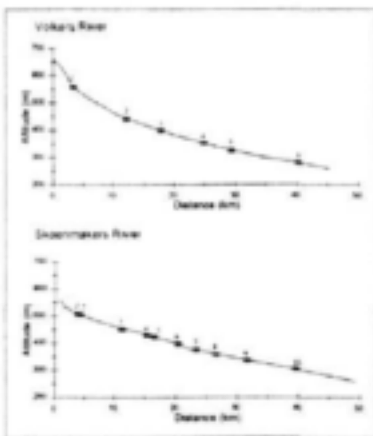


***Figure 5.3:** Long profiles of the Volkers and Skoenmakers rivers.*

Downstream variations in both channel morphology and riparian vegetation are in the first instance determined by the long profile of the river. The long profiles for both rivers, constructed by means of digitized Arc/Info covers, are illustrated in Figure 5.3. Reach breaks, based on a significant change in the channel gradient, are indicated by broken lines. Individual reaches are expected to show a characteristic channel form which reflects the local profile gradient.

As characteristic of many Eastern Cape rivers, the long profiles of these two semi-arid rivers do not follow the conventional concave form and tend to have a steeper profile due to rejuvenation in the recent geological past (Rowntree & Dollar, 1996). As a result, the 'normal' gradation from bedrock to alluvial channels is disrupted. Although bedrock dominates the steepest headwater areas and alluvial sections become more frequent downstream, these alluvial areas are interspersed with rock outcrops so that even the lower reaches may have significant bedrock and cobble sections. These reaches are classified as mixed or semi-controlled. Various combinations of bed and bank material were found in these mixed reaches. In some reaches the bedrock was exposed in the channel bed but the banks were composed of alluvium. Where the river was migrating laterally, one bank may have been formed in bedrock whilst the other was formed in alluvium. Both the Skoenmakers and Volkers Rivers have a strong meandering channel form, especially in their upper reaches.

The geology of the two catchments is illustrated in Figure 5.4. The dominant groups are represented by the Beaufort and Ecca Groups of the Karoo Sequence. The Beaufort Group consists of the Koonap Formation whilst the Ecca Group includes formations like Fort Brown, Ripon, Dwyka, Salnova and Waterford. These two groups are both characterised by highly erodible sedimentary rocks which contribute to sediment input into the channels. The Beaufort Group consists of the Koonap mudstones and sandstones while the Ecca Group has a large shale component - the Ecca shales. The Koonap formation dominates the upper Skoenmakers whilst the lower Skoenmakers and Volkers river catchments are dominated by the various formations of the Ecca Group. Not shown on the map are localised dolerite intrusions which are often associated with rapids.

The vegetation of the catchment is dominated by the vegetation types found within the Nama Karoo Biome. The dominant vegetation type is the Eastern Mixed Nama Karoo vegetation type which consists of a complex mixture of shrub- and grass-dominated vegetation types subjected to dynamic changes in

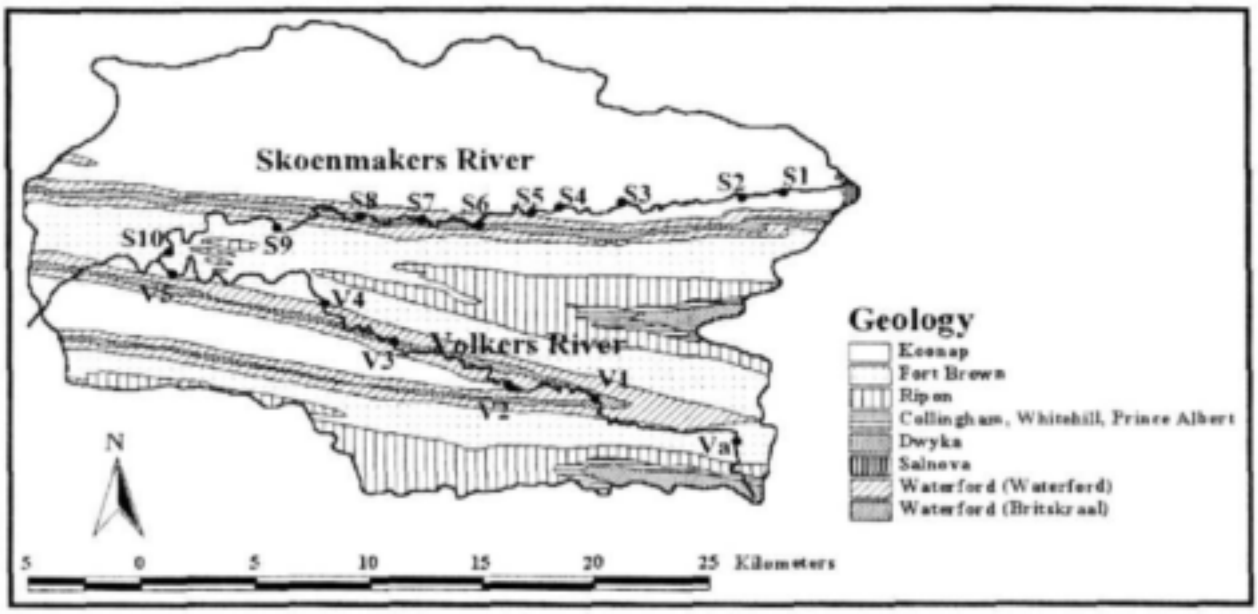


Figure 5.4: *Geology of the cathchment (Data Source: 1:250 000 geological map)*

species composition and is highly dependent on seasonal rainfall events. Trees, mostly *Acacia karroo*, are mainly found along the dry river beds (Hoffman, 1996).

The study area falls in the semi-arid Karoo region of the Eastern Cape and therefore within the summer rainfall area of South Africa. The mean annual rainfall for the Quaternary catchments is given as 318 mm against a potential evaporation of 1700 mm, resulting in an estimated mean annual runoff of 16 mm (Midgley *et al*, 1994).The highest average monthly rainfall occurs during December (Figure 5.5).

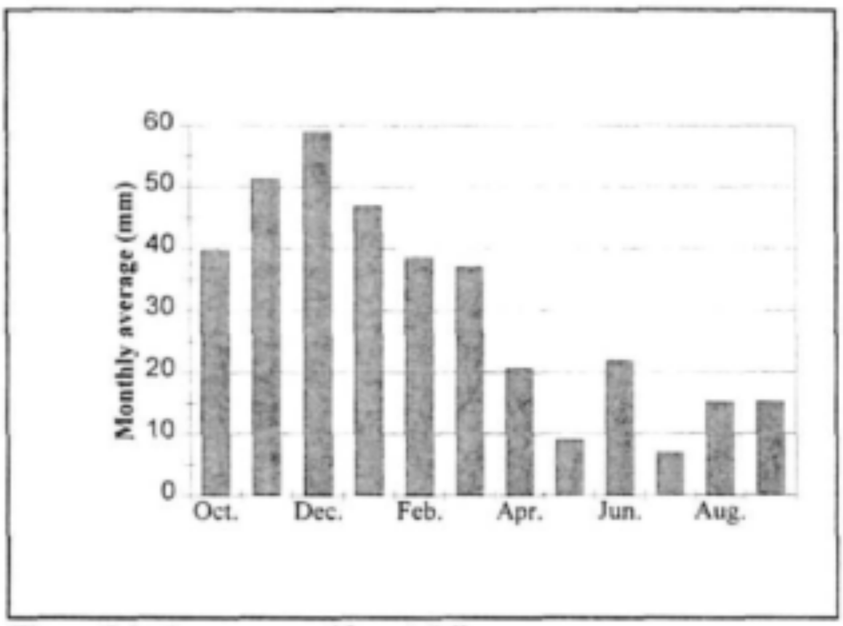


Figure 5.5: *Average monthly rainfall.*

5.3 The Orange-Fish-Sundays River Interbasin Transfer Scheme

As early as 1928 diversion of Orange River water to the Fish River had been proposed by the Director of the Department of Irrigation. In 1962 a comprehensive plan for the development of the Orange River was announced (Van Robbroeck, 1979). The Orange-Fish tunnel was completed in 1975, bringing water from the Gariep Dam into the Fish River system. The first flows into the Skoenmakers River date from this time, but the final system as operated at present was only put into operation in 1987.

The Skoenmakers River receives water that is diverted from the Fish River at the Elandsdrift weir near Cookhouse. The water is conveyed into the Little Fish River by way of the Cookhouse tunnel (See Figure 5.6). Originally water form the Little Fish was diverted by a diversion weir and pumped over the watershed to the Skoenmakers River at the Wellington Grove pumpstation (Van Robbroeck, 1979) but as a result of the high costs involved (R33 000 p.m.) an alternative method of diversion had to be found. In 1985 De Mistkraal Dam on the Little Fish was completed and water was let down the Skoenmakers Canal into the Skoenmakers River.

Water released into the Skoenmakers flows into Lake Darlington whence it supplies the Lower Sundays River Irrigation Scheme and the Port Elizabeth area. The amount of water let down the Skoenmakers depends on the demand downstream, especially from the irrigation farmers in the Sundays River irrigation area.

Before the completion of De Mistkraal Dam, water released down the canal was restricted to about four m^3s^{-1} by the Wellington Grove Pumpstation. After the completion of the dam the full capacity (up to 22 m^3s^{-1}) of the Skoenmakers Canal can be utilised. Water release from the dam is interrupted during May and June when repair work is done to the Skoenmakers Canal. During this 'dry period' the Skoenmakers River continues to flow for approximately two weeks after which streamflow almost comes to a standstill in the river and large pools are

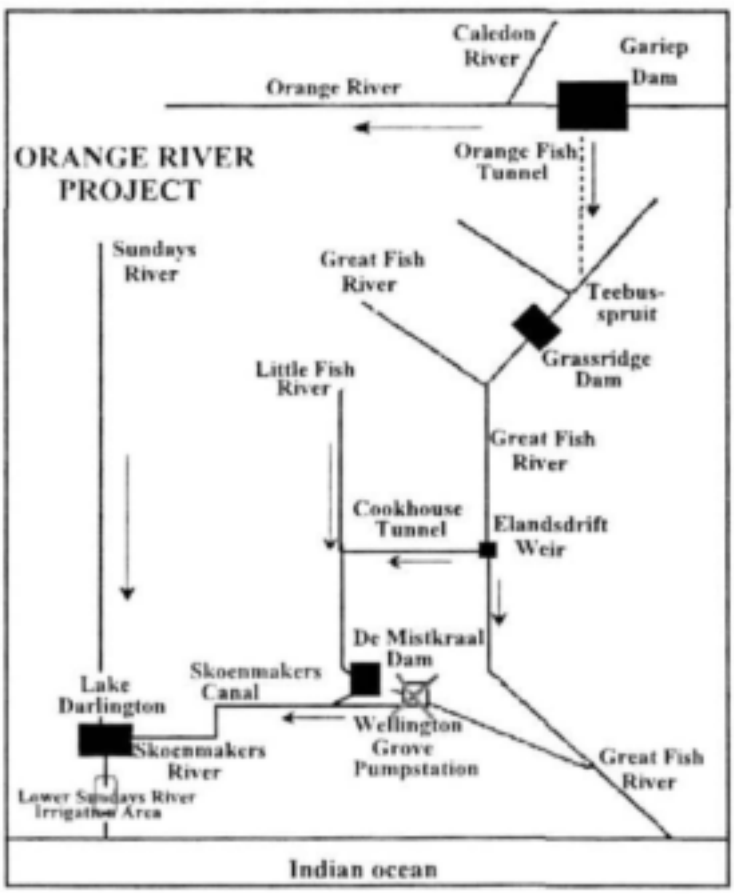


Figure 5.6: *Schematic outline of the Orange-Fish-Sundays Interbasin Transfer Scheme (Petitjean & Davies, 1988).*

formed. During floods upstream of De Mistkraal Dam water releases into the Skoenmakers Canal is cut off and the water is allowed to flow over the dam wall into the Little Fish. These flood events, therefore, do not have any effect on the Skoenmakers River (Faber, *pers. comm.*).

It is evident that the IBT has resulted in dramatic flow changes in the Skoenmakers River. The river has been changed from an ephemeral stream, typical of the semi-arid Karoo region of the Eastern Cape, to a near-perennial river. Moreover the distribution of flow down the length of the channel has changed markedly. High flows introduced at the top of the system are maintained at more or less the same volume down the length of the channel, except during the rare flood events which contribute water progressively down the system. Baseflow contributions have a minor effect in terms of augmenting flows down the channel length and will be more than counteracted by abstraction for local irrigation. The impact of these changes on the geomorphology and riparian vegetation of the Skoenmakers are addressed in this report.

5.4 *Research design*

Channel response to the IBT was assessed by comparing the receiving stream, the Skoenmakers, with the Volkers, an unregulated tributary that drains a catchment similar in its characteristics to that of the Skoenmakers. The investigation involved two main approaches: an analysis of available hydrological records to assess changes to the flow regime of the regulated river and a comparison of the channel morpholgy and vegetation structure between the regulated and unregulated rivers. An historic series of aerial photographs for the Skoenmakers River was used to assess changes over time in channel plan.

Downstream changes in channel morphology and vegetation were investigated by selecting transects at sites distributed down the length of the channel (figure 5. 7). At each survey site one cross-section was surveyed to characterise the channel morphology and its associated vegetation. The number of sites chosen along each river depended upon the botanical and geomorphological variation between the individual sites of the same reach as well as accessibility. Six representative sites were chosen along the Volkers. In comparison, ten sites were chosen for the Skoenmakers to take into account the higher diversity of the riparian vegetation. Table 5.1 presents the summary of the different site locations. Division of the two rivers into the three sections - upper, middle and lower reaches - was based on the reach breaks, identified from the long profile (see figure 5.3).

Historical surveys and aerial photographs were used to compare the channel pattern, channel width and riparian condition over time for the Skoenmakers.

Table 5.1: *Sites Location along the Volkers and Skoenmakers.*

Volkers			Skoenmakers		
Site	**Distance downstream (km)**	**Section of the river (Reach)**	**Site**	**Distance downstream (km)**	**Section of the river (Reach)**
Va	3.51	Upper	S1	3.79	Upper
V1	12.2	Upper	S2	4.27	Upper
V2	17.83	Upper	S3	11.52	Upper
V3	24.91	Middle	S4	15.21	Middle
V4	29.67	Middle	S5	16.88	Middle
V5	40.13	Lower	S6	20.21	Middle
			S7	23.42	Lower
			S8	26.74	Lower
			S9	31.59	Lower
			S10	39.75	Lower

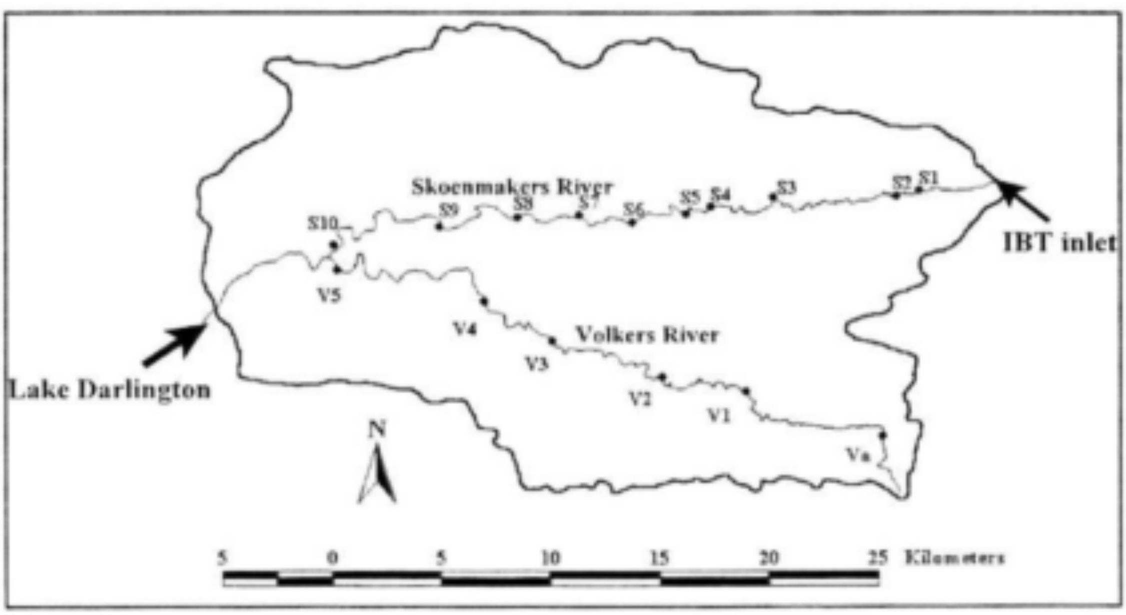


Figure 5.7: *Study sites along the Volkers and Skoenmakers Rivers.*

5.5 Data collection and analysis

5.5.1 Hydrology

Gauged data were available for the years 1978 to 1988 for a gauge on the Skoenmakers river below the confluence with the Volkers (N2H009-A01) and for the releases from De Mistkraal Dam for the period from 1989 to the present (gauge Q8R001). The gauge N2H009-A01) was closed down in March 1989. The gauged data was obtained from the Department of Water Affairs and Forestry (DWAF) in Cradock. No measured data were available for the pre-IBT period.

The pre-IBT hydrology was evaluated using the simulated data available from the WR90 data base for quaternary catchment N23A (*Midgley et al.* 1997). This catchment included the two tributaries of the Skoenmakers and the Volkers upstream from the confluence of the two rivers. It covers a catchment area of 537 km^2 with a mean annual runoff of 16 mm or 8.8 million m^3. The WR90 data base includes simulated monthly volumes of natural runoff in million cubic metres. This data was converted to mean daily flows in m^3sec^{-1} so that it could be compared with the modern data record.

No flood data was available for the pre-IBT period, but an indication of possible maximum floods was derived as follows. In semi-arid areas the flood hydrograph tends to be highly peaked and it is likely that a large component of the flow for one flood passes through the channel in one day. It was assumed, therefore, that for any given month a large proportion of the total could be allocated to one day. To get a first estimate of the daily flood peak at the confluence of the two tributaries the monthly flow volume was assigned to one day and converted to m^3sec^{-1}. In reality each flood may have extended over more than one day, or the monthly flow may have been generated by more than one flood. This estimate does, however, give a maximum value for flood peaks (mean daily flow) below the confluence of the two rivers. Flood peaks estimated for each year were plotted as a time series. The recurrence interval for floods of each magnitude were estimated according to standard methods (Gordon *et al.* 1996).

The gauged flow data forN2H009-A01 was in the form of mean daily flows and maximum flows for each month of record. The gauge could not measure flows in excess of 20 m^3sec^{-1}. The data from gauge Q8R001 were in the form of monthly flows in million cubic meters. The data from both stations were analyzed to derive mean monthly flows in m^3sec^{-1} for the period before and after the construction of De Mistkraal Dam (1978 - 1984) and (1986-1997). Monthly flow duration curves were constructed for these two time periods. The frequency of peak flows between 1978 and 1988 was counted from the record for N2H009-A01

5.5.2 Channel morphology

Cross-section profiles for each site were surveyed using a total station. Significant points (breaks in bank and bed slope, sediment change and so on) were recorded along the cross-section. A typical cross-section is shown in Figure 5.8. Morphological units were identified using the definitions given by Rowntree and Wadeson (1999) (Figure 4.2 and Table 4.1). The bed and bank conditions of the channel were assessed by means of on-site evaluation of the geology, sediment type and degree of erosion or deposition.

A distinction was made between the active channel and the macro channel. The active channel is the channel that is regularly filled to the bank top level and for which the morphology is formed by present day flows. The active channel may be contained within a macro-channel whose bank top is level with infrequently inundated terrace. An inset bench of shelf separates the bank top of the active channel form the bank sides of the macro-channel.

A number of variables were derived from the channel cross-sections. The channel geometry of the active channel was described in terms of channel width and channel depth. Channel width was measured off the cross-section, using morphological and vegetation criteria to establish 'bankfull'. Channel depth was estimated directly from the total station data by calculating the average depth of the total recorded points along the cross-section below the bankfull level. The following variables, thought to control the vegetation, were measured or categorised: elevation above the channel bed, distance away from the active channel, type of morphological unit, type of surface sediment and geology. Two sediment samples of between 300 g and 500 g were taken from each morphological unit present, for example the banks, shelves and channel bars. Two additional samples were also taken where a significant change in the sediment and vegetation type at each morphological was observed. Using an auger, all the samples were taken within the first 30cm of the soil surface. On-site observations showed the dominant sediment type to be coarse gravel to sand size particles. Sediment samples taken from the different sites were therefore analysed using the dry sieving method (Gordon *et al.*, 1992). The sediment was separated according to the Udden-Wentworth scale (Blatt *et al.*, 1980) into the sediment classes presented in Table 5.2.

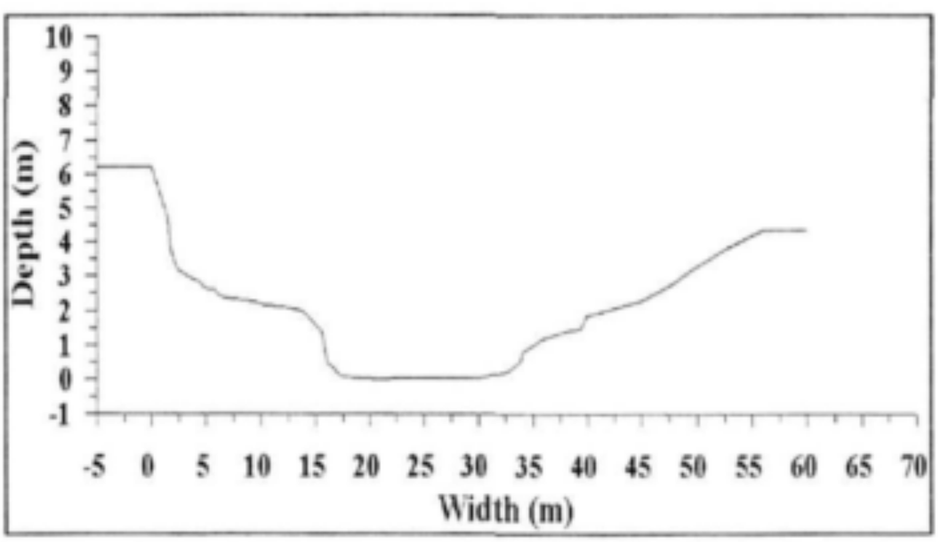


Figure 5.8: *An example of a cross-section profile for the Skoenmakers River.*

***Table 5.2:** Sediment size classes.*

Sediment size class	Symbol	size range (mm)	size range (ϕ)
Very coarse gravel	VCG	35 - 64	
Coarse gravel	CG	16 - 35	
Medium gravel	MG	8 - 16	
Fine gravel	FG	2 - 8	
Very coarse sand	VCS	1 - 2	
Coarse sand	CS	0.5 - 1	
Medium sand	MS	0.25 - 0.5	
Fine sand	FS	0.125 - 0.25	
Very fine sand	VFS	0.125 - 0.65	
Silt/clay	Si	< 0.65	

The present day hydraulic geometry for the two rivers was compared by plotting channel width and channel depth against distance downstream, derived from the GIS maps. Distance downstream was used as a surrogate for the natural channel forming discharge.

The top width of the macro-channel was measured off surveyors' maps (1:6 000) of the Skoenmakers in the pre-IBT stage (1970), obtained from the Department of Water Affairs and Forestry (DWAF) in Cradock. The site of each of the ten cross-sections was located on this map and the width of the macro-channel measured. These widths were compared with those measured from the surveyed cross-sections by plotting the historic and modern width as a function of distance downstream.

Aerial photographs were obtained from the Chief Directorate: Mapping and Surveying at Mowbray, Cape Town. These included photos for the pre-IBT phase (1960 at a scale of 1: 40 000) and the post-de Mistkraal phase (1990 at 1: 30000). The channel pattern at 1960 and 1990 was mapped from the aerial photographs for two reaches near the top of the system. Landuse change was mapped for the entire length of the river.

5.5.3 Riparian vegetation

According to Van Coller (1999:2) "Spatial distribution patterns derived from relationships with the physical environment are essentially descriptive". Purely statistical approaches to describing vegetation patterns can be misleading or unproductive (Zimmerman & Thom, 1982). In this study vegetation data were collected and described in both a quantitative and qualitative manner. The parameters used as the basis for the qualitative description of the vegetation followed the classification proposed by Thorne (1990) and included: type (grass, reed, shrub or tree); diversity (mono-stand, mixed or climax vegetation);

species (indigenous or exotic); density (sparse, moderate or dense); (v) height (short, medium or tall); extent (wide, medium or narrow); health (healthy, fair or poor); age (immature, mature or old); position (bottom, middle or top of bank, or bar); spacing (continuous, close or wide).

Quantitative data was collected at each site by means of belt transects taking the form of quadrats laid out next to each other along the transect line (Kent & Coker, 1992). Each transect was set up perpendicular to the channel and divided (according to the Braun-Blanquet method) into homogeneous transects or plots of a specific minimum size (Werger, 1973) determined using a species-area curve. These were established by counting the number of species for a progressive doubling of plot size following the method advocated by Kent & Coker (1992). Species-area curves for the Skoenmakers and Volkers indicated 50 m^2 to 200m^2 plots for woody species and 25 m^2 (5x5m) for grasses and sedges. The basal and foliage areas (square metres) were measured for each species and the number of individuals for each species was counted within each plot.

The quantitative data analysis followed the methods described by Brower *et al.* (1990) and Kent & Coker (1992). The total area sampled for each species was calculated as well as the number of individuals for each species at each site. These totals were used to calculate the following attributes for the vegetation communities (Brower *et al.*, 1990):

(a) *Density* (*D*) is the number of individuals in a unit area:

$$D_i = n_i / A \qquad \textit{(Equation 5.1)}$$

where D_i is the density for the species i, n_i is the total number of individuals counted for the species and A is the total area sampled.

(b) *Relative density (RD)* is the number of individuals of a given species (n_i) as a proportion of the total number of individuals of all species (Σn):

$$RD_i = n_i / \Sigma n \qquad \textit{(Equation 5.2)}$$

(c) *Frequency (f)* is the chance of finding a given species within a sample:

$$f_i = j_i / k \qquad \textit{(Equation 5.3)}$$

where f_i is the frequency of species i, j_i is the number of samples in which species i occurs, and k is the total number of samples taken.

(d) *Relative frequency (Rf)* is the frequency of a given species f_i as a proportion of the frequencies for all species (Σf):

$$Rf_i = f_i / \Sigma f_i \qquad \textit{(Equation 5.4)}$$

(e) *Coverage (C)* is the proportion of the ground covered by the aerial parts of the plant:

$$C_i = a_i / A_i \qquad \textit{(Equation 5.5)}$$

where a_i is the total area covered by species *i* (estimated from the foliage area), and *A* is the total habitat area sampled.

(f) *Relative coverage* (RC_i) is the coverage for species *i* (C_i) expressed as a proportion of the total coverage (*TC*) for all species:

$$RC_i = C_i / TC = C_i / \Sigma C_i \qquad (Equation\ 5.6)$$

where ΣC_i is the sum of the coverages of all the species.

g) An index called the *importance value* (IV_i) was calculated from the sum of the above three relative measures for species *i*:

$$IV_i = RD_i + Rf_i + RC_i \qquad (Equation\ 5.7)$$

The value of IV_i may range from zero to three

h) The *importance percentage* was derived by dividing IV_i by 3 and converting to a percentage. This value gives an overall estimate of the influence or importance of a plant species in the community.

The percentage cover and position of each species along the transect were used to construct graphs of the belt transects. These transects were then compared to the geomorphological transects and soil analysis for each site on the Skoenmakers and Volkers.

The distribution of species relative to elevation above the channel bed was summarised as follows. The lowest point on the cross-section for each site was used as the baseline for the calculation of the elevation values at each site for the bank top, the bank slope and in the channel (eg. mid-channel bars). The average elevation for each morphological unit (channel, bankslope, banktop) for the two rivers was then calculated. Cover percentages were calculated from the average for each species of each vegetation type at each site for the two rivers.

Temporal changes in the width of the riparian zone of the Skoenmakers were assessed from aerial photo analysis for the years 1960 and 1978 and from field observations for 1999.

Chapter 6: Results of the case study

6.1 Introduction

The results of the hydrological analyses and field surveys of channel morphology and riparian vegetation are presented in this chapter. The analysis of the runoff data for the regulated river (Skoenmakers River) is presented in Section 6.2. Section 6.3 examines the geomorphological response of the Skoenmakers River to the Orange-Fish-Sundays River Interbasin Transfer Scheme. Changes in the geomorphology compared to that of the unregulated Volkers river form the basis of the analysis. An analysis of aerial photographs for the period 1961 to 1990 were used to show the temporal response to the IBT in the Skoenmakers River system. Section 6.4 deals more specifically with the distribution of the riparian vegetation and the interrelationships with the river morphology. The data obtained from plot sampling and the resulting belt transects are presented. Aerial photography and other photographs were used as an additional information source.

6.2 Hydrological changes

The hydrological regime[1] of the Skoenmakers River has undergone dramatic changes since the completion of the IBT which transformed an ephemeral stream into a perennial river. The post-IBT phase of the river can be divided into two periods of distinctive changes in the hydrology of the river. The first period is from 1979 to the construction of De Mistkraal Dam in 1985, the second period follows the completion of De Mistkraal Dam up to the present.

Figure 6.1 represents the simulated natural maximum 1-day equivalent flows for the Skoenmakers River and Volkers River catchment based on data from Midgley *et al.*, (1994). As explained in Section 5.2.1, this analysis was carried out in order to arrive at a first approximation of flood magnitude below the confluence of the Skoenmakers and Volkers rivers prior to the IBT. It is evident from Figure 6.1 that flood events of high magnitude (30 m^3sec^{-1} or more) occurred infrequently, with a recurrence interval in the order of twenty years. These events are important in the channel forming processes of an ephemeral system.

An analysis of the flow exceedence of the simulated monthly data for the natural system showed that there was no flow in the river for 20 % of the time and that the flow was less than 0.6 m^3sec^{-1} for 90 % of the time. The ephemeral nature of the river prior to the IBT is clearly demonstrated. The maximum mean monthly flow was 1.17 m^3sec^{-1} and at the 2 % exceedence level the flow was only 0.34 m^3sec^{-1}.

The flow duration curves for the regulated river presented in Figure 6.2 show that the formerly ephemeral Skoenmakers River became a perennial river after the IBT. The river also changed from being a flood dominated system to a baseflow dominated system. As the main supply of water is the IBT which enters

[1] "The *regime* of a river refers to its seasonal pattern of flow over the year." (Gordon *et al.*, 1992:121).

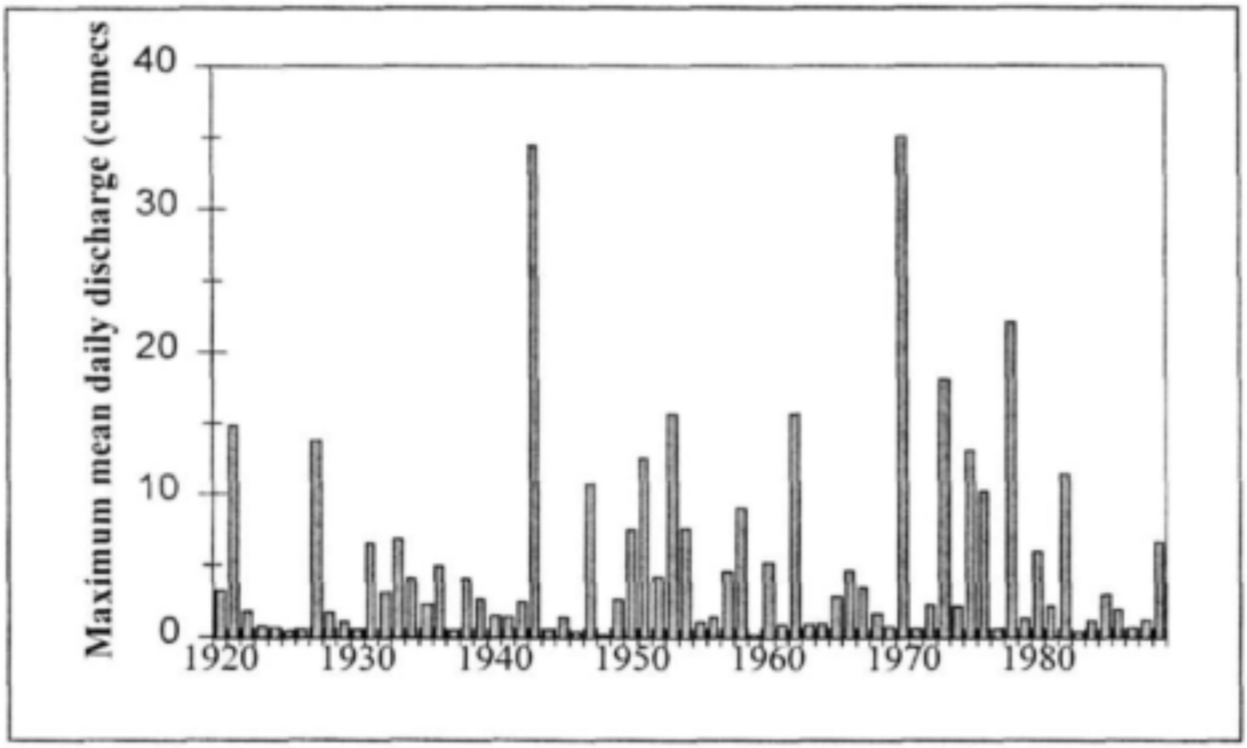


Figure 6.1: *Simulated natural maximum 1-day equivalent flows for quaternary catchment N23a (below the confluence of the Skoenmakers and Volkers River catchment. (Midgley et al., 1997).*

at the top of the system, this flow regime is more or less constant along the length of the channel. Only infrequent flood events superimposed on this system will cause a downstream variation of flow.

It is evident that De Mistkraal Dam had an influence on the hydrology of the Skoenmakers River system. From 1989 median flows changed slightly from about 2.5 m^3sec^{-1} to 3 m^3sec^{-1}. The biggest changes occurred at the extremes of the duration. Mean monthly flows exceeded 10 % of the time increased from about 4.5 m^3sec^{-1} to 6.0 m^3sec^{-1}, while the percentage exceedence of flows of five m^3sec^{-1} increased from 5 % to 20-25 %. Before the completion of the dam very low flows as well as periods of no flow conditions occurred for approximately 20% of the time whilst these flow conditions are absent from the data for the post-1985 curve.

It should be noted that the data presented in Figure 6.2 b&c represent the mean flow over the period of one month. Both higher and lower flows would be experienced for shorter periods of time (Figure 6.2a). For example, no flows were released for a period of two weeks in the winter period to allow maintenance to take place. Data on the maximum monthly peak flows indicated that between 1978 and the end of 1988 flows greater than 20 m^3sec^{-1} occurred 21 times at the downstream gauge N2H009-A01. This gave an average frequency of two such peak flows a year. The maximum recorded water level at the gauge was 2.42 m in July 1982. Flows of 10 m^3sec^{-1} were exceeded with a frequency of approximately 4 times a year. These high flows were probably due to floods generated from the catchment being superimposed on a base level of released flows. No peak flow data are available for the period after 1989.

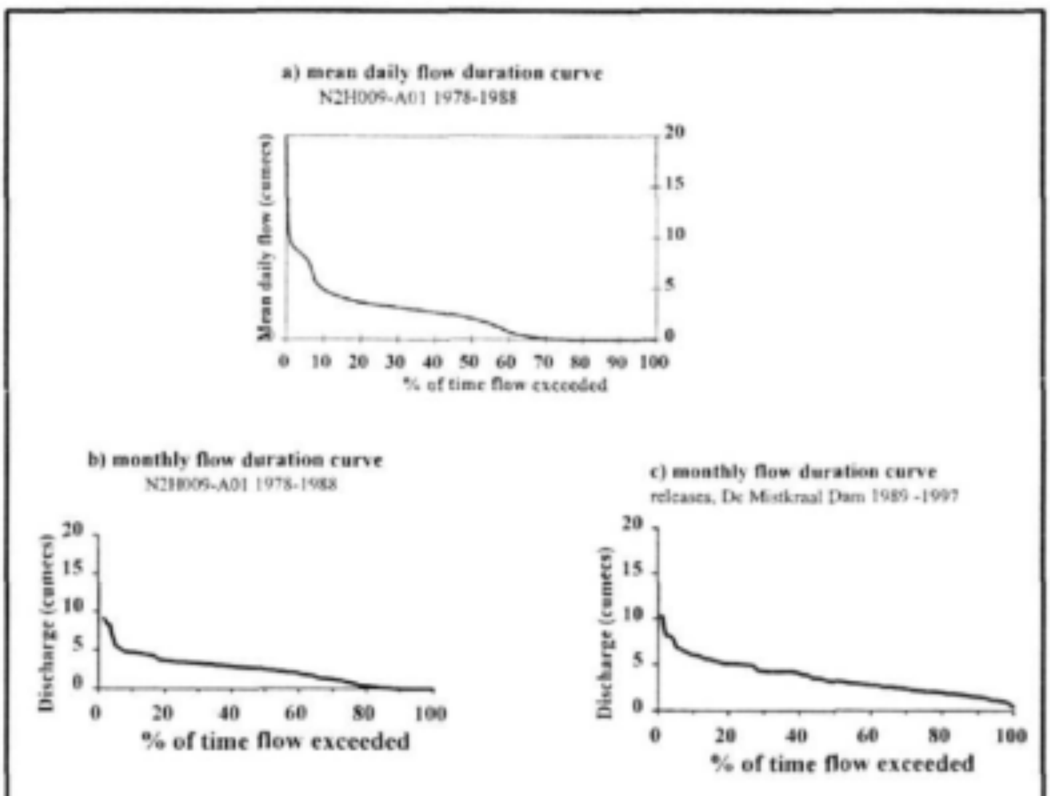


Figure 6.2: *Flow duration curves for the regulated Skoenmakers River a) mean daily flows prior to construction of De Mistral Dam b) mean monthly flows prior to the construction of De Mistral Dam c) mean monthly flows post construction of De Mistral Dam (Source: Department of Water Affairs and Forestry: Somerset East).*

Figure 6.3 compares the average monthly discharge for the Skoenmakers River before and after the completion of De Mistkraal Dam. The dam has led to a more distinct seasonal pattern for the

m^3sec^{-1}. During May and June the releases from the dam are cut off to allow repair work to the canal, thus the decrease in runoff for this period.

If the present 'base flows' are compared to the estimated flood flows presented in Figure 6.1 it is apparent that these base flows are equivalent to the smaller floods that were experienced in the lower reaches of the river, with a recurrence interval of about 3.5 years. Under natural conditions, these floods would be expected to play a significant role in channel processes. These flows now occur throughout the system for most of the summer. Their impact on geomorphological processes must be significant.

6.3 Geomorphological changes

6.3.1 Changes in channel pattern

Changes in the channel pattern of the Skoenmakers River were assessed by means of aerial photo analysis for the pre- and post-IBT phases. A comparison of *pre-IBT* (1960) and *post-IBT* (1990) aerial photographs for a section of the upper reaches in the Skoenmakers River indicates this lateral shift in the planform of the river resulted in a change in sinuosity. Measurements of channel length for the two dates indicated a change in the sinuosity of the Skoenmakers River for the post-IBT phase (Table 6.1). The sinuosity index (SI) for reach (a) decreased by 30 % from 1.70 to 1.91. Downstream at reach (b) the decrease was only 5 %. Thus the channel immediately below the release point became straighter.

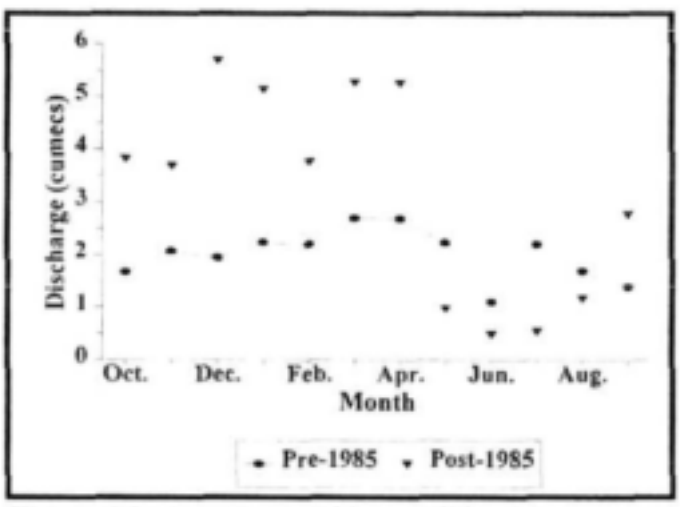


Figure 6.3: *Average monthly runoff for the Skoenmakers River before (1978 -1984) and after (1986,1987) construction of De Mistkraal Dam (Source: Department of Water Affairs, Cradock).*

***Table 6.1:** changes in sinuosity between 1960 and 1990*

reach	channel distance	down-valley distance	sinuosity	% decrease
a 1960	1.72	0.90	1.911	
a 1990	1.53	0.90	1.700	30
b 1960	2.12	1.20	1.767	
c 1990	2.07	1.20	1.725	5

6.3.2 Downstream hydraulic geometry

Active channel

An analysis of the downstream changes in the geometry of the active channel is presented in Figure 6.4. The impact of the IBT on the channel geometry can be summarized as follows:

In the upper reaches the increased flow relative to natural runoff produced a greatly widened channel and caused significant channel incision. Figure 6.4a supports field observations of the high degree of incision

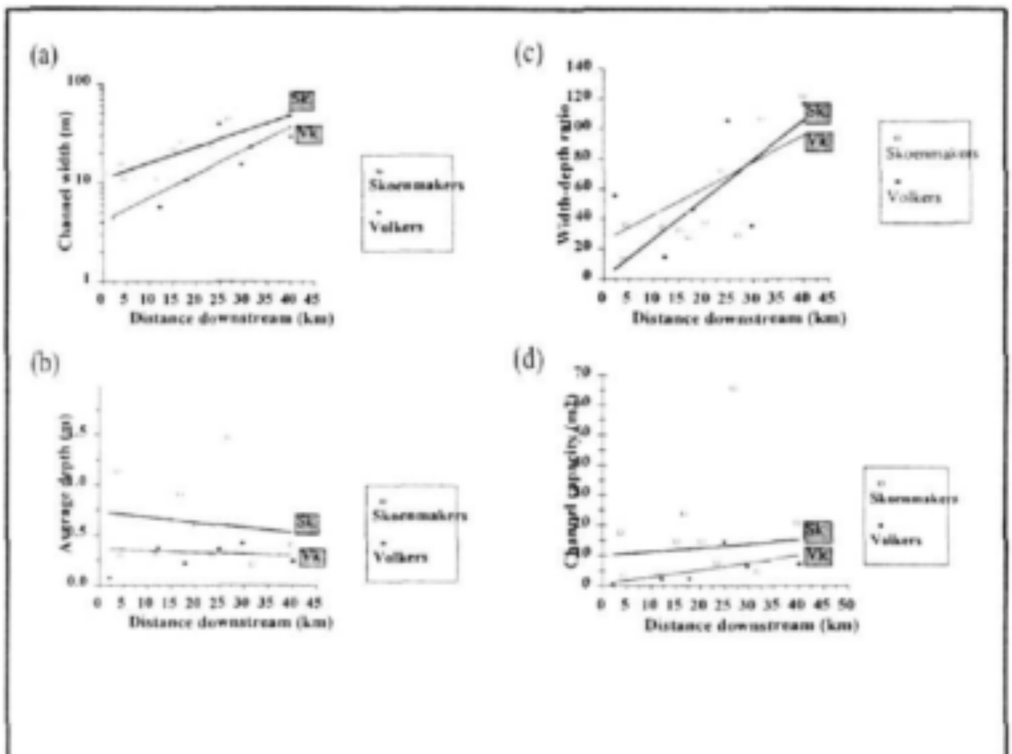


***Figure 6.4:** Downstream hydraulic geometry for the Volkers and Skoenmakers Rivers. Note that Site S8 has been excluded when fitting the best -fit lines for average depth and channel capacity.*

below the IBT inlet into the Skoenmakers and confirmed verbal information regarding incision obtained from local farmers. Channel widening continued down the length of the channel, but in the lower reaches the natural channel would have been better able to accommodate the IBT flows so that the increase in width was much less. The depth of the Skoenmakers' channel was highly variable, but remained more or less constant for the Volkers after a rapid increase over the first ten kilometers (Figure 6.4b). Width-depth ratios (Figure 6.4c) increased sharply down the river system for both the Volkers and the Skoenmakers. The combined effect of these changes was that the downstream increase in channel capacity was much greater for the Volkers than the Skoenmakers (Figure 6.4d). These results suggest that the main controls on channel form in the regulated system are, first, the IBT flow, second, local reach controls that impart variability to the system and, third, the natural flow regime which determined the pre-IBT channel form.

Macro-channel

The macro-channel width measured from the cross-sectional surveys (*post-IBT* phase) was compared to channel widths estimated from maps surveyed in 1970 (*pre-IBT* phase) to indicate the increase in the bank top width of the Skoenmakers over the 20-year period since the completion of the IBT (Figure 6.5). The pre-IBT data indicate two distinct sections of the channel. In the upper reaches there was a steady increase in width up to Site S5, between sites S5 and S6 the width increased threefold, thereafter width increased only slowly. Site S9 showed a marked decrease in width. The post-IBT data also showed that large increases in width occurred at the top of the system (sites S1 to S5), but only small increases were measured for the lower sites. The result was to smooth out the sharp increase in width in the middle reaches. The channel width at S7 actually decreased due to enhanced deposition.

The pre-IBT increase in width between S5 and S6 was probably due to the effect of a significant tributary which enters the Skoenmakers between these two sites. The impact of the tributary would have been overridden by the IBT flows.

6.3.3 Changes in channel cross-section morphology

Cross-sectional changes

The processes active at respective sites along the length of the channel can be inferred from an examination of the cross section form and on-site observations. Four pairs of sites will be used to compare the two channels at locations in the upper, middle and lower reaches, plus a location immediately below the IBT inlet.

Site S1 (Figure 6.6) was chosen to compare the channel 500 m below the IBT input point with a site (Va) on an equivalent position on the unregulated Volkers. At this point the Volkers had a shallow channel of less than 0.5 m in depth and 5 m wide. The only indication of the presence of a river channel was the riparian vegetation (*Acacia karroo*). In contrast, the Skoenmakers had incised a channel 6 m deep and 25 m wide at the bank top. Incision had progressed down to the bedrock. Undercutting of the banks was severe and large volumes of sediment were supplied to the channel. Trees at the top of the banks (*Acacia karroo*) were observed to contribute to bank instability through increased loading.

Plates 6.1 and 6.2 illustrate conditions at a point 3 km downstream from site S1. The severe erosion of the banks on either side is evident. Active undercutting, evident on the right-hand bank (Plate 6.2), had lead to instability of the banks. In comparison, although erosion was also observed in the upper reaches of the Volkers River, undercutting of banks was generally absent.

Two profiles in the middle reaches of the rivers, V3 and S6, are compared in Figure 6.7. At this point the Volkers had a wide, shallow channel with a relatively flat bed characteristic of semi-arid rivers (Reid and Frostick, 1997). In contrast the Skoenmakers had developed a channel with clear morphological features. The macro-channel was both deeper (6 m) and wider (55 m) than that of the Volkers (1 m and 35 m respectively), but the active channel was confined between shelves on both banks. A point bar had also developed on the right hand side of the channel. The resulting active channel was 27 m wide and had a maximum depth of 2 m. Thus, at this site, although channel incision was apparent, an alluvial channel geometry had been constructed

A greater similarity of the cross-sectional profiles for sites in the lower reaches of the two rivers is evident from Figure 6.8. The width of the macro-channels was similar (50 m for the Volkers and 60 m for the Skoenmakers) and the depth of the Volkers at this site actually exceeded that of the Skoenmakers (3 m against 2 m). This is the only site on the Volkers where a clear shelf was identified. This shelf confined an active channel of 34 m width which contained one mid channel bar. The channel of the Skoenmakers was dominated by two mid-channel bars which caused the flow to diverge in three separate low-flow channels. No distinction could be made between the active and macro-channel. The Skoenmakers at this point was dominated by deposition processes.

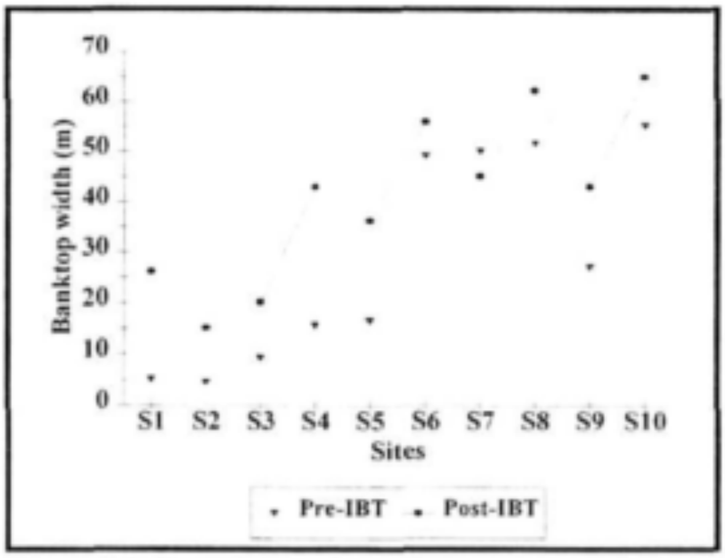
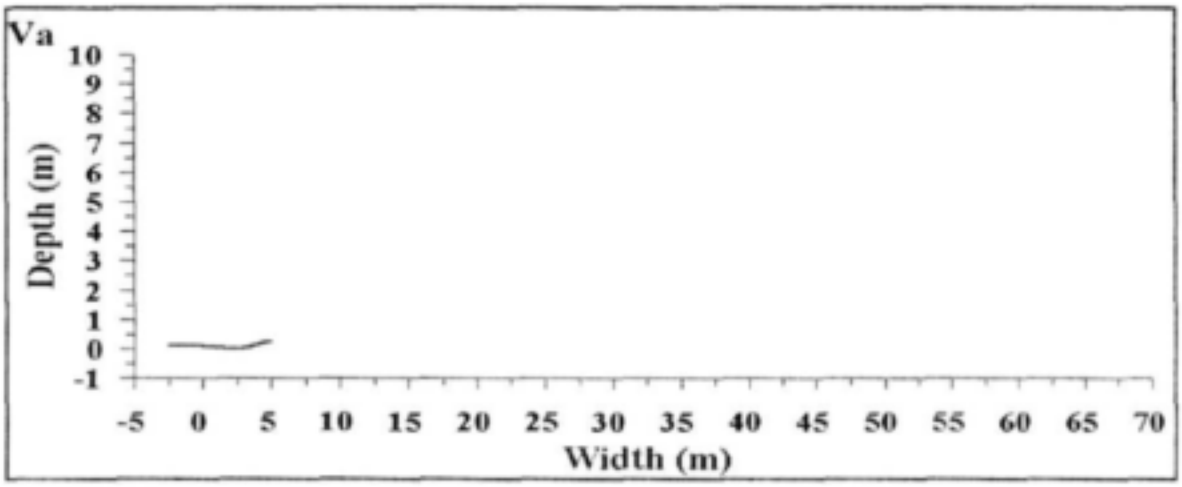


Figure 6.5: *Downstream change in macro-channel width.*



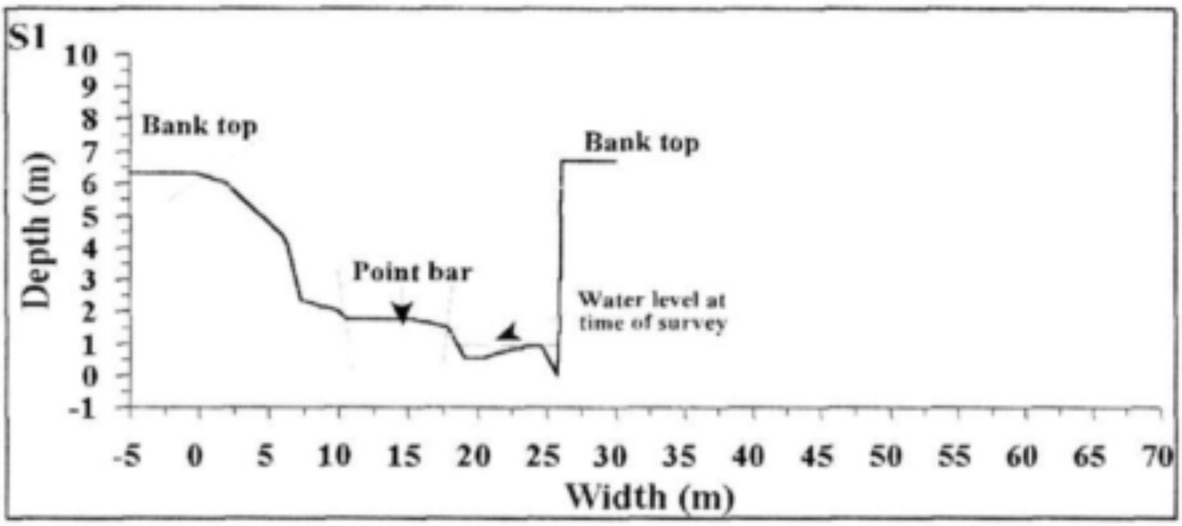


Figure 6.6: *Comparison of two cross-sectional profiles for the upper reaches of the Volkers (Va) and Skoenmakers River (S1) immediately below the point of inflow of the IBT.*

Plate 6.1: *Severe erosion and active undercutting of the right-hand bank evident for the upper reaches of the Skoenmakers River (approximately 3 km below the IBT inlet).*

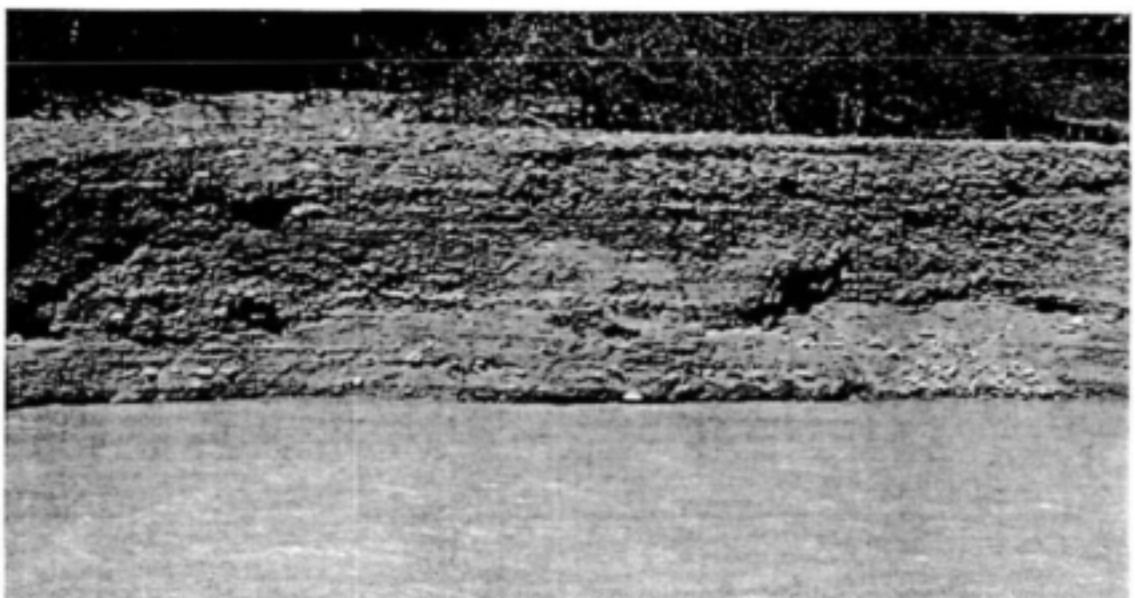
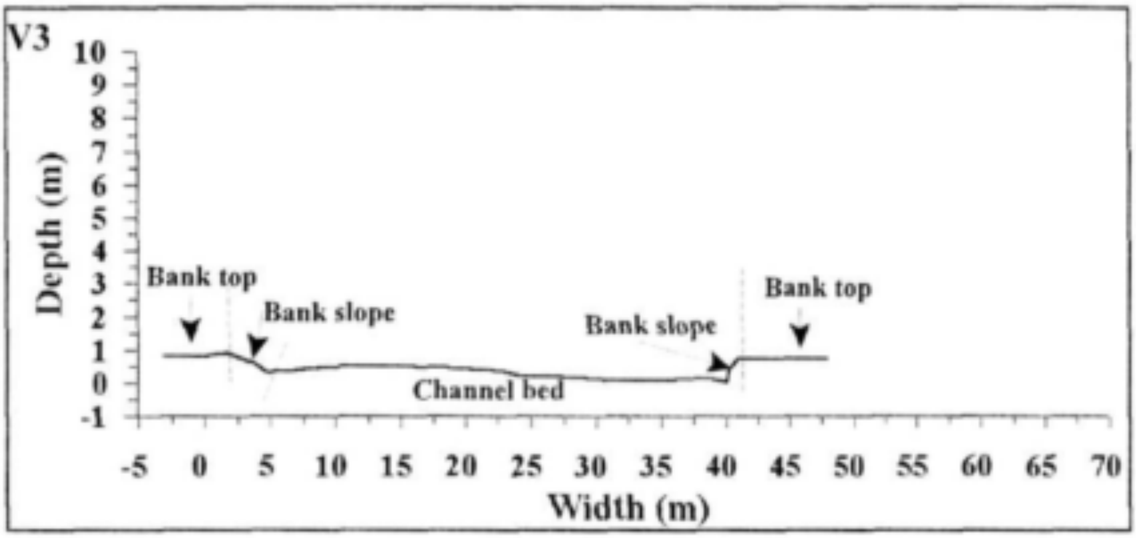


Plate 6.2: *Stratified lefthand bank for same site as Plate 6.1.*



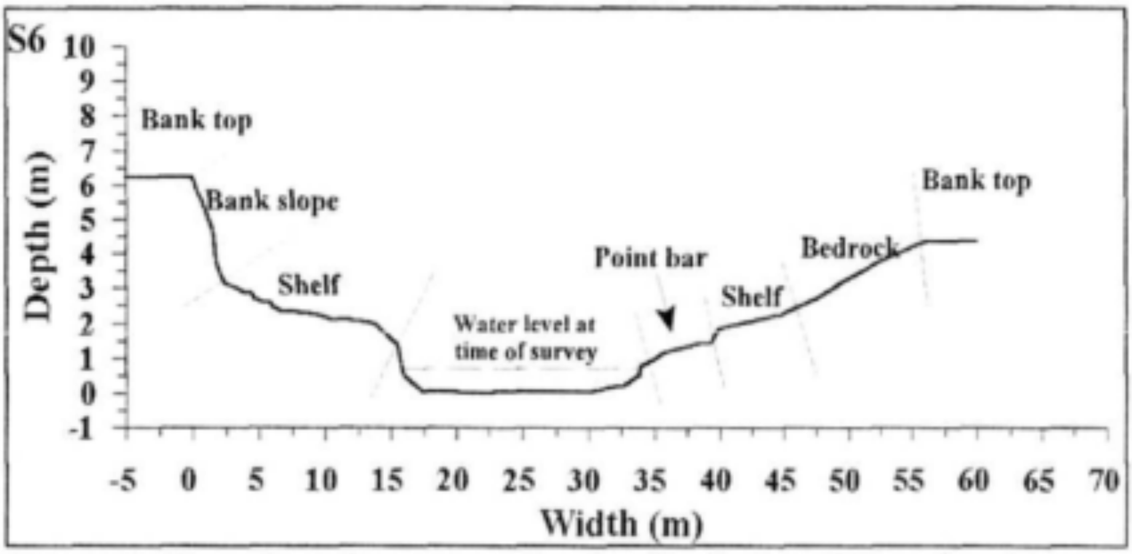
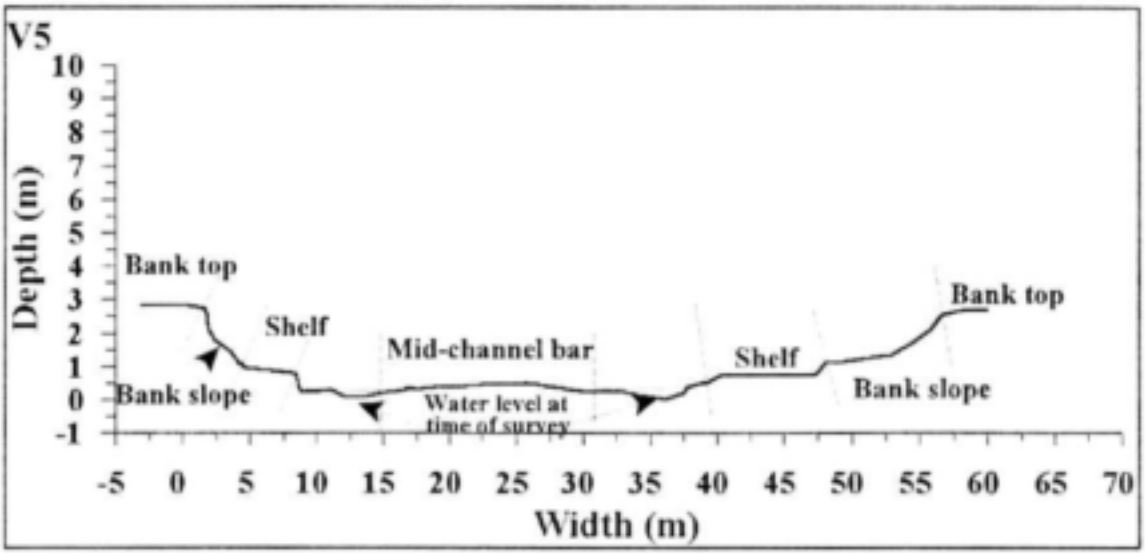


Figure 6.7: *Comparison of two cross-sectional profiles for the middle reaches of the Volkers (V3) and Skoenmakers (S6) approximately 25 km below the point of inflow of the IBT*



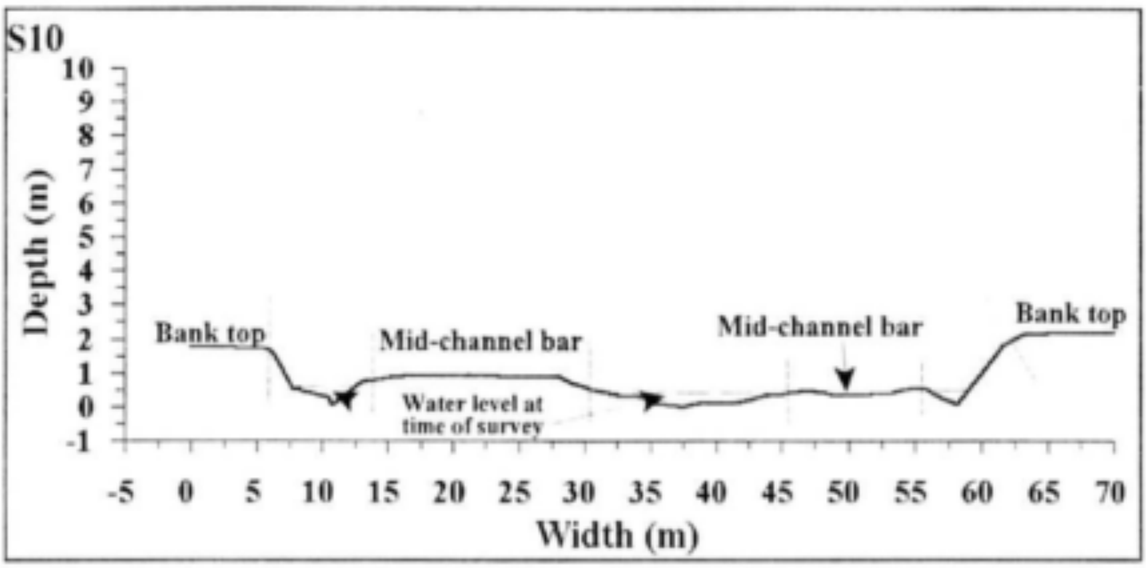


Figure 6.8: *Comparison of two cross-sectional profiles for the lower reaches of the Volkers (V5) and Skoenmakers (S10) approximately 40 km downstream for both rivers*

Channel morphology for sites along the two rivers is summarized in Table 6.2. Shelves and bars were not a characteristic feature of the Volkers River except at the most downstream site where mid-channel bars were also evident. Along the length of the Volkers the channel was characterised by stable banks, low erosion and moderate deposition The channel bed was dominated by coarse sands and gravels which formed a flat bed. The Volkers appears to be a typical semi-arid river as described by Reid and Frostick (1997). In contrast, the Skoenmakers can be divided into three zones, differentiated in terms of the presence of morphological features and the degree of erosion and deposition. These zones correspond well with the reaches identified in Table 5.1

The upper zone includes sites S1 to S3. Both bank and bed erosion tended to be severe; cobbles and bedrock were exposed in the channel bed. Point bars had developed on meander bends but shelf development was not evident. An analysis of channel pattern from the aerial photographs (Section 6.3.1.) revealed a reduction of sinuosity of up to 30 % immediately below the inlet point. This zone was therefore dominated by a decrease in sinuosity as well as erosion processes, leading to channel straightening, deepening and widening. The middle zone included sites S4 to S7. Conditions were variable with both erosion and deposition being characteristic of the banks. Shelves and point bars were present at all the sites, while the channel beds showed evidence of low rates of erosion and deposition. Coarse gavels where found in the bed at all sites. The lower zone included sites S8 to S10 and is dominated by deposition processes in the form of extensive mid channel bars.

6.3.4 Downstream changes in sediment composition

A comparison of the bank sediment and shelf sediment of the Volkers and Skoenmakers is presented in Figure 6.9. The composition of the banks was variable from site to site and there was no consistent downstream trend. In both rivers the bulk of the sediment lay between fine gravel and very fine sand. The sediment in the banks of the Skoenmakers tended to be somewhat finer than the Volkers, with a greater proportion overall of fine sands and very fine sands. There was also a slight tendency for sediment size to decrease downstream in the Skoenmakers, but there was no such trend for the Volkers.

***Table 6.2:** Morphological diversity of the Volkers and Skoenmakers.*

LOCATION		MORPHOLOGICAL UNIT PRESENT				
Site	Distance downstream (km)	Bank slope	Shelf	Point bar	Mid-channel bar	Bedrock intrusion
			Volkers			
Va	3.51	✔				
V1	12.2	✔				
V2	17.83	✔				✔
V3	24.91	✔				
V4	29.67	✔				
V5	40.13	✔	✔	✔	✔	
			Skoenmakers			
S1	3.79	Incised		✔		
S2	4.27	✔		✔		
S3	11.52	✔				✔
S4	15.21	✔	✔	✔		
S5	16.88	Incised	✔	✔		✔
S6	20.21	✔	✔	✔		✔
S7	23.42	✔	✔			
S8	26.74	✔			✔	
S9	31.59	✔	✔		✔	
S10	39.75	✔	✔		✔	

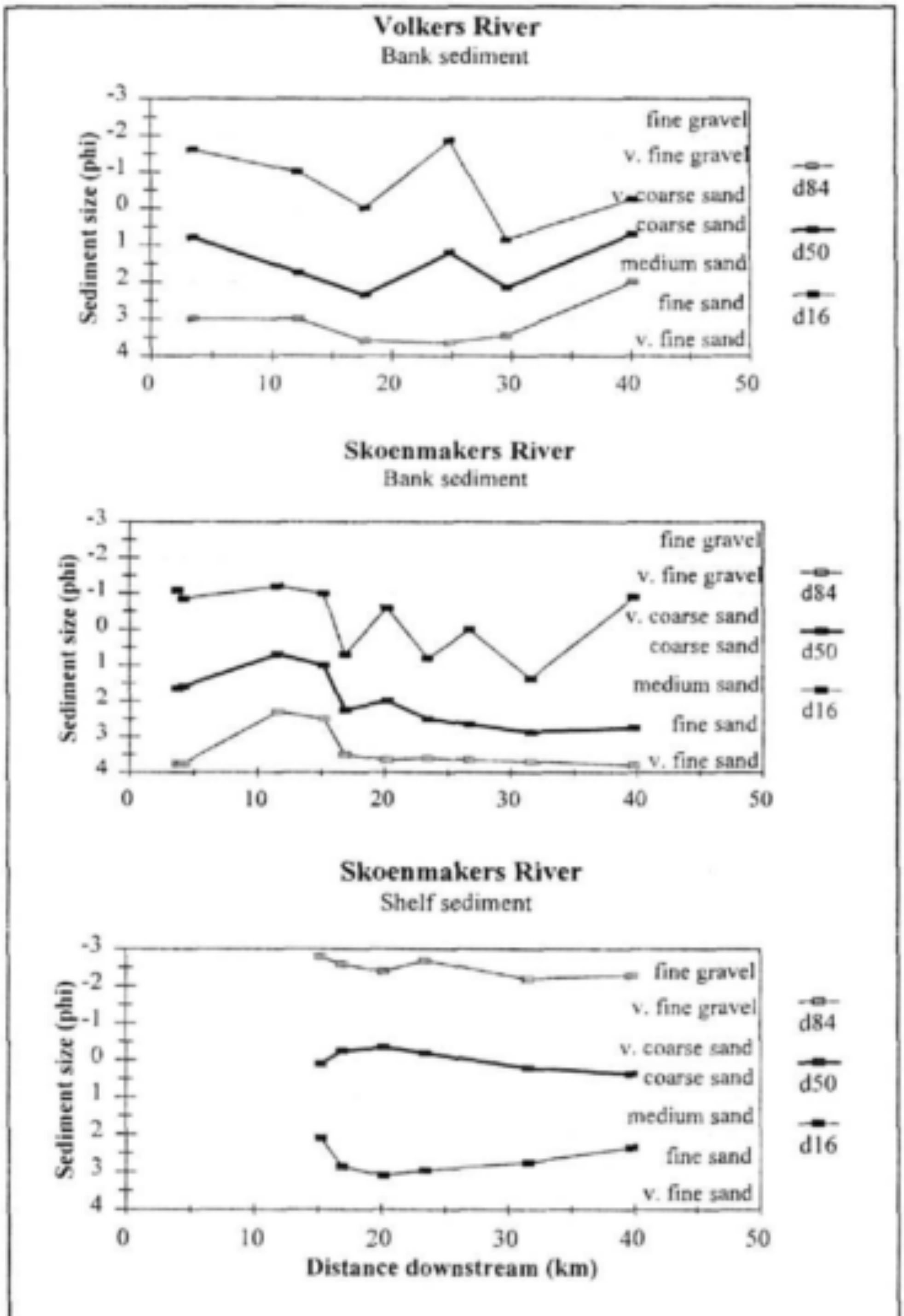


Figure 6.9: *Bank and shelf sediment sample analysis for the Volkers and Skoenmakers.*

Table 6.3: *Descriptive measures of the bank sediment size distribution for the river banks at each site along the Volkers and Skoenmakers Rivers.*

VOLKERS RIVER					
Site	**Sediment size (ϕ value)**				**Sediment size class for mean sediment size**
	D_{16}	**D_{50}**	**D_{84}**	**Mean (M_z)**	
Va	-1.6	0.8	3	0.73	Very coarse sand / Coarse sand
V1	-1	1.75	3	1.25	Coarse sand / Medium sand
V2	0	2.35	3.6	1.98	Medium sand
V3	-1.85	1.2	3.65	1	Coarse sand
V4	0.85	2.15	3.45	2.15	Medium sand / Fine sand
V5	-0.25	0.7	2	0.82	Very coarse sand / Coarse sand
SKOENMAKERS RIVER					
Site	**Sediment size (ϕ value)**				**Sediment size class for mean sediment size**
	D_{16}	**D_{50}**	**D_{84}**	**Mean (M_z)**	
S1	-1.1	1.65	3.75	1.43	Coarse sand / Medium sand
S2	-0.85	1.6	3.75	1.5	Coarse sand / Medium sand
S3	-1.2	0.7	2.3	0.6	Very coarse sand / Coarse sand
S4	-1	1	2.5	0.83	Very coarse sand / Coarse sand
S5	0.7	2.25	3.5	2.15	Medium sand / Fine sand
S6	-0.6	2	3.65	1.68	Coarse sand / Medium sand
S7	0.8	2.5	3.6	2.3	Medium sand / Fine sand
S8	0	2.65	3.65	2.1	Medium sand / Fine sand
S9	1.37	2.87	3.7	2.65	Medium sand / Fine sand
S10	-0.9	2.75	3.8	1.88	Coarse sand / Medium sand

The macro-channel banks of both rivers were formed as a result of long term geomorphological processes and differences between the two systems do not represent impacts of the IBT. Rather the bank composition determines factors such as modern bank stability and therefore the possible response to an IBT. An increase in fine sediments, especially silt, enhances stability and therefore the banks of the Skoenmakers should be more stable than the Volkers. It is interesting to note that the variability of width of the macro-channel of the downstream sites of the Skoenmakers (Figure 6.5) follows the variability in the size of the D_{84}. Sites with a high proportion of gravel in their banks tended to have the widest macro-channel.

The sediment composition of the shelves is presented in Figure 6.9c. Only six sites on the Skoenmakers and one on the Volkers had significant shelf features. The median particle diameter for the Skoenmakers' sites decreases progressively downstream from very coarse sands to coarse sands. The overall size distribution of the shelf sediment was significantly coarser than that in the banks. As the banks supply the bulk of the sediment contributing to the shelves, this points to a net loss of the finest sediments as wash load to downstream sinks, most probably Lake Darlington.

Table 6.4: *Descriptive measures of the shelf sediment size distribution along the Volkers and Skoenmakers Rivers.*

River	Site	Sediment size (ϕ value)				Sediment size class for mean sediment size
		D_{16}	D_{50}	D_{84}	Mean (M_z)	
Volkers River	V5	-2.3	-0.35	2.5	-0.03	Fine gravel / Very coarse sand
Skoenmakers River	S4	-2.8	0.1	2.1	-0.18	Fine gravel / Very coarse sand
Skoenmakers River	S5	-2.6	-0.25	2.85	0.02	Very coarse sand
Skoenmakers River	S6	-2.4	-0.35	3.1	0.13	Very coarse sand / Coarse sand
Skoenmakers River	S7	-2.7	-0.2	2.95	0.02	Very coarse sand
Skoenmakers River	S9	-2.2	0.21	2.75	0.27	Very coarse sand / Coarse sand
Skoenmakers River	S10	-2.3	0.37	2.35	0.16	Very coarse sand / Coarse sand

Table 6.5: *Qualitative assessment of bank conditions for the Volkers and Skoenmakers Rivers.*

LOCATION			BANK GEOMETRY	BANK CONDITION			BANK MATERIAL
Reach	**Site**	**Bank**	**Shelves present**	**Stable**	**Erosion**	**Deposition**	**Particle size**
1	Va	Right	No	Yes			Coarse Sand
		Left	No	Yes			Coarse Sand
1	V1	Right	No	Yes		Medium	Medium Sand
		Left	No		Low		Coarse Sand
2	V2	Right	Yes		Low		Medium Sand
		Left	No	Yes		Medium	Fine Sand and Bedrock
3	V3	Right	No		Low	Low	Coarse Sand
		Left	No	Yes		Medium	Coarse Sand
3	V4	Right	No		Low	Low	Fine Sand
		Left	No		Low	Medium	Medium Sand, Fine Sand
4	V5	Right	Yes		Medium	High	Fine Sand, Coarse Sand, Silt
		Left	Yes	Yes		Medium	Coarse Sand, Very Coarse Sand
1	S1	Right	No		Severe		Medium Sand, Coarse Sand
		Left	Yes		Medium		Fine Sand, Coarse Sand
1	S2	Right	No		Severe		Coarse Sand, Silt
		Left	Yes (Small)		Medium	Medium	Coarse Sand, Silt
2	S3	Right	No		Medium	Low	Coarse Sand, Bedrock
		Left	No		Low		Very Coarse Sand, Coarse Sand
2	S4	Right	Yes		Low	Low	Coarse Gravel, Cobble
		Left	No		Severe		Coarse Sand, Cobble
2	S5	Right	No		High		Clay, Fine Sand, Coarse Gravel
		Left	Yes			High	Clay, Fine Sand, Medium Sand
3	S6	Right	Yes			Medium	Coarse Sand

		Left	Yes			High	Medium Sand, Fine Sand
4	S7	Right	Yes		Low		Fine Sand
		Left	Yes			Medium	Medium Sand, Fine Sand
4	S8	Right	No		High		Medium Sand, Fine Sand
		Left	No		Medium		Fine Sand
4	S9	Right	Yes			High	Fine Sand
		Left	Yes		Low		Fine Sand
5	S10	Right	Yes		Low	Medium	Coarse Sand, Medium Sand
		Left	Yes			High	Coarse Sand, Bedrock

Table 6.6: *Qualitative assessment of channel conditions for the Volkers and Skoenmakers Rivers.*

SITE	CHANNEL GEOMETRY				CHANNEL BED CONDITION			CHANNEL MATERIAL
	Planform	Pattern	Degradation or Aggradation	Morphological unit	Stable	Erosion	Deposition	Bed composition
VOLKERS RIVER								
Va	Straight	Single	Aggradation				High	Medium sand
V1	Meander	Single	Aggradation				High	Coarse Sand
V2	Straight	Single	Aggradation				High	Coarse Gravel, Cobbles
V3	Meander	Single	Degradation				Medium	Coarse Sand, Coarse Gravel
V4	Straight	Single	Degradation			Low	Medium	Coarse Sand, Fine Gravel
V5	Straight	Braided	Aggradation	Mid-channel bar			High	Coarse Sand, Fine Gravel
SKOENMAKERS RIVER								
S1	Meander	Single	Degradation	Point bar		Severe		Cobble, Bedrock
S2	Meander	Single	Degradation	Point bar		High		Cobble, Coarse Sand, Silt
S3	Meander	Single	Degradation	Bedrock intrusion		High		Cobble
S4	Meander	Single	Degradation	Point bar		Severe		Cobble and Bedrock
S5	Straight	Single	Degradation	Point bar		Low	Low	Loose gravel
S6	Meander	Single	Degradation	Point bar		Low		Cobble, Coarse Gravel
S7	Meander	Single	Aggradation	Point bar		Low	Low	Cobble, Coarse Gravel, Fine Gravel
S8	Meander	Braided	Degradation	Mid-channel bar		Medium	High	Coarse Gravel, Cobble, Coarse Sand
S9	Meander	Single	Aggradation	Point bar		Medium		Coarse Gravel, Cobble, Bedrock
S10	Straight	Braided	Aggradation	Mid-channel bars (vegetated + unvegetated)			High	Silt, Fine Sand, Cobble, Coarse Gravel, Bedrock

6.4 Riparian vegetation.

6.4.1 Vegetation community composition

A total of 13 species were identified in the Skoenmakers and Volkers rivers. These included representatives of woody species, grasses, sedges and reeds as given in Table 6.7. The vegetation composition varied between the two rivers as well as within the individual systems. Downstream changes and changes over the cross-section related to river morphology were observed.

Table 6.7: *Species grouping according to the different vegetation types.*

Vegetation type	Woody	Grass	Sedges	Reeds
Species name	*Acacia karroo*	*Cynodon dactylon*	*Asclepias fruticosa*	*Phragmites mauritianus*
	Rhus lancea	*Pennisetum setaceum*	*Asparagus plumosus*	
	Lycium oxycarpum	Other grass species	*Cyperus dives*	
	Tamarix chenensis			
	Nicotiana glauca			
	Melianthus major			

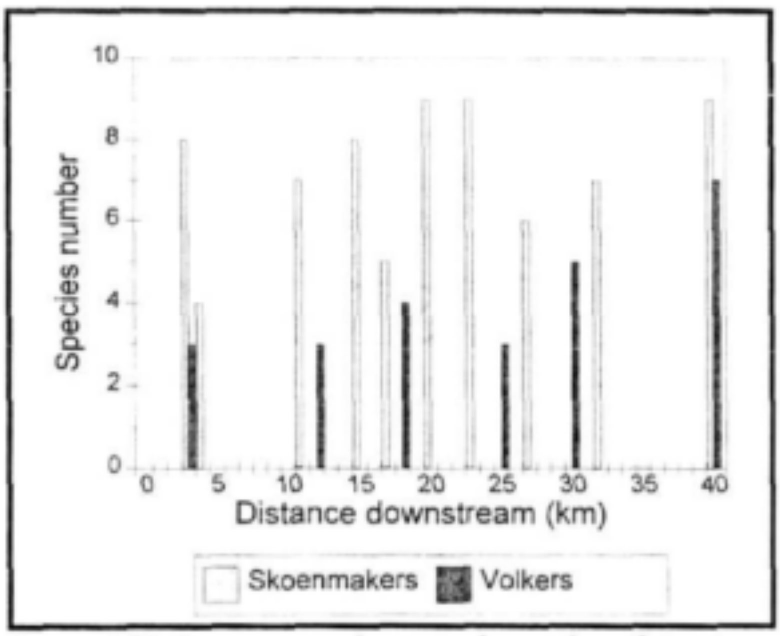


Figure 6.10: *Downstream change in the number of riparian vegetation species for the Volkers River and Skoenmakers River.*

One measure of the composition of a vegetation community is the number of species for a given site. Figure 6.10 shows the downstream changes in riparian vegetation number of species numbers for the two rivers. A longitudinal vegetation gradient (Van Coller, 1992) can be seen as an increase in the number of species along the length of the non-regulated river, particularly in the lower reaches. There were more species overall along the Skoenmakers, but the downstream pattern is less clear.

Three important quantitative attributes of a vegetation community are the relative density, relative

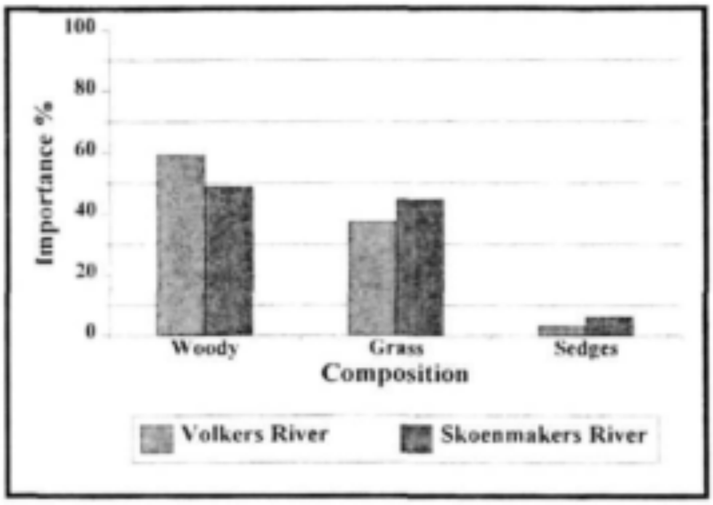
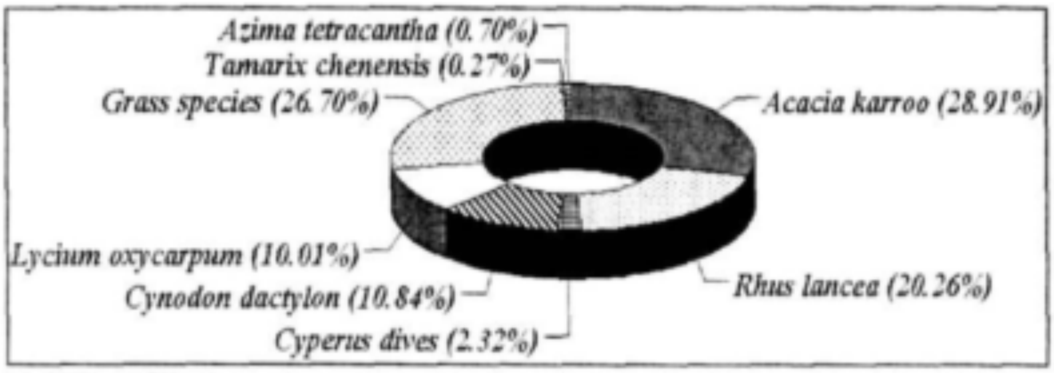


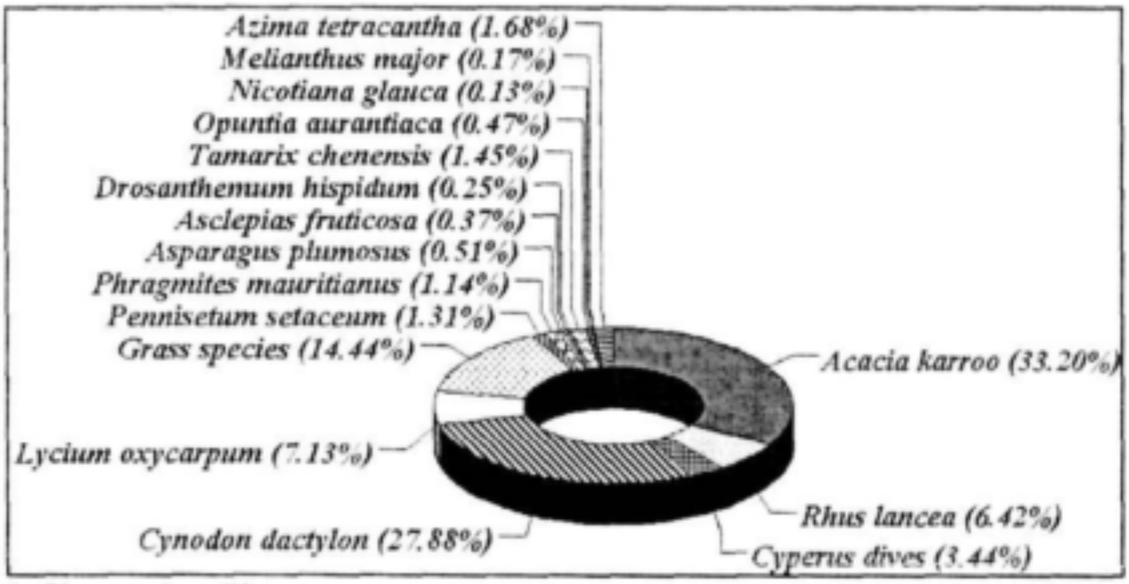
Figure 6.11: *Importance percentage for vegetation types in the Skoenmakers river.*

frequency and relative coverage, and any kind of disturbance would be reflected in these parameters. Importance values were calculated from these three parameters and then converted into importance percentages for each species at each site. Importance percentages were summarized according to the different vegetation types: trees, grass and sedges (Figure 6.11) to give an overall estimate of their influence or importance in the community. A lower value for woody species and significantly higher values for grass and sedge species were apparent for the regulated river in comparison to the non-regulated river. The importance value for sedge species, which normally become established along the water's edge, more than doubled for the regulated river compared to the ephemeral Volkers which lacked permanent water except at the lower-most site. These importance percentages for all species give an overall estimate of the their influence or importance in the community. (Figure 6.12)

The overriding effect of the IBT was to transform the Skoenmakers from an ephemeral to a perennial river. The effect of this dramatic increase in the availability of water can be judged from the above comparison of the species composition for the two rivers. Water availability can be seen as one of the primary factors limiting riparian vegetation community composition and spatial distribution in a semi-arid region such as the Karoo.



a) Volkers River.



b) Skoenmakers River

Figure 6.12: *Importance percentages for species of a) the non-regulated Volkers River and b) the regulated Skoenmakers River.*

6.4.2 Riparian zone width

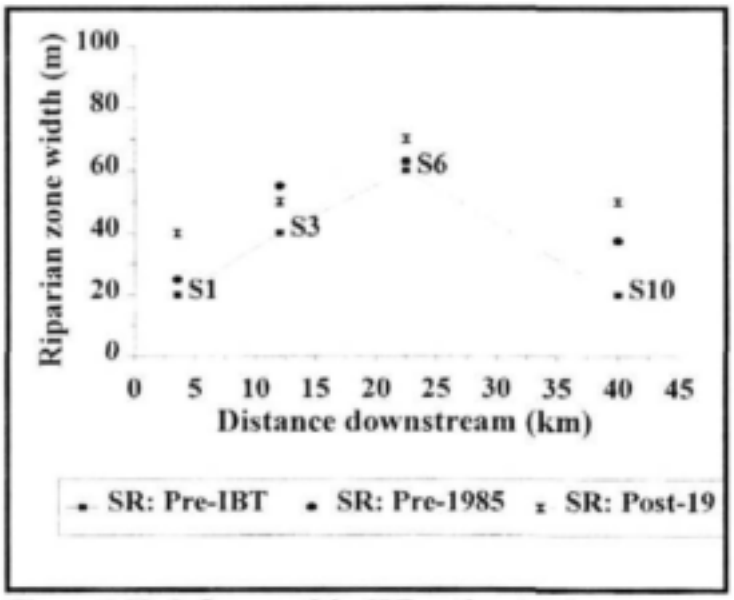


***Figure 6.13:** Influence of the IBT on the riparian zone width along the Skoenmakers River.*

The post-IBT phase can be subdivided into the pre-1985 and post-1985 periods after the completion of De Mistkraal Dam. The effect of the additional water supplied to the recipient stream was evident from the comparison of the riparian zone width for selected sites along the regulated Skoenmakers River (Figure 6.13). The riparian zone width was derived from an analysis of aerial photographs for the different phases (pre- and post 1985) of the Skoenmakers River's hydrological regime.

A definite increase in the riparian zones for each section of the regulated Skoenmakers River was seen when comparing the present conditions to the period before the completion of De Mistkraal Dam and before the IBT itself. The additional water available to the riparian species since the completion of the IBT in 1978 and De Mistkraal Dam in 1985 will have had a significant role to play in this process.

It must be mentioned that the width of the riparian zones for the two rivers was greatly influenced by landuse activities and landuse changes close to the rivers. This was evident at site S3 for the post-1985 period and can be explained by the clearance of riparian vegetation at this site for cultivation. The overall increase in the riparian zone width for the other sites on the post-1985 curve indicates the impact of the increased flow caused by the completion of De Mistkraal Dam.

6.4.3 Landuse changes

Riparian vegetation clearance is evident from field observations for both the rivers. The clearance along the Skoenmakers River is most evident in the upper reaches as farmers started to cultivate the land close to the river. The additional water from the IBT had increased the capacity of the river for this purpose. A series of aerial photos (1960 to 1990) for the area along the Skoenmakers River was analysed and a comparison was made between the pre-IBT and post-IBT phases to indicate the influence of the IBT on the riparian zone. Results of the aerial photo analysis indicate an overall increase in the density of the riparian vegetation for the upper, middle and lower reaches. This increase in density is most evident in the lower reaches of the Skoenmakers River and also along the tributaries of the river, where a consequent reduction in the degree of erosion can be seen (Figure 6.16). Areas of cultivation showed an increase for all three river sections. A decrease in the riparian vegetation density was noticed for these cultivated areas due to riparian vegetation clearance. This is especially true for the upper reaches of the river where riparian vegetation (especially tree species, *Acacia karroo*) has been cleared to the extent that virtually no riparian zone is left.

6.4.4 Relationship of riparian vegetation to channel morphology

Morphological diversity has been proposed as an important factor influencing the spatial distribution of riparian vegetation. The distribution of riparian vegetation species across a site is highly dependent upon the change in elevation above the river bed (Van Coller, 1992). Figure 6.17 presents a summary of this relationship for the two rivers combined. Tree species (*Acacia karroo* and *Rhus lancea*) tended to be the dominant vegetation type farther away from the active channel, at a higher elevation. Closer to the active channel, on the bank slope and shelves, grass species became established along with juveniles of the woody species. The bottoms of the banks, the water's edge and channel bars (mid- and point bars) were dominated by sedge species (eg. *Cyprus dives*), reeds (*Phragmites mauritianus*) and grass species. This distribution is closely related to the horizontal vegetation gradient identified by Van Coller (1992) and can be related to the effect of morphology on water availability.

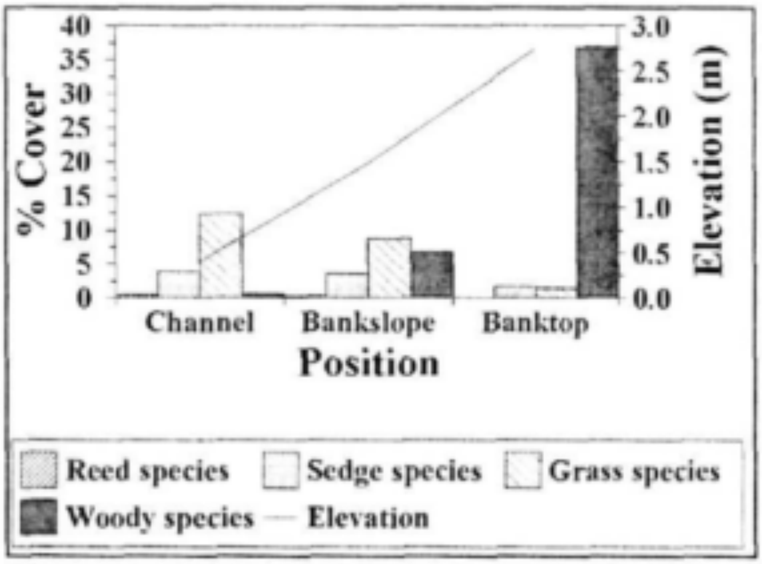


Figure 6.14: *Relationship between the average elevation above the channel bed and vegetation type for the Volkers and Skoenmakers Rivers.*

The impact of the IBT on the heterogeneity of the physical habitat noted above (Section 6.3) would be expected to also impact on the vegetation. Between-site variability of species numbers can be related in part to differences in morphological diversity or heterogeneity as reported in Table 6.8. A regression analysis evaluating the relationship between species diversity and morphological diversity gave an R squared value for the two rivers combined of 0.65, indicating a positive correlation between the number of morphological units and the number of species at each site. It was concluded that morphological heterogeneity has a significant influence on the composition of the riparian vegetation.

Table 6.8: *Relationship between the morphological and the riparian vegetation species diversity.*

Site	Number of morphological units	Number of species	Site	Number of morphological units	Number of species
VOLKERS RIVER			SKOENMAKERS RIVER		
Va	5	3	S1	5	7
V1	3	5	S2	4	5
V2	4	5	S3	7	5
V3	5	3	S4	8	7
V4	5	5	S5	5	5
V5	8	7	S6	8	9
			S7	9	6
			S8	7	6
			S9	7	8
			S10	9	9

Regression analysis output Constant	-1.090
Standard error of Y estimation	1.433
R^2	0.654
Number of observations	16
X Coefficient	1.180

A further analysis of the results from the plot sampling was performed to compensate for 'between site variation' of the riparian zone width. The following transformed species richness equation (Nilsson, *et al.*, 1997) was used to perform this analysis:

$$\text{Species Richness} = \frac{\text{Number of species}}{\log_{10} \text{area sampled}} \qquad (\textit{Equation 6.1})$$

The results of this analysis for the Skoenmakers River are presented in Figure 6.18. Comparison of this data with that of Table 6.4 suggests that if species richness is a function of the area sampled, then morphological diversity is also a function of area (i.e. channel width). High degrees of bank incision were observed at sites S2 and S5 which resulted in a decrease in the area sampled. Species richness values calculated for these sites were lower than for the other sites, indicating that a decrease in

morphological diversity (due to incision) directly influenced the riparian vegetation richness. A possible explanation for the decrease in species richness at site S8 is the high degree of disturbance at this site in the form of cultivation and riparian vegetation clearance right up to the river bank.

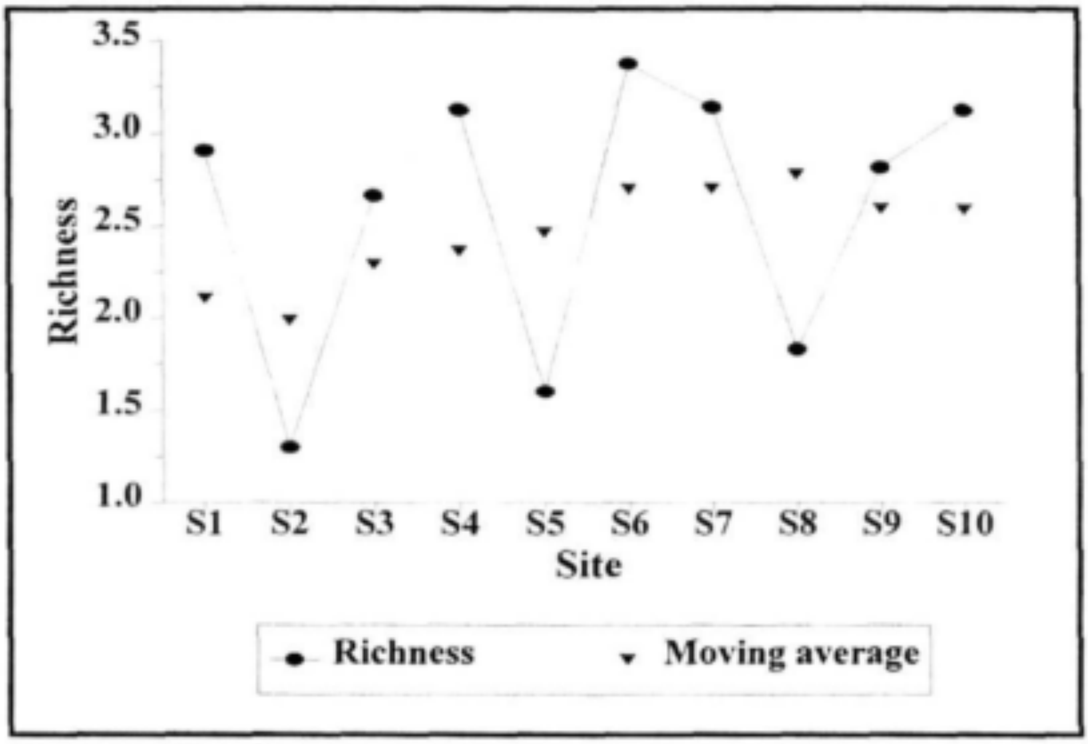
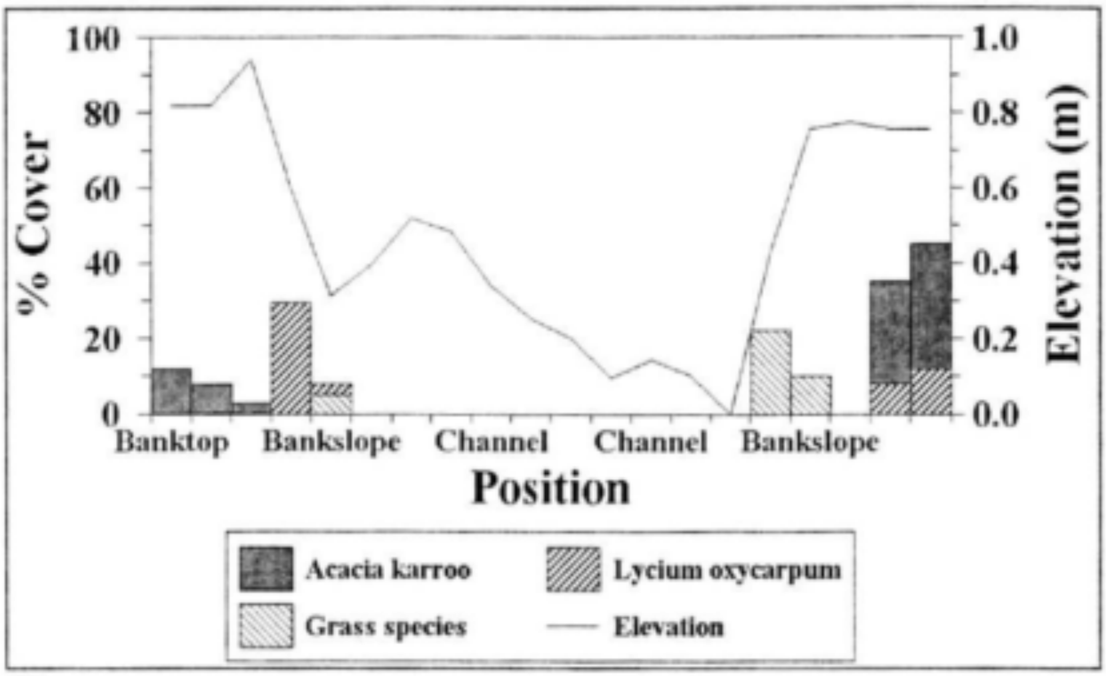


Figure 6.15: *Transformed species richness for the Skoenmakers River.*

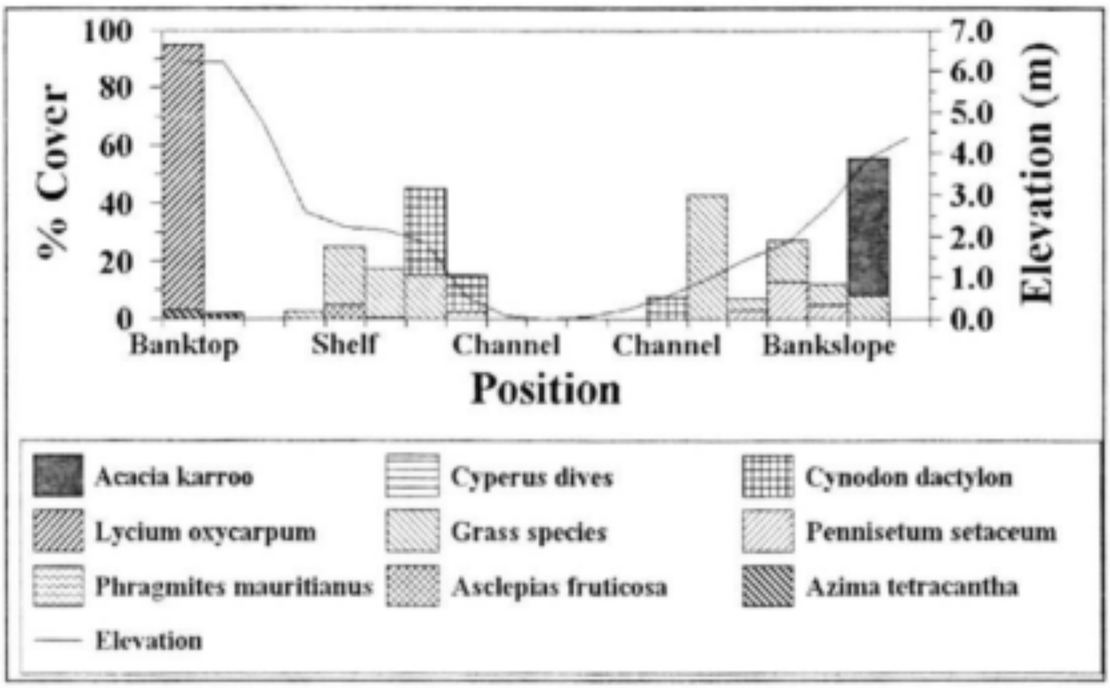
The relationship between morphological diversity and species distribution was examined further by overlaying the belt transects surveyed across the channel sections on the channel morphology. This will be illustrated using sites from the middle and lower reaches of the two river.

The middle reaches are represented by site S6 and V3 (Figure 6.19) The site on the Skoenmakers (S6) has both a higher species diversity and an overall higher cover percentage. Of particular note are the sedge species established on the shelves; both shelves and sedges are absent from site V3.

The lower reaches are represented by sites V5 and S10 (Figure 6.20). It is evident that tree species (*Acacia karroo* and *Rhus lancea*) tended to be the dominant vegetation type farther away from the active channel. Closer to the active channel, on the bank slope and shelves, grass species became established along with juveniles of the woody species. The bottoms of the banks, the water's edge and channel bars (mid- and point bars) were dominated by sedge species (eg. *Cyprus dives*), reeds (*Phragmites mauritianus*) and grass species.

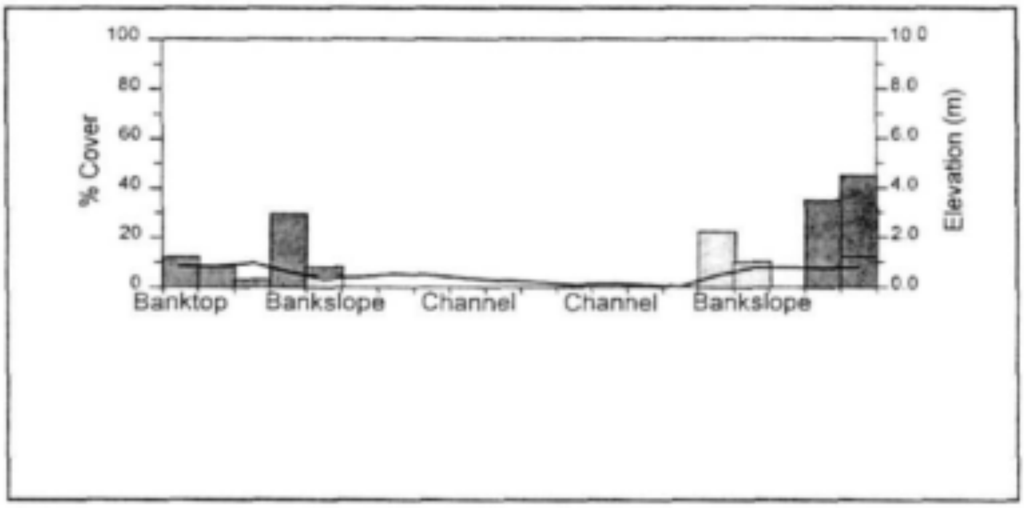


V3

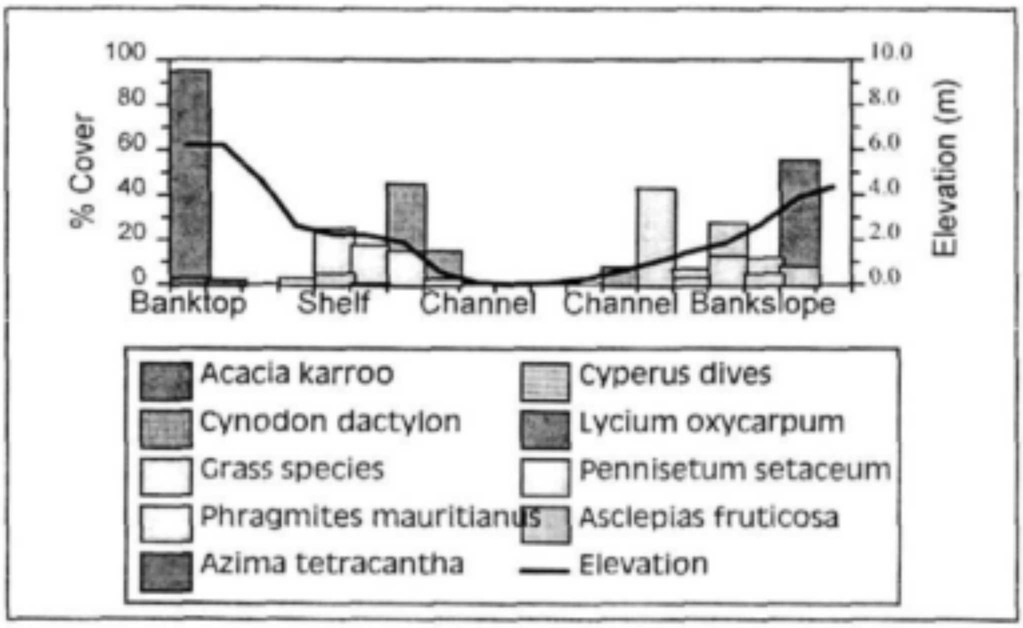


S6

Figure 6.16: *Belt transect for site V3 and S6 in the middle reaches of the Volkers and Skoenmakers rivers.*



V5



S10

Figure 6.17: *Belt transect of the riparian vegetation for two selected, representative sites in the lower reaches of the Volkers (V5) and Skoenmakers (S10) Rivers.*

The presence or absence of certain species at particular sites can be linked in part to the sediment sorting processes. Results of the overall bank sediment sizes for the Volkers and Skoenmakers Rivers indicated a higher percentage of finer sediment (fine sand, very fine sand and silt/clay) for the Skoenmakers River. Sites located in the middle reaches of the Volkers River and Skoenmakers River respectively can be seen in Plates 6.3 and 6.4. Sedge and grass species present at site S4 was associated with the higher percentage of finer sediment deposited on the shelf. Although the point bar deposition in Plate 6.3 created the ideal site for these vegetation types, the coarse sediment (lack of finer sediment) and lack of water prevented these species becoming established.

Plate 6.3: *Point bar deposition upstream from site V3 in the middle reaches of the Volkers River.*

Plate 6.4: *Vegetated bar at site S4 in the middle reaches of the Skoenmakers River.*

6.4.5 Geomorphological effects of the riparian vegetation

The influence of the geomorphology on the riparian vegetation is evident from the results presented above. The channel morphology determines the availability of both water and rooting substrate. Vegetation in turn effects channel morphology. Some examples of vegetation effects were noted. Results from the sediment sample analysis indicated that vegetation enhances the deposition of finer sediment. For example at site S10 on the Skoenmakers River, higher percentages of the finer sediment classes (fine sand, very fine sand and silt) was recorded for the vegetated bar.

Field observations and a qualitative assessment of bank stability indicated that attributes of the vegetation such as the health, age, type and density influenced bank stability. It was observed that the *Acacia karroo* trees decreased the bank stability in the upper reaches of the Skoenmakers River below the IBT inlet. The weight of the trees resulted in bank collapse, especially in areas where undercutting of the banks occurred. Lower down the system the marginal vegetation such as sedge species induced local deposition on banks by reducing near-bank flow velocities and played a major role in controlling erosion of the river bed and banks. Thus channel form of the river was greatly influenced by the binding effects of vegetation on the banks and this, in turn, influenced the morphological diversity of the system

6.5 Summary of results and conclusion

The results presented in this chapter showed the temporal changes in both riparian vegetation and geomorphology since the completion of the IBT in 1978. The spatial distribution of these changes in the two river components is related to the interactions between these two factors which had changed in response to changes in the flow.

The primary factor influencing all the other components was the change in discharge for the Skoenmakers River from an ephemeral to a perennial river. The higher flows and reduction in seasonality caused by the IBT had a dramatic influence on the geomorphological diversity (morphological unit types) found in certain areas of the Skoenmakers River which, in turn, has led to changes in the riparian vegetation distribution and community composition.

It was evident from the results that a number of interrelationships exist between all the components of the river system. The complex multi-faceted nature of this kind of study was evident throughout the analysis of field and other data. The first order impacts of the IBT was to increase water availability and induce morphological change. The increased water availability due to the transfer was further moderated by morphological changes that affect access to water by the vegetation.

Section D: Conclusion

Chapter 7: Concluding remarks

In a country such as South Africa that suffers from water deficits, engineering solutions are used widely to address the spatial and temporal disparities in water supply. South Africa has a well developed network of dams and interbasin transfers that are used to store water and transfer it to areas of need. Both dams and interbasin transfer schemes can have significant geomorphological impacts over the long term due to changes in the flow and sediment regime. These impacts have been the focus of this report.

The downstream effects of dams are well recognised by geomorphologists worldwide. Petts (1984) was one of the first researchers to make a systematic study of their geomorphological impacts, basing his research on dams in Britain. His model of three orders of impact provided a useful link between the time scales over which interrelated hydrological, geomorphological and ecological impacts occur. In the South African RDM procedure, flow recommendations for the ecological reserve are made in the context of the ecological response to changing flows, implicitly assuming that the channel morphology will remain constant in the long term. Petts' model (Petts, 1984) highlights the need to take account of longer term geomorphological processes and the strong possibility that changes in channel form may give rise to a modified stream ecosystem.

Many other researchers have added to our understanding of downstream impacts of dams. The review by McGregor (Chapter 2 of this volume) points to the complexity of the response and provides a warning that each river system must be evaluated with respect to its own fluvial geography. The effect of a dam depends on many factors. The most important is probably the changing balance between sediment inputs and the transport capacity of the flow with distance from the dam wall. Sediment free water may cause increased bank or bed erosion immediately below the dam, but if sediment is introduced into the main channel by tributaries, the reduced capacity of regulated flow in the main channel may result in a net balance towards deposition and channel constriction in lower reaches. Reach characteristics which determine channel stability and the propensity for change are also important. Steep bedrock reaches are resistant to erosion and are unlikely to store much sediment even under much reduced flow conditions; morphological change will therefore be minimal resulting in what Petts termed accommodation adjustment. (Accommodation adjustment refers to the condition where the flow occupies a smaller width within an unchanged channel morphology.) In contrast, in alluvial reaches the channel morphology will be free to adjust to the changes in flow and sediment. Other local factors such as the condition of the riparian vegetation will also contribute to controlling the direction and rate of change. In South Africa accommodation adjustment may be common in the steeper bedrock controlled reaches common in rejuvenated river reaches, but where degraded catchments produce a high sediment load downstream of a dam, the chances of channel constriction will be increased. Petts (1984) found that in Britain noticeable morphological change was restricted to cases where the dam controlled at least 40 % of the upstream catchment area. Runoff generation from the British catchments included in his study would have been relatively uniform compared to South African catchments where a much higher proportion of the runoff is generated in the upper catchment. For example 65 % of the discharge in the Orange River is generated by 7 % of its catchment area. It is therefore likely that the impacts of dams will be propagated further down the length of the river as the natural discharge will recover only slowly, if at all.

South African research into the geomorphological impacts of dams has been limited. To the knowledge of the project researchers, at the time when this project started the only substantive work carried out in South Africa was that by McGregor on the Keiskamma River (McGregor, 2000). Predictions of post-impoundment geomorphological change have therefore been based on international experience. The models presented in Chapter 2 provide a qualitative framework for a more rigorous assessment of channel response to impoundment that takes into account the complexity of fluvial systems in South Africa. Combined with the hierarchical model proposed by Rowntree and Wadeson (1999), this could make a powerful tool for predicting the spatial pattern of this response. Further research is needed to test this suite of models in the South African context.

While there is a considerable body of literature on downstream impacts of dams, little research has been documented on the geomorphological impact of interbasin transfer schemes. The recently published review by Snaddon *et al.* (1999) underlined the lack of studies world wide. This is surprising given the magnitude of the changes to flow regimes, at least in the upper reaches of receiving rivers. In South Africa a number of schemes are either already in operation or planned. Field observations on test releases into the upper Nahoon and Yellowwood rivers near East London in the Eastern Cape and into the Mpofone river in the Mgeni catchment, KwaZulu Natal all point to significant impacts under a full release programme (Chapter 3, this volume). Releases from the Katse Dam into the Axil River have already resulted in large scale instability.

The study presented here on the Skoonmakers River, part of the Orange-Fish River transfer scheme, illustrates the dramatic changes to channel morphology that can result when a steady volume of water is released into a first order stream. By comparing the regulated Skoonmakers River with the unregulated Volkers River, it was apparent that, over the first ten kilometres below the dam, incision and channel widening transformed a small channel in the order of five metres wide and one half to one metre deep to a channel some twenty five metres wide and six metres deep. A secondary impact was the redistribution of the eroded sediment down the length of the channel, and in the downstream storage dam, Lake Darlington. In the middle reaches of the river lateral benches were formed, whilst in the lower reaches deposition of sediment in the form of braid bars resulted in a multiple channel.

Vegetation has an important influence on channel processes and plays a significant role in controlling channel form. Vegetation can increase the stability of the bank against erosion and can also enhance deposition processes. In turn water availability and geomorphological processes influence the growth of vegetation. The Skoonmakers interbasin transfer scheme had a significant impact on the vegetation of what was originally an ephemeral river. The primary effect was undoubtedly the dramatic increase in the availability of water. Bank erosion and sediment deposition were also important in changing the availability of different habitats for vegetation growth. In the upper eroding reaches instability of both bed and banks resulted in loss of riparian vegetation without the creation of new stable habitat. In the middle to lower reaches, however, species diversity increased relative to the natural vegetation characteristic of the ephemeral Volkers River. This raises the question of whether maximum biodiversity is always the best measure of river health. If the ecological status is to be measured against the natural condition, the more diverse Skoonmakers system is clearly significantly modified in terms of hydrology, geomorphology and ecology as a result of the interbasin transfer. The implications of this change for the regional ecology are unknown.

River regulation, whether by water storage behind a dam or transfer of water via an IBT, results in a change in the magnitude and frequency of flows and a consequent change in the dynamics of sediment entrainment, transport and deposition. It is these changes that are responsible for morphological change and, ultimately, change in both instream and riparian habitat. These changes take place over a time span measured in decades. In the short term, spatial and temporal changes in habitat availability result directly from changes in the flow regime. The nature of these changes will depend on the initial geomorphology of the channel. The shape of the channel cross section and the longitudinal pattern of pools, riffles, rapids and other fluvial features determine the spatial pattern of depth, velocity and other hydraulic variables at any given discharge. Channel shape also controls the frequency at which different morphological units in the riparian zone are inundated. Managing flows in order to maintain ecosystem function is therefore about managing their magnitude and frequency. This provides the focus of the second volume of this report.

References

Alexander, W.J.R. 1985. Hydrology of low latitude southern hemisphere land masses. *Hydrobiologia,* 125, 17-23.

Arnell, N.W. 1992: Impacts of climatic change on river flow regimes in the UK. *Journal of the Institute of Water and Environmental management* 6, 432-42.

Assarin, A.E.; Baranova, N.S.; Terentiev L.I. & Vassiliev A.B. 1994. Some examples of river bed degradation gained from reservoirs in operation. *Proceedings of the Eighteenth International Congress on Large Dams,* 7-11 November, Durban. Published by the International Commission on Large Dams. 753-763.

Beaumont, P. 1978. Man's impact on river systems: a worldwide view. *Area,* 10, 38-41.

Benn, P.C. & Erskine, W.D. 1994. Complex Response to flow regulation: Cudgegong River below Windermere dam, Australia. *Applied Geography,* 14, 153-168.

Blatt, H., Middleton, G. & Murray, R. 1980. *Origin of sedimentary rocks*, Second edition, Prentice-Hall, New Jersey.

Bless, C. & Higson-Smith, C. 1995. *Fundamentals of social research methods: An African perspective*, Second edition, Creda Press, Cape Town.

Blum, M.D.; Toomey, R.S. and Valastro, S. 1994. Fluvial response to late quaternary climatic and environmental change, Edwards Plateau, Texas. *Palaeogeography, Palaeoclimatology, Palaeoecology* 108, 1-21.

Bray, D.I. & Kellerhals, R. 1979. Some Canadian examples of the response of rivers to man-made changes. In: Rhodes D.D, and Williams, G.P. (Eds), *Adjustments of the Fluvial System*. George Allen and Unwin, London, 351-372.

Brierly, G. 1994. River reach analysis as a geomorphic tool for river classification. In Uys, M.C., editor, *Classification of rivers as environmental health indicators. Proceedings of a joint SA Australian workshop, February 7-14 1994, Cape Town, South Africa. Water Research commision Report* TT63/94, Pretoria: Water Research Commission.

Brookes, A. 1988. *Channelized Rivers: Perspectives for Environmental Management*, John Wiley, Chichester.

Brookes, A. & Shields, F.D.Jr.1996. *River channel restoration- Guiding principles for sustainable projects*. John Wiley & Sons Ltd., Chichester.

Brower, J.E.; Zar, J.H.; Von Ende, C.N. 1990. *Field and laboratory methods for general ecology*, Third edition, Wm. C. Brown Publishers, Duduque.

Buma, P.G. & Day, J.C. 1977. Channel Morphology below reservoir storage projects. *Environmental Conservation*, 4, 4, 279-284.

Byren, B.A. & Davies, B.R. 1989. The effect of stream regulation on the physico-chemical properties of the Palmiet River, South Africa. *Regulated Rivers: Research and Management*, 3, 107-121.

Cambray, J.A. 1984. Fish populations in the middle and lower Orange river, with special reference to the effects of stream regulation. *Journal of the Limnological Society of Southern Africa*, 10: 37- 49.

Chien, N. 1985. Changes in river regime after the construction of upstream reservoirs. *Earth Surface Processes and Landforms*, 10, 143-159.

Church, M. 1995. Geomorphic response to river flow regulation: Case studies and time-scales, *Regulated Rivers: Research and Management*, 11, 3-22.

Chutter, F.M. 1969. The effects of silt and sand on the invertebrate fauna of streams and rivers. *Hydrobiologia*, 34, 57-76.

Collett, D. 1996. *Effects of the Orange-Fish Inter-basin Transfer Scheme on riparian vegetation in relation to morphological change in the Great Brak River*, Unpublished Geography Honours Thesis, Rhodes University, Grahamstown.

Cowan, W.L. 1956. Estimating hydraulic roughness coefficients. *Agricultural Engineering*, July, 473-480pp.

Cummins, K.W. 1992. Catchment characteristics and river ecosystems, In: Boon, P.J., Calow, P. & Petts, G.E. (Eds.), *River conservation and management*, John Wiley, Chichester.

Davies, B.R. 1996. Pers comm. SASSAQS Conference, Victoria Falls, Zimbabwe, 15-19 July.

Davies, B.R. & Day, J. 1997. *Vanishing Waters*. UCT Press, Cape Town.

Davies, B.R.; O'Keeffe, J.J. & 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.

Davis, J. A., Rutherford, I.D. and Finlayson, B.L., 1999. The Eppalock soil conservation project, Victoria, Australia: the prevention of reservoir sedimentation and the politics of catchment management. *Australian Geographical Studies* 37, 37-49.

De Jong, S.M. 1994. Derivation of vegetation variables from a landsat TM image for modelling of soil erosion, *Earth Surface Processes and Landforms*, 19, 165-178.

De Coursey, 1975, cited in Petts, G.E. 1979. The adjustment of river channel capacity downstream from reservoirs in Great Britain. Unpublished PhD thesis, University of South Hampton.

De Ploey, J. 1989. *Soil erosion map of western Europe*. Cremlingen-Destedt: Catena Verlag.

Dolan, R.; Howard, A. & Gallenson A. 1974. Man's Impact on the Colorado River in the Grand Canyon. *American Scientist*, 62, 392-406.

Dollar, E.S.J., 2000. *The determination of geomorphologically effective flows for selected eastern sea board rivers in South Africa*, unpublished PhD thsesis, Rhodes University, Grahamstown, South Africa.

Dollar, E.S.J. & Rowntree, K.M. 1995. Hydroclimatic trends, sediment sources and geomorphic response in the Bell River Catchment, Eastern Cape Drakensberg, South Africa, *South African Geographical Journal* 77, 1, 21-32.

Du Plessis, A.J.E. 2000. The response of the two interrelated river components, geomorphology and riparian vegetation, to interbasin water transfers in the Orange-Fish-Sundays River Interbasin Transfer Scheme, unpublished Msc thesis, Rhodes University.

Engman, E.T. 1986. Roughness coefficients for routing surface runoff, *Journal of Irrigation and Drainage Engineering*, 112, 1, 39-53.

Erskine, W.D. 1985. Downstream geomorphic impacts of large dams: the case of Glenbawn Dam, NSW. *Applied Geography*, 5, 195-210.

Erskine, W.D. 1986. River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949. *Australian Geographical Studies*, 24, 88-107.

Erskine, W.D. & Warner, R.F. 1988. Geomorphic effects of alternating flood and drought dominated regimes on NSW coastal rivers, In: Warner, R.F. (Ed.), *Fuvial Geomorphology of Australia*. Academic Press, Sydney, 223-244.

Fergus, T. 1997. Geomorphological response of a river regulated for hydropower: River Fortun, Norway. *Regulated Rivers: Research and Management*, 13, 449-461.

Finlayson, B.1997, Pers comm. Rhodes University, Grahamstown.

Frissel, C.A., Liss, W.J., Warren, C.E. and Hurley, M.D. 1986. A hierarchical framework for stream classification viewing streams in a watershed contaxt. *Environmental Management* 10, 199-214.

Fuggle, R.F. & Rabie, M.A. 1992. *Environmental Management in South Africa*. Juta, Cape Town.

Galay. V.J. 1983. Causes of riverbed degradation. *Water Resources Reseach.* 19, 5,1057-1090.

Gale, B.A. 1992. The effects of regulation by two impoundments on an acid, blackwater Cape mountain stream. Unpublished PhD thesis, Freshwater Research Unit, University of Cape Town.

Gibbins, C.N.; Jeffries, M.J.; Soulsby, C. & Elliott, C.R.N. 1996. Modelling instream flow needs: The effects of a water transfer scheme on macroinvertebrate communities in the receiving River Wear, In: Leclerc, M.; Capra, H.; Valentin, S.; Boudreault, A. & Côte, Y. (Eds.), Ecolhydraulics 2000, Volume B, *Proceedings of the 2nd International Symposium on Habitat Hydraulics*, June 1996, INRS-Eau, Quebec.

Gill, D. 1973. Modification of Northern Alluvial Habitats by River Development. *Canadian Geographer*, 17,2, 138-153.

Gilvear, D.J. 1994: Fluvial geomorphology at work: a UK perspective. *Journal of the Scottish Association of Geography Teachers* 23, 30-42.

Gilvear, D.J.; Waters, T.M. & Milner, A.M. 1995. Image analysis of aerial photography to quantify changes in channel morphology and instream habitat following placer mining in interior Alaska, *Freshwater Biology*, 34, 389-398.

Gordon, N.D; Mc Mahon, T.A. & Finlayson, B.L. 1996. *Stream Hydrology: An Introduction for Ecologists*. John Wiley, West Sussex.

Graf, W.L. 1980. The effect of dam closure on downstream rapids. *Water Resources Research*, 16,1, 129-136.

Gray, D.H. & Macdonald, A. 1989. The role of riparian vegetation in river bank erosion, In, Ports, M.A., (Ed.), *Hydraulic engineering*, Proceedings of the 1989 Conference on hydraulic engineering, August 1989, New Orleans, Louisiana, 218-223pp.

Grayson, R.B., Kenyon, C., Finlayson, B.L. and Gippel, C.J. 1998. Bathymetric and core analysis of the Latrobe river delta to assist in catchment management. *Journal of Environmental management* 52, 361-72.

Gregory, K.J. & Park, C. 1974. Adjustment of river channel capacity downstream from reservoirs. *Water Resources Research*, 10, 4, 870-873.

Gregory, K.J. & Gurnell, A.M. 1988. Vegetation and river channel form and process, In: Viles, H.A. (Ed.), *Biogeomorphology*, Blackwell, Oxford.

Hadley, R.F. & Eschner, T.R. 1982. Effects of water development on the hydrology and morphology of Platte river channels, south-central Nebraska, In: Walling D.E. (Ed.) *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield.* International Association of Hydrological Sciences, Exeter, 3-12.

Hails, J.R. (Ed.) 1977. *Applied geomorphology: A perspective of the contribution of geomorphology to interdisciplinary studies and environmental management*, Elsevier, New York.

Hammad, Y.H. 1972. River bed degradation after closure of dams. *American Society of Civil Engineers Journal of the Hydraulics Division*, 98, 591-607.

Harrison A.D. and Elsworth J.F. 1958. Hydrobiological studies on the Great Berg River, Western Cape Province. Part I. General description, chemical studies and main features of the flora and fauna. *Transactions of the Royal Society of South Africa* 35: 125-226.

Haslam, S.M. 1978. *River plants*, Cambridge University Press, Cambridge.

Hellawell, J.M. 1988. River regulation and nature conservation, *Regulated Rivers: Research and Management*, 2, 425-443.

Hellier, C. 1990. Draining the rivers dry. *Geographical magazine*, July, 27-29.

Heritage, G.L. 1995. *Mpofana-Mgeni Water Transfer Scheme: Receiving river geomorphology, channel stability evaluation and ameliorative measures*, Draft report.

Heritage, G.L. van Niekerk, A.W., Moon, B.P., Broadhurst, L.J., Rogers, K.A. and James, C.S. 1995. *The geomorphic response to the changing flow regimes of the Sabie and Letaba river systems. Water Research Commission Report* K5/376. Pretoria: Water Research Commission.

Hickin, E.J. 1984. Vegetation and river channel dynamics, *Canadian Geographer*, 28, 111-126.

Hickin, E.J. & Nanson, G.C. 1984. Lateral migration rates of river bends, *Journal of Hydraulic Engineering*, 110, 11, 1557-1567.

Hoffman, M.T. 1996. Eastern Mixed Nama Karoo, Nama Karoo Biome, In: Low, A.B. & Rebelo, A.G. (Eds.), *Vegetation of South Africa, Lesotho and Swaziland*, Department of Environmental Affairs and Tourism, Pretoria.

Hrabowski, W.; Ponikiewska, H.; Mrozinski, J. & Spaleny, M. 1994. Monitoring and prediction of environmental changes in storage reservoirs and in their vicinity. *Proceedings of the Eighteenth International Congress on Large Dams*, 7-11 November, Durban. Published by the International Commission on Large Dams. 189-197.

Hughes, J.M.R. 1990. Lotic vegetation dynamics following disturbance along the Swan and Apsley Rivers, Tasmania, Australia, *Journal of Biogeography*, 17, 291-306.

Hughes, D.A. (Ed.) 1994. *Nahoon River release: Environmental monitoring of the release of Kubusi River water from the Wriggleswade Dam and canal system into the Nahoon River catchment with specific reference to water flow, chemistry, invertebrate biology and geomorphological characteristics*, Report to Subdirectorate Environmental Studies, Department of Water Affairs and Forestry by the Institute for Water Research and Department of Geography, Rhodes University, Grahamstown, Department of Water Affairs and Forestry Report No. VS/600/08/E001.

Hupp, C.R. 1988. Plant ecological aspects of flood geomorphology and paleoflood history, In: Baker, V.R.; Kochel, R.C. & Patton, P.C. (Eds.), *Flood geomorphology*, John Wiley, New York, 335-356pp.

Hupp, C.R. 1990. Vegetation patterns in relation to basin hydrogeomorphology, In: Thornes, J.B., (Ed.), *Vegetation and erosion*, John Wiley, Chichester, 217-236pp.

Ikeda, S. & Izumi, N. 1990. Width and depth of self-formed straight gravel rivers with bank vegetation, *Water Resources Research* 26, 2353-2364.

Illgner, P. 1991. *Downstream riparian change on the upper Buffalo River, Eastern Cape: Vegetation and river channel dynamics*, Unpublished Geography Honours Thesis, Rhodes University, Grahamstown.

Jacobs, T.A.; Koehn, J.D.; Doeg, T.J. & Lawrence, B.W. 1994. Environmental experience gained from operation of reservoirs in the Murray-Darling basin, Australia. *Proceedings of the Eighteenth International Congress on Large Dams*, 7-11 November, Durban. Published by the International Commission on Large Dams, 561-587.

Kearsley, L.H.; Schmidt J.C., & Warren, K.D. 1994. Effects of Glen Canyon Dam on Colorado River Sand Deposits Used in Grand Canyon National Park, USA. *Regulated Rivers, Research and Management*, 9 137-149.

Keller, E.A. & Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes, *Earth Surface Processes*, 4, 361-380.

Kellerhals, R. & Gill, D. 1973. Observed and Potential Effects of Large Storage Projects in Northern Canada. *Transactions, Eleventh International Congress on Large Dams*, Vol 1, Madrid, 731-753.

Kent, M. & Coker, P. 1992. *Vegetation description and analysis*, John Wiley, Chichester.

Kinaway, I.Z.; Wafa, T.A.; Labib, A.H. & Shenoouda, K. 1973. Effect of Sedimentation in Higha Aswan Dam Reservoir. *Transactions, Eleventh International Congress on Large Dams*, Vol 1, Madrid. 959-975.

Kira. 1972. Cited in Williams, G.P. & Wolman, M.G. 1984. Downstream Effects of Dams on Alluvial Rivers. *Geological Survey Professional Paper 1286*, United States Government Printing Office, Washington.

Knighton, A.D. 1987. River channel adjustment - the downstream dimension, In: Richards, K. (Ed.), *River channels: Environment and process*, Basil Blackwell, Oxford, 95-125pp.

Knighton, A.D. 1998. *Fluvial forms and processes: a new perspective*, Arnold, London.

Knighton, D. & Nanson, G. 1997. Distinctiveness, diversity and uniqueness in arid zone river systems, In: Thomas, D.S.G., 1997: *Arid zone geomorphology: Process, form and change in drylands*, Second edition, John Wiley, Chichester, 185-204pp.

Kondolf, G.M.; Webb, J.W.; Sale, M.J. & Felando, T. 1987. Basic hydrologic studies for assessing impacts of flow diversions on riparian vegetation: Examples from streams of the eastern Sierra Nevada, California, USA, *Environmental Management*, 11, 6, 757-769.

Lachat, B. 1996. Bioengineering techniques to prevent shore erosion, In: Leclerc, M.; Capra, H.; Valentin, S.; Boudreault, A. & Côte, Y. (Eds.), Ecolhydraulics 2000, Volume B, *Proceedings of the 2nd International Symposium on Habitat Hydraulics*, June 1996, INRS-Eau, Quebec, 683-701pp.

Lane. 1890. Cited in Buma, P.G. & Day, J.C. 1977. Channel Morphology below reservoir storage projects. *Environmental Conservation*, 4, 4, 279-284.

Lawson, L.M. 1925. Effect of Rio Grande storage on river erosion and deposition: Engineering News-Record, 95, 10, 372-374. Cited in Williams G.P. & Wolman, M.G., 1984. Downstream Effects of Dams on Alluvial Rivers. *Geological Survey Professional Paper 1286*, United States Government Printing Office, Washington.

Leopold, L.B.; Wolman, M.G. & Miller, J.P. 1964. *Fluvial processes in geomorphology*, W.H. Freeman, San Fransisco.

Li *et al.* 1980. Cited in Galay. V.J. 1983. Causes of riverbed degradation. *Water Resources Research* 19, 5,1057-1090.

Linder.1952. Cited in Schumm, S.A. & Lichty, R.W. 1963. Channel widening and floodplain construction along Cimarron River in southwestern Texas. *US Geological Survey, Professional Paper 352*

Low, A.B. & Rebelo, A.G. (Eds.), 1996. *Vegetation of South Africa, Lesotho and Swaziland*, Department of Environmental Affairs and Tourism, Pretoria.

Macklin, M.G., and Lewin, J. 1992: Channel changes since 1783 on the regulated river Tay, Scotland: implications for flood hazard management. *Regulated rivers* 23, 113-26.

Mangelsdorf, J.; Scheurmann, K. & Weiβ, F.-H. 1990. *River morphology: a guide for geoscientists and engineers*. Springer-Verlag, Berlin.

McCabe, G.J. and Hay, L.E. 1995. Hydrological effects of hypothetical climate change in the East River Basin, Colorado, USA. *Hydrological Sciences Journal* 40, 303-18.

McCully, P. 1996. *Silenced Rivers: The Ecology and Politics of Large Dams*. ZED Books, London and New Jersey.

McGregor, G.K. 2000. *The geomorphological impact of impoundments with particular reference to tributary bar development on the Keiskamma River, Eastern Cape*. Unpublished Msc thesis, Rhodes University.

Midgley, D.C.; Pitman, V.W. & Middleton, B.J. 1994. *Surface Water Resources of South Africa 1990. Digital Data, second edition, 1997*. WRC, report no. 298/1/94.

Moon, B.P., van Niekerk, A.W. and Heritage, G.L. 1997. A geomorphological approach to the management of rivers in the Kruger National park: the case of the Sabie River. *Transactions, Institute of British Geographers* NS 22, 31-48.

Murgatroyd, A.L. & Ternan, J.L. 1983. The impact of afforestation on stream bank erosion and channel form, *Earth Surface Processes and Landforms*, 8, 357-369.

Naiman, R.J.; Lonzarich, D.G.; Beechie, T.J. & Ralph, S.C. 1992. General principles of classification and the assessment of conservation potential in rivers, In: Boon, P.J.; Calow, P. & Petts, G.E. (Eds.), *River conservation and management*, John Wiley, Chichester, 96-115pp.

Navarro, O. & Pujal, A. 1994. Environmental impact of hydro-electric developments in the Comahue region of Argentina. *Proceedings of the Eighteenth International Congress on Large Dams*, 7-11 November, Durban. Published by the International Commission on Large Dams. 695-709.

Neill. 1968. Cited in Benn, P.C. & Erskine, W.D. 1994. Complex Response to flow regulation: Cudgegong River below Windermere dam, Australia. *Applied Geography*, 14, 153-168.

Newson, M.D. & Newson, C.L. 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*, 24,2 195-217.

Nilsson, C.; Grelsson, G.; Johansson, M. & Speerens, U. 1989. Patterns of plant species richness along riverbanks, *Ecology*, 70, 1, 77-84.

Nilsson, C.; Ekblad, A.;Gardfjell, M. & Carlberg, B. 1991. Long-term effects of river regulation on river margin vegetation, *Journal of Applied Ecology*, 28, 963-987.

Nilsson, C. & Jansson, R. 1995. Floristic differences between riparian corridors of the regulated and free-flowing Boreal rivers, *Regulated Rivers: Research and Management*, 11, 55-66.

Nilsson, C.; Jansson, R. & Zinko, U. 1997. Long-term responses of river-margin vegetation to water-level regulation, *Science*, 276, 5, 798-800.

Palmer, R.W. & O'Keeffe, J.H. 1990. Downstream effects of impoundments on the water chemistry of the Buffalo River, (Eastern Cape), South Africa. *Hydrobiologia*, 202, 71-83.

Palmer, C.G. 1991. Benthic assemblage structure and Feeding Biology of 16 Macroinvertebrate functional Feeding Groups in the Middle and Lower reaches of the Buffalo River, Eastern Cape, South Africa. Unpublished PhD thesis, Rhodes University.

Park, C.C. 1977. Man induced Changes in Stream Channel Capacity. In : Gregory, K.J. (Ed.)1977. *River Channel Changes*. John Wiley and sons, Chichester, 121-144.

Petitjean, M.O.G. & Davies, B.R. 1988: Ecological impacts of inter-basin water transfers: Some case studies, research requirements and assessment procedures in Southern Africa, *South African Journal of Science*, 84, 819-828.

Petryk, S. & Bosmajian, G. 1975. Analysis of flow through vegetation, *Journal of Hydraulics Division*, July, 871-884pp.

Petts, G.E. 1979. The adjustment of river channel capacity downstream from reservoirs in Great Britain. Unpublished Phd thesis, University of South Hampton.

Petts, G.E., 1980. Long term consequences of upstream impoundment. *Environmental Conservation* 7 (4) 325-332.

Petts, G. E. 1984. Sedimentation within a regulated river. *Earth Surface Processes and Landforms*, 9, 125-134.

Petts, G.E. and Amoros, C. 1996. *Fluvial Hydrosystems: a management perspective*. In Petts, G.E. and Amoros, C. 1996. Fluvial Hydrosystems, Chapman and Hall, London, pp. 263-278.

Petts, G. E. & Pratts, J.D. 1983. Channel Changes Following Reservoir Construction on a Lowland English River. *Catena*, 10, 77-85.

Petts, G. E. & Thoms, M. C. 1986. Channel Aggradation Below Chew Valley Lake, Somerset, U.K.. *Catena*, 13, 305-320.

Petts, G. E. & Thoms, M. C. 1987. Morphology and Sedimentology of a Tributary Confluence Bar in a Regulated River: North Tyne, U.K. *Earth Surface Processes and Landforms*, 12, 433-440.

Poesen, J.W.A. and Hooke, J.M. 1997: Erosion, flooding and channel management in Mediterranean environments of Southern Europe. *Progress in Physical Geography* 21, 157-99.

Powell, K.E.C. 1978. Weed growth - a factor of channel roughness, In: Herschy, R.W. (Ed.), *Hydrometry: Principles and practice*, John Wiley, Chichester, 327-352pp.

Qiwei, H; Wang, Y. & Xiang, X. 1982. Erosion and recovery of sediment concentration in the river channel downstream from the Danjiankou Reservoir. In: Walling D.E. (Ed), *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield.* IAHS Publication no. 137, 143-153.

Reid, I. & Frostick, L.E. 1997. Channel form, flows and sediments in deserts, In Thomas, D.S.G. (Ed.) *Arid zone geomorphology*, Wiley, Chichester, 205-229.

Rhoads, B.L. 1994. Fluvial geomorphology. *Progress in Physical Geography* 18,103-23.

Richards, K. & Greenhalgh, C. 1984. River Channel Change: Problems of Interpretation Illustrated by the River Derwent, North Yorkshire. *Earth Surface Processes*, 9, 175-180.

Rogers, K.H. & Van der Zel, D.W. 1989. Water quantity requirements of riparian vegetation and floodplains, In: Ferrar, A.A. (Ed.), *Ecological flow requirements for South African rivers*, South African National Science Programme, Report no. 162, FRD/CSIR, Pretoria, 94-109pp.

Rooseboom, A. 1992. Sediment transport in rivers and resevoirs - a southern African perspective. WRC, report no. 297/1/92.

Rosgen, D. 1996. *Applied river morphology*. Pagesa Springs, MN: Printed media copies.

Rowntree, K.M. 1991. An assessment of the potential impact of alien invasive vegetation on the geomorphology of river channels in South Africa, *South African Journal of Aquatic Science*, 17, 1/2, 28-43.

Rowntree, K.M. and Wadeson, R.A., 1996. Translating channel morphology into hydraulic habitat: application of the hydraulic biotope concept ta an assessment of discharge related habitat calnges. *Proceedings 2nd IAHR International Symposium on Hydraulics and Habitats*, Quebec city, June 11-14, 1996.

Rowntree, K.M., and Wadeson, R.A. 1997. A hierarchical model for the assessment of instream flow requirements. *Geoöko plus* 4, 85-100.

Rowntree, K.M. and Wadeson, R.A., 1998. Geomorphological framework for the assessment of instream flow requirements. *Aquatic Ecosystem Health and Management*, 125-141.

Rowntree, K.M. & Dollar, E.S.J. 1999. Vegetation controls on channel stability in the Bell river, Eastern Cape, South Africa, *Earth Surface Processes and Landforms* 24, 127-134.

Rowntree, K.M. & Wadeson, R.A. 1999. *A hierarchical geomorphological model for the classification of selected South African rivers*, Water Research Commission, Report number 497/1/99, Pretoria.

Rowntree, K.M. and Ziervogel, G., 1999. *Development of an index of stream geomorphology for the assessment of river health*, NAEBP Report Series No.7, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

Rowntree, K.M. and Wadeson, R.A., 2000. *Field manual for channel classification and condition assessment*, NAEBP Report Series No 13, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

Schumm, S.A. 1977. *The fluvial system*, John Wiley, New York.

Schumm, S.A. & Lichty, R.W. 1963. Channel widening and floodplain construction along Cimarron River in southwestern Texas. *US Geological Survey, Prof. Paper 352*-D.

Shalaby, A.M. 1986. High Aswan Dam, and environmental impact. *Proceedings of the Sixteenth International Congress on Large Dams*. Published by the International Commission on Large Dams, 2-14

Sherrard, J.J. & Erskine, W.D. 1991. Complex Response of a sand-bed stream to upstream impoundment. *Regulated Rivers: Research and Management*, 6, 53-70.

Simon, A. & Hupp, C.R. 1990. The recovery of alluvial systems in response to imposed channel modifications, West Tennessee, USA, In: Thornes, J.B. (Ed.), *Vegetation and erosion*, John Wiley, Chichester, 145-160pp.

Snaddon, C.D. & Davies, B.R. 1997. *An analysis of the effects of interbasin water transfers in relation to the new water law*, Report submitted to the Department of Water Affairs and Forestry, January 1997, Pretoria.

Snaddon, C.D.; Davies, B.R & Wishart, M.J. 1999. A Global Overview of Inter-basin Water Transfer Schemes, with an appraisal of their Ecological, Socio-Economic and Socio-Political Implications, and Recommendations for their Management. Water Research Commission Report No. TT 120/00.

Stanford, J.A.; Ward, J.V.; Liss, W.J.; Frissell, C.A.; Williams, R.N.; Lichatowich, J.A. & Coutant, C.C. 1996. A general protocol for restoration of regulated rivers, *Regulated Rivers: Research and Management*, 12, 391-413.

Stormberg, J.C. 1993. Instream flow models for mixed deciduous riparian vegetation within a semiarid region, *Regulated Rivers: Research and Management*, 8, 225-235.

Tariq, S.M. 1994. Environmental Impact of Tarbela Reservoir. *Proceedings of the Eighteenth International Congress on Large Dams*, 7-11 November, Durban. Published by the International Commission on Large Dams, 351- 369.

Thomas, D.S.G. 1988. The biogeomorphology of arid and semi-arid environments, In: Viles, H.A. (Ed.), *Biogeomorphology*, Blackwell, Oxford., 193-201pp.

Thomas, M.F. and Thorp, M.P. 1995. Geomorphic response to rapid climatic and hydrologicchange during the late Pleistocene and early Holocene in the humid and sub-humid tropics. *Quaternary Science Reviews* 14 193-207.

Thorne, C.R. 1990. Effects of vegetation on riverbank erosion and stability, In: Thornes, J.B., (Ed.), *Vegetation and erosion*, John Wiley, Chichester, 125-144pp.

Thorne, C.R., Hey, R.D. Newson, M.D. 1997. *Applied fluvial geomorphology for river engineering and management*, New York.

Trimble, S.W. 1990. Geomorphic effects of vegetation cover and management: Some time and space considerations in prediction of erosion and sediment yield, In: Thornes, J.B. (Ed.), *Vegetation and erosion*, John Wiley, Chichester, 55-65pp.

Trimble, S.W. 1997. Stream channel erosion and change resulting from riparian forests, *Geology*, 25, 5, 467-469.

Tsujimoto, T.; Kitamura, T. & Murakami, S. 1996. River-bed degradation influenced by growth of vegetation along a stream, In: Leclerc, M.; Capra, H.; Valentin, S.; Boudreault, A. & Côte, Y. (Eds.), Ecolhydraulics 2000, Volume A, *Proceedings of the 2nd International Symposium on Habitat Hydraulics*, June 1996, INRS-Eau, Quebec, 389-394pp.

Turner, R.M. & Karpiscak, M.M. 1980. Recent Vegetation Changes Along the Colorado River Between Glen Canyon Dam and Lake Mead Arizona. *Geological Survey Professional Paper 1132*. US Government Printing Office, Washington.

Van Coller, A.L. 1992. *Riparian vegetation of the Sabie River: Relating spatial distribution patterns to the physical environment*, MSc Thesis, University of the Witwatersrand, Johannesburg.

Van Coller, A.L. & Rogers, K.H. 1996. *A basis for determining the instream flow requirements of riparian vegetation along the Sabie River within the Kruger National Park*, Centre of Water in the Environment, University of the Witwatersrand, Johannesburg, Report No. 2/96.

Van Robbroeck, T.P. 1979. Inter-basin water transfers in South Africa, *Civil Engineer in South Africa*, 21, 2, 29-35.

Van Veelen, M. & Stoffberg, F.A. 1987. Water resources development in the eastern Cape, In: Hughes, D.A. & Stone, A.W. 1987. (Eds), *Proceedings of the 1987 Hydrological Sciences Symposium*. Rhodes University, Grahamstown, 34-49

Viles, H.A. (Ed.). 1988. *Biogeomorphology*, Blacwell, Oxford.

Viles, H.A. 1990. 'The agency of organic beings': A selective review of recent work in biogeomorphology, In: Thornes, J.B. (Ed.), *Vegetation and erosion*, John Wiley, Chichester, 5-24pp.

Wadeson, R.A., IWR Environmental, pers. comm.

Wadeson, R.A. 1996. The development of the hydraulic biotope concept within a hierarchical geomorphological model, unpublished Ph. D. thesis, Rhodes University, Grahamstown, South Africa.

Wadeson, R.A. and Rowntree, K.M. 1998. Application of the hydraulic biotope concept to the classification of instream habitats. *Aquatic ecosystem Health and Management* 1, 143-57.

Walker, K.F. 1985. A Review of the ecological effects of river regulation in Australia. *Hydrobiologia*, 111-129.

Werger, M.J.A. 1973. On concepts and techniques applied in the Zurich-Montpellier method of vegetation survey, *Bothalia*, 11, 309-324.

Williams, G.P. & Wolman, M.G. 1984. Downstream Effects of Dams on Alluvial Rivers. *Geological Survey Professional Paper 1286*, United States Government Printing Office, Washington.

Woo, H. & Yu, K. 1994. Prediction of river profile changes downstream of the Daechong Dam by using the computer program HEC-6. *Proceedings of the Eighteenth International Congress on Large Dams*, 7-11 November, Durban. Published by the International Commission on Large Dams, 99-110.

Zhang, D.D. 1998. Geomorphological problems of the middle reaches of the Tsangpo River, Tibet. *Earth Surface Processes and Landforms* 23, 889-903.

Zimmerman, R.C. & Thom, B.G. 1982. Physiographic plant geography, *Progress in Physical Geography*, 6, 45-59.

Appendix 1

Review of literature on the geomorphological impacts of river regulation

Review of literature on the geomorphological impacts of river regulation

UNITED KINGDOM

Petts, 1979, conducted an extremely derailed survey of 14 reservoirs in Britain. Summarised details of the reservoirs catchment, as well as the findings in each case are summarised below.

***Table A:** Summary of primary impacts on rivers studied by Petts, 1979.*

Map No.	River and Reservoir	Primary impact
20	Fernworthy, S. Teign R.	Peak flow reduction: 28%
22	Avon, Avon R.	Peak flow reduction 16%
21	Meldon, West Okement R.	Peak flow reduction 9%
2	Camps, Camps Water	Peak flow reduction 41%
4	Daer, Daer Water	Peak flow reduction 56%
3	Cowgill, Cow Gill	Peak flow reduction 58%
1	Leadhills, Elvan Water	Peak flow reduction 47%
16	Blagdon, Yeo R.	Peak flow reduction 51%
19	Sutton Bingham, Yeo r.	Peak flow reduction 35%
17	Chew Valley Lake, Chew R.	Peak flow reduction 73%
5	Catcleugh, Rede R.	Peak flow reduction 71%
24	Lady Bower, Derwent R.	Peak flow reduction 42%
8	Stocks, Hodder R.	5yr flood reduction: summer - 50%; winter - 8%; Peak flow reduction 70%
11	Vyrnwy, Vyrnwy R.	Peak flow reduction 69%

General description of the Upper Clyde Reservoirs: catchments are well vegetated with grass, heather and moss, and large tracts of peat. Despite a high MAR of 1500mm, the sands, gravels and peat in the catchment reduce runoff, which gives a low degree of flow variability, and slows the likely increase in channel capacity with distance. These channels, set mostly in mobile materials have adjusted their capacity by a reduction in channel width, which occurs where the channel has an actively meandering planform. Vegetation encroachment in catchments of less than 5km^2 seems to control the direction, rate and magnitude of change. Large reservoirs on small systems, result in straightforward accommodation adjustment, where only flood events are competent enough to do any work, whereas moderate size impoundments evoke a more complex response.

Leadhills: located on Elvan Water, impounds a catchment of 3.4km^2. Channel capacity immediately below the dam was reduced to 46% of the predicted value, but recovered to 15% below the entrance of the first tributary, which increased the unregulated area to 60% of the regulated catchment area. Above the tributary channel width was reduced, downstream, width and depth were reduced probably due to sediment input from the tributary.

Cowgill Upper: located on Upper Cow Gill River, impounds a catchment of 3.33km^2. Channel capacity immediately below the dam was reduced to <20% of the predicted value. There was a complete change in channel form, with width reduction enhanced by vegetation growth. It appeared that in a small catchment such as this (<5km².) vegetation played a dominant role in channel adjustment. By the time the catchment area is 29.25km² (2.3x the regulated area) the channel is within 20% of its predicted capacity.

Camps: located on Camps Water impounds a catchment of 24.59 km². This is an actively migrating meander system, which becomes less sinuous four kilometres below the dam where the stream is constricted by bedrock controls. Channel capacity immediately below the dam was increased by 80% due to degradation, but reduced to 50% of predicted value within 250m. The reduced capacity was maintained until the unregulated catchment area reached 25% of that feeding the reservoir. Once the unregulated area equalled 50% of the regulated area, channel capacity reached the predicted natural values. A number of processes were operating in this system: bank erosion due to bed armouring, deposition of the load in the form of channel side berms and point bars, all in the process of downstream meander migration.

Daer: located on Daerwater, impounds a catchment of 47.33 km². Immediately below the dam, boulders and concrete blocks prevented degradation. A compound channel shows evidence of the pre- and post dam morphology, with the bankfull stage of both regimes evident. An in channel bench formed, delineating the new bankfull capacity, thereby reducing capacity by 50%. Below the first major tributary junction, (about 8km) 13 km downstream, the channel is 68% of its former size. This has been achieved by a reduction in channel width within the actively migrating meander system. Distribution and sorting of sediment introduced by the tributary has occurred. Above this reach, flows are accommodated within the old channel form. 26km downstream capacity returns to normal after the entrance of another tributary.

***General description of the Dartmoor reservoirs**: high rainfall area, a flashy flood regime and steep slopes have led to the occurrence of coarse lag deposits in the streams. The rate of channel adjustment in this region is linked to sediment supply from tributaries, particularly where the channel has a stable form controlled by bedrock outcrops and vegetation.*

Fernworthy: closed in 1942, with a catchment area 9.95 km². Immediately below the dam the channel is well protected by a cobble and boulder bed. Development of a bench has reduced the channel capacity to 33%. Along the 3 reaches which were investigated on 35km stretch of river, there was some significant reduction, but in many places capacities were as predicted. Stable sites with wooded banks were found to show little change, whereas areas where there was some active channel migration had reduced their capacity. Channel slope was found to play a part too. Sedimentological analysis showed a decrease in sediment size in a downstream direction.

Avon: closed in 1958, with a catchment area of 12.03km². Reduction of channel capacity to less than 60% of predicted values and a change in channel slope were identified, until the unregulated catchment reached 18 km² and the channel entered a bed rock reach. Although Bala Brook joins the main stream 3km below the dam, increasing the unregulated area by 50%, it is not until the unregulated catchment reaches 2.5 times the regulated catchment, 7.75km downstream that the channel form reaches predicted dimensions. Along bedrock channel sections, changed flow levels are linked to lichen growth. In other reaches, channel berms and side benches are indicative of the changed regime. Change is related to the availability of sediment and the frequency of competent discharges to sort it.

Meldon: closed in 1970, with a catchment area of 16.83 km². There is a major sediment input 750m downstream of the dam wall in the form of an alluvial fan draining from a quarry. The stream then flows through a short gorge before emerging onto a floodplain. Accommodation adjustment has been identified immediately below the dam, with reduction in capacity of up to 60%. Downstream of the gorge, capacity has been reduced by 50% due to deposition, but as the distance from the sediment source increases, so the degree of reduction decreases.

The Lowland Reservoirs: *Mean annual rainfall and runoof for these reservoirs is similar - about 100mm and 510mm respectively. However , Sutton Bingham has a much larger mean annual flood of 350m^{3}s^{-1}/1000km than Chew Blagdon which is only 200m^{3}s^{-1}/1000km. The rate of adjustment in this region seems to be dependent on the capability of flows. Cohesiveness of banks prevents erosion, but slumping and tributary input may provide a source of sediment which results in channel contraction. In the absence of competent flows, and no additional sediment input, simple accommodation would be the expected response.*

Sutton Bingham: located on a tributary of the Yeo river, impounds a catchment of 30 km^2. The channel bed is paved with gravel which protects it from degradation. Change has been primarily a reduction in width, except in the vicinity of Gallica Brook Junction, which increases the unregulated catchment to 70% of the impounded area, where there has been aggradation. The channel is incised into the valley bottom sediments and most channel narrowing has been achieved by bank slumping and erosion and redistribution of the material. By the time the unregulated area reaches 67 km^2, reduced channel capacity is 68% of predicted values.

Blagdon and Chew Reservoirs: Together they drain an area of 85km^2, each comprising about 8% of the surface area of their catchments, so their impact is substantial. The impact of Chew Valley Lake is such that the 100yr flood did not even overtop the wall. Below Blagdon there has been channel contraction of 70% by bench formation of silt/clay (45%) over gravel, for a distance of 250m, beyond which dimensions approach those that would be expected. 5km below the dam aggradation in the vicinity of a tributary has probably caused reduced capacities too. Chew Valley controls a catchment of 58 km^2. For 1.5km below the dam the channel bed is composed of fine sediment and organic material. It is only the first 150m stretch in which there has been channel contraction of 50%. Tree dating on the bench in this reach suggests that bench formation coincides with the date of dam closure (1955). Beyond the compensation outflow point, dimensions are regular. There is some coarse material deposition at Chew Stoke Brooke entrance and channel contraction of 50% below that, but dimensions gradually approach normal. For the 3-12km reach, where the channel is incised into the alluvium, bank slumping and subsequent deposition has occurred, resulting in channel contraction of 60%. The lack of a riffle-pool sequence suggests that the pools have been filled with sediment under the low flow regime. Because of the size of the impoundments, these two streams are probably still adjusting. In the absence of any significant sediment inputs competent discharges will be the controlling force in maintaining the channel.

'Other' reservoirs

Lake Vyrnwy: located on the river Vyrnwy impounds an area of 73.87 km^2 with a high mean annual rainfall of 1908mm, and a high conversion to runoff of 75% (1437mm), which causes high magnitude floods. The reservoir occupies 6.1% of the catchment, and thus has a large impact on floods. The channel bed is of cobbles and pebbles, leading into a bedrock and boulder channel 8km downstream of the dam. Riparian vegetation stabilises the system further. The two large tributaries which enter the system are also dammed. Reduced channel capacities were identified downstream of small tributaries (where sediment was deposited in a delta form, or more widely spread depending on the volume) and in active meanders where deposition had occurred on the channel perimeter. In the stable channel section, reduced flows were simply accommodated within the channel.

Stocks Reservoir: located on the river Hodder controls a catchment of 37.45 km^2, with a mean annual rainfall of 1656mm, and a mean annual runoff of 1195mm (72%). The area is prone to high magnitude flooding. The dam with an area equal to 3.7% of its catchment has a significant effect on floods. Channel slope is controlled by bedrock outcrops and the channel is stable except in one meandering reach. Degradation below the dam doubled the channel capacity, but channel capacity was reduced to 50% of the predicted value within 300m. Eroded sediment deposited in the form of a bench and subsequently vegetated was the main means of capacity reduction. The channel proportions returned to normal once the unregulated catchment area reached five times that of the dam catchment.

Catcleugh: on the river Rede, controls a catchment of 39.9 km^2, with a mean annual rainfall of 1255mm, and a mean annual runoff of 1026mm (82%). Although the runoff conversion is high, and the catchment surface is impermeable, the low slope of the catchment prevents high magnitude floods. The dam with an area equal to 2.72% of its catchment has a significant effect on floods. It also traps the fairly high coarse sediment load from its catchment. Immediately downstream of the dam the channel is poorly defined, but within 100m, a greatly reduced channel (40% of predicted value), confined by bench development and vegetation encroachment is identifiable. 200m downstream the channel pattern is of unconstrained meanders incised into clay, which straighten out further down and are stabilised by woody vegetation. Channel capacity reaches as little as 20%, but recovers progressively with an increase in unregulated catchment area. Where tributaries join the mainstream there is evidence of aggradation, and a reduction in capacity due to reduced depth at these points. About 27km downstream of the dam, with the entrance of Sills burn, the unregulated catchment reaches three times that controlled by the reservoir and the impact of the dam on channel form is no longer identifiable. Channel change appears to have occurred where the channel is unstable, whereas stable reaches only respond to sediment inputs and very high flood flows.

Leighs: on the river Ter, controls a catchment of 29.9 km^2, with a mean annual rainfall of 587mm and a mean annual runoff of 100mm (17%). It is a pumped storage reservoir, operated to augment summer baseflows. Despite a low slope and high evapo-transpiration, flood peaks may be high. Immediately below the dam the channel capacity has doubled, but soon reduces to between 107% and 20% of predicted values. Substantial bank erosion of up to 1m and increased depth has created capacities of up to 30% more than the predicted values. Investigations of the bank stability gave no clear relationship between erosion and silt/clay proportions, but it is likely that the magnitude of change is related to the resistance of the bank sediments to erosion. Change appeared to be greatest where channel dimensions were small and banks were erodible. The reservoir is operated to increase baseflows in the summer and this appears to increase the susceptibility of the banks to erosion. The problem is likely to be intensified at high discharges.

Lady Bower: on the River Derwent, built in 1945. Rates of runoff in the catchment are variable due to differing geology. Immediately below the dam, a stable gravel and boulder bed resulted in accommodation adjustment. Most change has occurred in a reach 4-9km downstream. Using aerial photographs change was identified just below the Noe confluence, where benches had developed since dam closure, reducing channel capacity by as much as 50%. Sedimentological analysis revealed that the benches were formed of coarse sand and gravel, with a coating of finer sand and silt, whereas the terrace materials were composed of 16-45% silt and clay, more like the bank materials. Tree ring evidence suggested that the benches were less than 51yrs old, whereas the terrace top was dated at 100yrs. Bankfull estimates put the five year flood at 38.7m^3s^{-1} immediately below the dam, and 50 m^3s^{-1} at the Noe confluence. Overall there has been a reduction of channel capacity in response to reduced flows with sediment for the benches derived from the unregulated Noe river.

Significant findings from Petts' study can be summarised as follows:

The rate of river response will depend on the frequency of competent releases and sediment input from regulated sources. The quantity and calibre of sediment introduced from non-regulated sources impacts significantly on channel form in a regulated system. Rate and direction of change is related to the area of the reservoir as a proportion of its catchment and the level of the reservoir at the time of flood. Examples from Britain show that the main impact is on moderate size, more frequent events, rather than rare large events. Impact will also depend on the catchment condition at the time of the flood as that will influence runoff. As the flood frequency decreases, so does the reservoir impact. Change below large reservoirs whose purpose is flood regulation may be slower than below smaller reservoirs where competent discharges occur more frequently. The stability of the pre-dam channel planform, the composition of its banks and dimensions of the channel at individual locations before dam closure all affect the degree of change which can occur. River channels having a meandering planform appear to be more sensitive to change, straighter, more stable ones are less affected. Baseflow augmentation can have a significant effect where banks are non-cohesive.

Downstream of British reservoirs, the main response has been channel contraction, and in free meander systems an increase in sinuosity. The result is a reduction of channel slope and an increase in deposition. The downstream impact decreases as the unregulated catchment area increases. Once the unregulated contributing area reaches 40% of the regulated catchment, the river channel returns to normal dimensions.

No. 18, Gregory and Park (1974) suggest that there are two forms of adjustment: where floodwaters are released as surges, the channel can adjust by increasing its capacity, or, where floodwaters are impounded a decrease in capacity would be expected. This change was investigated on the river Tone, below Clatworthy Reservoir (1959) in Somerset.

Channel cross sections showed a multiple channel with only an active inner element, which is the present bankfull channel, delineated by vegetation. 14 sites were surveyed, eight showed these characteristics, the others showed reduction by the accumulation of sediment as shoals, which were vegetated and thus stabilised. Multiple cross section reaches occurred where the channel slope was greatest. Scour has only occurred on reaches with the greatest slopes.

To compare pre/post dam capacity, 15 sections above the dam were surveyed. Results show that the channel has reduced to 54% of its expected capacity immediately below the dam, and increases to normal capacity where the catchment area reaches 78.5km^2, 11km downstream. This amounts to four times the area controlled by the reservoir. They were able to come up with a formula for the relationship between channel x-section and catchment area above the dam. An assessment of high flows of channel forming/maintenance proportions, by comparison with similar neighbouring streams, and predicted flows. As the drainage area increases the flows approach >normal.= Based on the regional pattern, post dam flows could be expressed as proportions of the expected values:

Q2.33 - 33.8% (about 3m^3 vs 9m^3)
Q1.5 - 39.5%.(about 2.6m^3 vs 6.5m^3)

With the drainage increased to 57.8km^2:

Q2.33 - 39.5% (about 24m^3 vs 9m^3)
Q1.5% - 35.7% (about 9m^3 vs 17m^3)

Overall they showed that discharges have been reduced by a third to half of their expected proportions.

No. 17. A paper by **Petts and Thoms (1987)** describes the morphology and sedimentology of a tributary confluence bar formed at the junction of Tarset Burn, which drains a catchment of $108km^2$ and the North Tyne river, regulated by Kielder reservoir ($188Mm^3$) which controls a $241.5km^2$ catchment. Mean annual runoff in the catchment is 1026mm which is 82% of the mean annual precipitation. The primary impact of the reservoir has been to reduce peak flows by 30 - 50 % which has created flow conditions that have allowed the development of a bar at the junction only 3 years after reservoir construction. It has formed by lateral accretion on the inside of the tributary dominated flow thalweg, and extends for nearly 100m (three times bankfull width) and has an exposed surface area of about $900m^2$. A riffle separates the main thalweg into two components. Opposite the mid bar lobe the thalweg is forced to the west side of the channel, upstream it flows on the east. Further erosion is prevented by anti-erosion works on the west bank.

The bar consists mainly of pebbles and cobbles with mean grain size ranging from 8mm to 64mm. Sample data display a pattern of lateral coarsening towards the main channel with the exception of the bar tail, which is in a slack zone. Bar pit samples showed a sequence of upward coarsening, with one exception.

>In gravel bed rivers bedload transport is characterized by a distinct threshold below which little gravel moves, = (Petts, 1987). A small reduction in flows can have a dramatic effect on sediment movement. The highest pre-impoundment high flow in the North Tyne exceeded $250m^3$, while a discharge of $175m^3$ was exceeded four times in 1966. The regulated release pattern is dramatically different: irrigation flows are $1.32m^3s^{-1}$ in summer and $0.66m^3\ s^{-1}$ in winter. They are supplemented by hydro-electric releases of $15m^3s^{-1}$. Calculations suggest that the volume of bedload moved by the stream amounts to $800m^3$. The volume of sediment stored in the bar amounts to about $650m^3$ which suggests that most of the load brought down by Tarset Burn is located in the 100m stretch below the confluence. Peak flows in Tarset Burn exceed $50m^3s^{-1}$, 2 to 3 times per year, with a maximum discharge of $81m^3s^{-1}$ since dam closure.

Processes at the bar were observed at a special dam release of $50m^3s^{-1}$, which created flows of $58m^3s^{-1}$ below the Burn. The bar provided major flow resistance, maintaining a steep energy gradient over and around it. Tracer pebbles placed on the bar were recovered after the event and results showed that all those with a b-axis of <35mm were removed. Fine rippled sand draped the bar tail, and a layer of sand up to 10cm deep had been deposited on the upstream portion of the bar head where eddies occurred. Opposite the bar, channel width is constricted by stable, erosion resistant banks, so a narrower (20m vs 35m) high velocity section is created. Under present conditions, the burn flow controls the geomorphology of this reach by increasing the competence of the channel and facilitating the movement of progressively coarser sediment through this reach.

No.14. Higgs and Petts (1988) study concentrates on the primary impacts of the Clywedog reservoir on the river Severn. It is a purely analytical approach looking at the change in flood distributions, variability of flows, low flows *etc.* and is suited to a system with a flow monitoring network. Two sets of factors were considered: the morphometry of the reservoir basin and its spillweir characteristics and a second set which refer to reservoir operational characteristics.

They found that relatively frequent events were greatly affected, the more extreme ones less so. The 10 year flood was reduced by 5%, while the 1.5year flood was reduced by 17%. Seasonally there was an effect too: the magnitude of the 5yr winter flood was reduced by 8%, but the 5 year summer flood was reduced by 50%. Looking at the low flows they found that extremely low flows had been eliminated, while there had been an increase in the duration of low flows, linked to downstream demands in industry. Pulse releases had increased to meet requirements from canoeists, flushes, irrigation and hydropower demands. The results of the study were complicated by land-use changes and by climatic changes, which serves to illustrate the difficulty of isolating impacts. Overall they found a decline in flood frequencies and in the size of the mean annual flood. Median flows have been reduced by about 50%, mean annual floods by 30%, and low flows maintained at 225% higher than the natural flow with a duration period of 95%.

No. 25. Richards and Greenhalgh' (1984) study assesses the impacts of diverting water from the River Derwent via the Sea Cut, to the sea to prevent flooding in winter. This feature has been in operation since the early 1800's, and has caused the channel to change from a gravel bed upland stream to a sluggish stream with heavy summer weed growth, where it transports sand over a paved bed in the Forge Valley sites.

Reach analysis was carried out above and below the Cut, with transects done on riffles. Based on estimations of bankfull capacity, it was found that the channel is 31% of the expected size based on upstream trends. There has been a 61% reduction ratio for width and 47% for depth. The stream no longer has the capacity to transport sand sized sediment through the Forge Valley sites. Substrate size declines for d_{84} values from 30cm in the headwaters to 3cm above the Sea Cut, to sand over an inherited paved surface in the Forge valley. The sand and silt have accumulated in lateral berms within the original channel, with their tops just below the level of the original floodplain. Sedimentation on the river banks has been encouraged by weed growth, which survives well with the low water levels and stagnant conditions.

No.15, Petts and Pratts (1983) study on the river Ter makes an important contribution to understanding the impact of baseflow augmentation on cohesive channels. Erosiveness of discharges depends on >pre-conditions= especially wetting. The study was carried out on the river Ter where since 1967 the Leighs irrigation storage reservoirs filled from groundwater supplies, have augmented summer flows. The area has a relatively low MAR of about 700mm, with a high evapotranspiration rate of 80% of the MAR. Most major flooding is produced by low intensity winter rainfall coinciding with small floods. Baseflow increases rapidly in a downstream direction - the 50% duration discharge increases from 0.023 m^3s^{-1}, to 0.085 m^3s^{-1}. Baseflow is increased by 0.25 m^3s^{-1} in the summer months for irrigation.

Based on surveys carried out at14 sites before the reservoir was built, with re-surveys in 1975 and 1981 it was possible to measure the change in channel dimensions. Overall there has been an increase in channel capacity by 45%, although the change was complex in time and space. During the first 8 years, 3 sites immediately below the dam were eroded and increased their capacity significantly from 1.96m^2 to 4.23m^2, (81%) while other sites only increased by 25%. The range of change was from a 43% increase to a decrease of 21%, with an average increase of 18%. From 1975 to 1981, the 3 near dam sites continued to expand but only by 18%. Many of the downstream sites started to aggrade, compensating for the previous period of erosion. There was erosion of the bank and channel bottom, as well as deposition on the channel bottom, and aggradation of fines on the banks, by >plastering=. Feedback mechanisms were in operation - when the bed degraded , the banks aggraded and vice versa. Overall though the dominant impact has been an increase in channel width. It is likely that this is the result of increased baseflow duration which makes the banks susceptible to erosion. The fact that there has been no climatic change and therefore no change in high flows (the mean annual flood in particular) make it unlikely that the change is a response to a new dominant discharge. The increase of baseflow and augmented low flows have probably affected channel bank stability and increased the susceptibility of the bank materials to erosion. The study emphasizes the need to monitor change over longer time periods: changes occurring in the first ten years may be counteracted in the next ten.

No. 17, Petts and Thoms (1986) study of the impact of Chew Valley Dam on the river Chew is an extremely detailed study of channel substrate response to impoundment. The lake impounds a 58km^2

catchment and has a surface area of 8% of the catchment. MAR is 1050mm, of which 530mm is converted to runoff. Summer drawdown results in most of the winter floods being stored to such an extent that the 100yr flood in 1968 did not spill over the dam wall. The maximum recorded discharge below the dam in a five year period was 4.21 $m^3 s^{-1}$, and for Strode brook, 0.8 $m^3 s^{-1}$. The number of competent flows with a D_{60} of 0.72 $m^3 s^{-1}$ was much greater in the brook (281 to 109). For 1km below the dam, channel capacity has been reduced by more than 40% . Changes are related mainly to the influence of sediment loads introduced by Strode Brook. The former gravel bed has aggraded since 1953 to form a sand bed as a result of the deposition of tributary injected sediments.

The study area was a 100m reach below the dam incorporating the Strode Brook entrance, and two control reaches below that. Sediment samples from the control sites were predominantly gravels, with less than 10% by weight of fine sediment, arranged in a self supporting open framework. In the study reach, bulk samples have a 28% fine sediment composition (finer than 4mm, mode of 1.5mm) with the remainder of the substrate 8-32mm in size. The Stoke tributary substrate sample showed poorly sorted sands and gravels with a mean size of 3.6mm, and 35% of the samples are finer than 2mm. Samples from Strode brook were also poorly sorted with 55% of the sample finer than 2mm. Freeze core results were different but comparable. They represented the grain size characteristics of the gross deposit and gave an idea of the general pattern of aggradation, while the bulk samples were representative of the surface sediments and related to recent hydrological history.

Sediment was found to have accumulated in a deposit of up to 1.5m in height on the pool bottom. Grain size distribution is predominantly sand with 50-10% of the sample finer than 2mm, and is comparable to that of the Strode brook samples, and offers a contrast to the control site samples. Just above the confluence, a backwater forms a settling area for silts (finer than 4 phi) which makes up 21-48% of the deposit. Aggradation below the confluence has produced a substrate dominated by poorly sorted sands in a gravel-sand mixture. There are some fine slackwater deposits at points along the channel margin associated with the thalweg meandering. As would be expected, grain size relates to the pool riffle sequence with fine r material in the pool and coarser material on the riffle. Pool and slack water deposits show erratic variation in grain size, whereas riffle deposits show a definite increase in mean grain size: 0.3mm, 5m below the confluence, to 1.2mm, 42 metres downstream. The freeze cores show a different pattern: coarse sediments of 0.88mm are found near the confluence, with finer sediments of 0.25mm in the sample taken 20m downstream.

Channel sedimentation at and downstream of tributary confluences is being recognised increasingly as a feature of impounded gravel bed rivers. **No.12. Petts (1984)** study investigates the situation on the River Rheidol where the Peithnant tributary with a catchment area of 4.1km^2 joins the main stream 2km below the Nant-y-Moch Reservoir. Alluvial rivers commonly show an inverse relationship between bed material size and distance downstream, but where a tributary enters with a steep average gradient, and an unregulated flow from a sediment productive catchment, coarse sediment is injected into the main stream. Due to the regulated releases in the mainstream the reach will be dominated by the tributary processes.

The main channel is relatively wide (17.5m average) and shallow, with a bankfull depth of 0.5m; channel slope averages 0.002)units) ; the bed is lined with boulders. The general appearance of the aggrading reach under low flow conditions of 0.16 m^3s^{-1} is of a braided channel. Pre-dam bankfull width was estimated at 17-24m, while the present bankfull is only 6-8m. At this stage the drainage area of the stream has been reduced from 65 km^2 to 7.5 km^2, so a reduction of channel dimensions is to be expected. The Peithnant bed consists of mostly poorly sorted gravels with an average size of 18mm, the largest being 90mm. Landuse practices in the catchment (ditching) have made coarse sediment available from disturbed colluvium.

Gravel deposits on the boulder bed of up to 130cm deep have accumulated. The distribution of particle size is competence related: sand only forms 15% of the bulk sediment sample but increases in relation to competence in a downstream direction. Mean particle size ranges from >65mm at the top of the reach to less than 2mm, 250m downstream. In the lower third, a low velocity zone of aggradation at the >old bar= causes average grain size to decrease rapidly. A sand matrix amongst some of the gravels is assumed to have been deposited during receding flood stages. Even amongst the sands there is size sorting in a downstream direction. Characteristically, coarse sediments line the active channel, finer sediments are found on the bars except on the upper lobate bar where the tributary comes in.

The dominant feature is a lobate bar, 60m long, up to 1m in height and 12m in width. It is 20cm higher than the former bankfull level. Sediment deposits are coarser than in the adjacent channel. This type of bar is a typical feature at a junction, but under the regulated conditions it has become permanent. The bar tails off in a downstream direction, backing up a long deep pool above the tributary entrance, which traps sediment moving in the main stream. Lying parallel to the flow direction, just below the old bankfull level, are elongate bars composed of sediments finer than the adjacent channel. In some cases they form channel side berms. At the lower end of the reach submerged even at low flow, is a transverse bar. Up to 65cm in height it is composed mainly of fine gravel and sands. The deepest and fastest flow occurs at its upstream end where the bar begins to slope upward and forms the new channel bed where it maintains a critical channel depth necessary for sediment transport. The channel has adapted to a narrower and deeper form to facilitate sediment transport under the new conditions

No. 67, Hey's (1975) study is based on geomorphological theories relating to magnitude and frequency of channel forming events and sediment transport. He looks at these theories in the context of river regulation, in an attempt to come up with some predictive ideas about what will happen to a river reach under regulated conditions. He outlines a program to test the thresholds of bedload transport in a section on the Severn, which would be receiving Inter Basin Transfer water from the Wye basin. He predicted that under regulated conditions, riffles would be scoured and pools would fill with sediment, leading to the formation of a braided channel. Cobbles of different sizes would be marked and tagged before reservoir releases were made upstream from Llyn Clywedog Reservoir. The thresholds of movement for various sizes of sediment under different flow conditions could then be determined, and releases could be determined which would not erode the stream bed. The stability of the system could then be maintained.

THE REST OF EUROPE

No. 40, Hrabowski (1994) concentrates on the impact of reservoirs on the surrounding environment, particularly with reference to groundwater movement and its effect on the stability of surrounding land. He also includes a comment on the changes to the river bed, downstream of an impoundment, which are particularly severe in river beds composed of easily erodible material such as sand and silt. He discusses the significant potholing which has occurred below Debe Dam on the Narew River, Poland, as a result of a poorly designed outlet. It occurred mainly as a result of a flash flood which eroded the river bed and the surrounding slopes, despite the protective measures which were in place. The weir was eroded seriously on the upstream side, but more significant was the formation of a pothole 50m downstream with an area of $1500m^2$, and a depth of 11m, below the weir. A quantity of $56000m^3$ was estimated to have been eroded. It has seriously compromised the stability of the whole structure. The water level of the downstream reach has been significantly reduced

No. 76, Fergus (1997). The study is carried out on the river Fortun in Norway. It has a total catchment area of 508km^2, of which 367km^2 or 73% is regulated by three hydro-electric power stations, built between 1959 and 1963. Mean annual precipitation is 800mm, most of which falls as snow. High flows occur in mid July as a result of snow melt and glacial runoff. Heavy precipitation coincident with glacial runoff causes autumn floods. Sediment production rates are high due to the natural processes such as avalanches, debris flows, tributary flooding and glacial erosion. None of the minor tributaries are regulated.

Detailed cross sections surveyed in 1973, 1989 and 1995 were available for a 1600m reach of river just above the third power station. The surveys are extremely detailed, with only a channel width between cross sections which provides some impressive results. From 1973 to 1989 the volume of aggradation amounted to 27000m^3, with degradation of about 15000m^3. The summarized results are as follows: aggradation has occurred in the upper half of the reach, degradation has occurred in the lower half, resulting in a longitudinal change to a steeper channel bed. The slope of the water has increased from 0.0016 to 0.0023 at a flow of 80 m^{3}s^{-1}. In response to the aggradation the channel has widened, eroding the unarmoured right bank and in the confined bedrock section, it has broken through the armoured left bank eroding laterally up to 30m before being stopped by plastering with large stones. Complete erosion of a vegetated bar has also occurred. Sediment moving into the reach has accumulated around islands in the middle of the reach, which has reduced velocities and allowed stabilization by vegetation. Benches and bank bars have been vegetated and so have in channel bars. It appears from diagrams in the paper that side channels have been closed by vegetation encroachment. Vegetation debris adds to the process of aggradation by creating dams and backwaters ideal for sedimentation. Below profile 41 the channel substrate of bedrock has prevented any change, a case of simple accommodation adjustment.

Degradation for the 1989-1995 period was estimated at 5400m^3 and aggradation at 3900m^3, with a net degradation of 1500m^3. The pattern and location of these processes was the same as before. The annual degradation rate for this period was 900m^3 as opposed to 940m^3 for 1973-1989, while aggradation averages were 650m^3 and 1700m^3. This reduction is probably an indication that the channel has adjusted to the new flood regime. Adding to this effect is the fact that three major (>100 m^{3}s^{-1}) floods occurred in that period. Because of reduced flows, a lowering of the water table was expected. Instead, the raised channel bed has raised the water table and caused problems of water logging in adjacent fields.

Discharge has been considerably reduced with post regulation values 35% of the natural discharges. The mean annual flow has been reduced from 20 m^{3}s^{-1} to 7 m^{3}s^{-1}, and the mean annual flood from 140m^{3}s^{-1} to 86 m^{3}s^{-1}. The magnitudes of post-regulation floods are to a great extent dependent on reservoir conditions at the time of the event. Sediment supply to the channel has not changed - but the frequency of competent flows has with the result that aggradation has been the dominant process.

The result of steepening of the reach is that the channel bed is raised and overbank flooding occurs at lower more frequently occurring flows: a 25 m^{3}s^{-1} flow now reaches the level of a pre-regulation 50 m^{3}s^{-1} flow. The implications of this are significant for the farmers who have riparian lands.

ASIA

No. 45, Tariq (1994) discusses the main impacts of Tarbela dam, Pakistan, which regulates a 10360 km^2 area of the Indus River (6% of the total upper Indus drainage area of 169635 km^2). With a surface area of 260km^2, the reservoir was built in 1974, for irrigation purposes as well as for hydroelectric power. It only stores 15% of the annual 79 billion m^3 river flow, but when operated in tandem with Mangla reservoir plays a major role in flood mitigation. It supplies 12km^3 of water to the Indus basin irrigation system. Like all dams, it has a high sediment trap efficiency with only 2-3% of the suspended load passing through it By 2057, the reservoir will have lost 80% of its original capacity. The drainage area is geologically unstable and it therefore has a high sediment production rate. According to Tariq, the reservoir has not had any impact on the downstream channel because the cobble size channel substrate has armoured it against the effects of scour.

Chien (1985) has documented the impact of impoundments on some major Chinese river systems.

Sanmenxia Reservoir (no. 27) on the Yellow river was built in 1960 as a storage reservoir. Due to excessive sedimentation, design alterations were carried out from 1965 in several stages to allow for the sluicing of trapped sediments. Due to its increased capacity, it now serves as a flood detention reservoir from July to October and stores water for irrigation and power generation for the rest of the year. Flood peaks have been reduced by up to 60%, while the duration of medium flows have increased, from 130 to 204 days per year. Pre and post dam sediment concentrations in the river are on a par, (average annual sediment concentration of 37.4kg/m^3.) Below the dam, the river showed has shown an alarming rate of aggradation, making the water level higher than the adjacent lands, with the result that the river has actually become a dividing ridge across the flood plain. Prior to impoundment along one reach, 3.6 % of the sediment load accumulated from 1953-1960. After impoundment from 1973-1980, this reach 'gathered' 29.3% of the total load.

Chien has identified some impoundment impacts with reference to the sediment load, which are characteristic of the flood detention reservoir. The incoming flood peak is collected and released gradually to minimize downstream impacts. The natural sediment/discharge relationship is reversed: the flood flow carrying a large load, is attenuated by the dam, causing it to drop its load. The subsequent low and medium flows already loaded with sediment, are loaded with an additional supply from the reservoir, which they carry to the downstream reaches. This obviously has a far reaching effect on the fluvial processes downstream. A braided stream under these conditions, will tend to aggrade; under flood conditions it will down cut, but overall, the bed will rise. This change is commented on by Li *et al* (1980) cited in Galay (1983) who describes a rapid change from a braided channel to a single thread channel with occasional side channel bars. Secondary channels are silted up and no longer flow. While the high flows free of sediment may degrade the reach below the dam, their impact is not sufficient to balance the rate of aggradation. The floodplain receives little sediment as high overbank flows are infrequent, of short duration, and carrying only a small load they do not supply the floodplain anymore. These factors together raise the bed, and reduce the difference in elevation between the river and the floodplain.

The impoundment of the Han River by the Danjiankou Reservoir (no29) cut off the rivers sediment supply, attenuated flood peaks, increased >low water= discharges and extended the duration of medium flows. In the absence of any tributary entries downstream the sediment load cannot recover. Leveling off of flood peaks has reduced the rivers transport capacity by 41 %. The more frequently occurring low flows have the energy to move fines, but not bigger material, resulting in coarsening of the bed material. Coarsening in turn increases roughness and further reduces velocity . In terms of bed degradation, most of the reaches have stabilised, but this effect is identifiable as far as 480km downstream and seems to be moving further downstream. Four years after dam closure it was found that due to bed degradation, the water level at a discharge of 3,000m^{3}s^{-1} was lowered between 0.6 and 1.3m, for a 490km stretch Chien has found that the first 26km of the channel are stable, the next 40km stretch only erodes under flood conditions, in the next 43km reach sediment moves as bedload, and the last 138km is the most extensively downcut reach. Based on these observations Chien predicts that the 800km stretch to the junction with the Yangste will eventually be degraded. It may take some time for channel pattern to change, but Chien has made some preliminary observations: because of the reduction in floods, in-channel bars have stabilised and accreted, side channels flow less frequently and at low velocities conducive to aggradation and channel contraction. The increase in medium size flows leads to channel deepening, width reduction, and leveling of bed undulations (ie: reduced heterogeneity of substrate). There is also a reduction in the radius of curvature of river bends. In the braided reach from the dam to Huangzhang, 15 out of the 26 'large' branches were found to be silted up, resulting in the amalgamation of the small islands/mid channel sand bars into point bars. Change from a braided to a meandering river is gradually taking place, and seems to be similar to the changes described on the Yellow River, by Li *et al*, (1980) cited in Galay (1983).

The Liu River has an annual average sediment load of 52kg/m^3, which was greatly increased after the construction of the Naodehai Reservoir, due to increased activity in the catchment. In the absence of competent flows, aggradation has dominated the downstream reaches. Bedrock sections have become smothered in sand and the bed has risen 1.5m in 10 years. The channel banks have receded to form a wider and shallower channel.

Qiwei, *et al* (1982) have also done an detailed study of the sediment load in the Hanjiang river since the construction of the Danjiankou (no. 30), reservoir. Their work on the changes in sediment transport capacity, is based on the theory of non-equilibrium transportation of nonuniform sediment. (Han, 1979) With regard to the state of post-impoundment sediment characteristics, they have made the following observations:

- recovery occurs over a long distance
- the rate of increase in sediment concentration is uniform
- corresponding to the change in concentration, the size distribution of the suspended load becomes more uniform and finer along the channel.
- the degradation and aggradation characteristics of each particle size group are different. Generally the fine fractions are scoured more than the coarse. The coarse sediments may even be deposited during the scouring process. Hence the average particle size of the load becomes finer with distance and the settling velocity also becomes smaller.
- the development of the degradation and the increase in sediment transport along the river are not due to an increase in flow intensity.

In the same reach after dam construction the sediment carrying capacity will be much less because the particles of the suspended load are much coarser with larger settling velocities. With the flood peaks reduced the annual sediment transport capacity of the river is also reduced. As a result of erosion of the channel immediately after closure, the flow velocity is smaller and the depth greater for the same discharge. The bed material becomes finer along the river course, due to the exchange which occurs between the bed and the load, with the coarser fraction being deposited while the fines get picked up. The average particle size of the load becomes finer, while settling velocity becomes smaller, and the transport capacity increases. Therefore the amount of erosion exceeds deposition. This occurs at a very low rate in a downstream direction and extends for some distance.

No. 42. Assarin (1994) discusses the impact of three reservoirs in Poland, Lithuania and Vietnam.
The Zimlayanskaya dam is part of a hydro-electric power scheme on the Don River, with a storage capacity of 23.8 x 10^{9}m^3, which is greater than the mean annual river discharge of 22 x 10^{9}m^3. The bed is of fine sand with 0.25-0.05mm the prevalent size. The alluvium is up to10m thick in place, underlain by coarser alluvial material with some gravel\pebble intrusions. Degradation has been observed for 50km below the dam, in an irregular pattern. Progressive scour and fill, has led to changes in width and depth. An estimated 8 x 10^{6}m^3 of sediment was removed from the first 20km reach. Coupled with dredging on the channel banks, and straightening of the rivers course there has been a 0.92m lowering of the water level.

No. 43. Kaunas HPP on the Neman River, Lithuania, regulates $0.46 \times 10^9 m^3$, of the rivers total runoff of $9.2 \times 10^9 m^3$. The channel is trough shaped, 180-300m wide, and 1.5-2.5m in depth in the low season. It has a substrate of gravel and sand bed, of up to 8m in thickness. Coarseness decreases in a downstream direction. Under natural conditions the river bed was hardly movable, change was due to sediment drift. During and after impoundment, the river bottom in a 4km stretch was noticeably degraded. The most affected section, a 0.9km stretch below the dam was lowered by 0.6m on average, with scour of up to 2m in places. The zone of degradation moved downstream with time extending 8km after 5years, it had move down 8km. An increase in bed material size within the ninth kilometre downstream of the dam, effectively halted the process of degradation. Of particular concern in this case was the accompanying reduction in water level - 0.65m in total.

No. 44. Hoa-Binh HPP on the Da river, Vietnam, impounds $9.5 \times 10^9 m^3$, of the mean annual normal flow of $57.2 \times 10^9 m^3$. The channel substrate of thick sand strata was particularly susceptible to degradation. Immediately downstream of the dam, (0.3-0.6km) degradation was severe, with scour of 5-6m, and even 8-10m. Degradation of 4-4.5m and 2-3m at downstream sites was predicted and confirmed for up to 57km downstream.

No. 26. Woo & Yu (1994) are mainly concerned with predicting channel degradation using computer modeling. They investigated the impact of the Daecheong multipurpose dam on the Keum River, Korea. The reservoir has a storage capacity of $1.49 \times 10^9 m^3$, representing 60% of the annual inflow of $2.5 \times 10^9 m^3$. There is regular spillage from the dam. It is an alluvial stream, with a bed of fine and medium sands. Degradation was measured by assessing 2 channel surveys, 10 years apart, from pre and post dam periods. Actual change was found to have occurred below the regulatory dam, 10km downstream of the main reservoir. The study reach extended for 78km and incorporated 2 major tributary junctions.

Below the regulatory dam for a 15km stretch, degradation of 2-3m was evident. However due to the exposure of gravel and cobble substrate degradation has ceased. Downstream of that, degradation was less severe. Some of the degradation must be attributed to gravel mining which is allowed for in the modeling. In the last 20km of the study reach, aggradation of 0-1m was measured. Using the HEC-6 modeling program, the field results were matched with modeled predictions, and a good correlation was found. The model was found to be useful on a general scale, rather than on localised sites.

AMERICA

No.'s 54-74. Williams and Wolman (1984) is a major undertaking looking mostly at the primary impact of big dams in the USA. The study focused on was measuring changes in bed elevation and width of channel after river regulation. Channel changes below 21 dams in the USA were investigated, through an assessment of 287 cross sections, which have been periodically re-surveyed since dam closure. Pre- and post dam flow records were available for all the studies. Gauge height-water discharge information was available for 14 gauging stations. Pre- and post dam sediment concentration data were available for a limited number of dams. The sort of changes found here are great enough to be attributed to the impact of a dam as they greatly exceed natural fluctuations about a mean. However, due to the number of variables operating in the system and the range within each variable, as well as the variability between samples, it was not possible to characterize the post-dam conditions, but thorough assessments were made for each case.

Their study records the changes that have taken place in terms of the channel dimensions. They do not describe the actual morphological change in any detail. They consider the following aspects of change:

water discharges, sediment loads, mean bed elevation, bed material and degradation, channel width change and vegetation change. Their results showed a number of trends which are summarized be;ow.

Average annual peak discharges have been reduced by 3-91% of pre-dam values, while mean daily flows and average annual low flows have increased and decreased. Degradation of the channel bed was the most common adjustment, occurring in all 21 cases. The rate of degradation ranged from 0.1-1m/yr to as much as 7.7m/yr, with a depth range of 1-7.5m at certain points. In a reach with a gradient of 1 to 3m/km, 1m of degradation has a significant effect on the longitudinal profile. Maximum degradation was usually near the dam, and decreased in a downstream direction. Based on observations made, average rates of degradation and changes in channel width could be described by the equation:

$$(1/Y) = C_1 = C_2\,(1/t)$$

y is either bed degradation in metres or relative change in channel width
C_1 and C_2 are empirical coefficients
t is the time in years after onset of change

The accuracy of the equation would be dependent on the presence of controlling variables such as a bedrock outcrops, coarse substrate, erodible banks *etc.* which would determine the 'conformity' of change.

Variations in the length of the degraded reach ranged from 4km on the Neches river, to 120km on the Colorado below Hoover dam. Time wise, this front could continue migrating, or might have stopped already, depending on flow releases, bed material and topography. If degradation is occurring in one reach, aggradation must be happening somewhere else.

Closely linked to degradation is the nature of the substrate. Few channels are underlain by uniform sediments and in the absence of varied flows, transport becomes highly selective, moving particles of a particular size, which leaves coarser fragments behind in an armoured layer. Livesey (1965) has shown that as little as 10% coarse material while provide bed armour. Armour is only a veneer, beneath it is unsorted, unwinnowed material. There is no documented work on it , but the veneer is only likely to be disrupted by large discharges, with high competence.

The variations in bed material size after dam closure was also examined by d_{50} median grain size assessment at various times by the US Army Corps. of Engineers. Initially size increased, particularly at sites close to the dam. Over a ten year period the change stabilised and there was sometimes a reversal, possibly due to sediment input from a tributary, breakup of the armour, channel migration, or sampling inaccuracies. This effect lessens in a downstream direction because a river with a bed of mixed particle sizes will be sorted by size in a downstream direction. Kira (1972) has shown a gradual decrease in the mean diameter of bed surface materials with distance over a 5 year period on the Aya river, Japan, after impoundment. This was also the case on the Red river, below Denison Dam. On the Colorado below Hoover dam, bed material sizes were measured before closure, and the changes which occurred after the building of the dam could definitely be attributed to impoundment. In the first year, a 10km reach downstream of the dam was affected, after years the affected reach extended 20km. After 13 years, it was estimated to have an extent of 135km.

According to Williams and Wolman, erosion will continue until a combination of the following factors leads to a new, stable channel:

- local controls of bed elevation such as bedrock or armoured alluvium. Degradation should decrease with time as the bed tends towards a stable state via the armouring process, or until the channel slope becomes too flat for the bed material to be moved (reduced velocity and competence). Results showed that 50% of the degradation takes place in the first 5% of the time, and 75% of the degradation will be reached in 13% of the time.

- on encountering base level controls such as a lake, larger river, man made structures or an ocean
- a decrease in flow competence (flattening of slope due to degradation) due to an increase in channel width and reduced velocity
- an infusion of sediment from a tributary to restore the balance between arriving and departing sediment
- the growth of vegetation which binds materials

They also found tremendous changes in channel width: it narrowed, widened or stayed constant . On four rivers where the post dam channel was greatly reduced, reduced mean bed elevation occurred because only the lowest part of the channel was occupied. In the various studies, bank erosion was found to be a major source of sediment, particularly in reaches with non-cohesive banks. The location of controls and fluctuations in discharge accounted for the varying rates of erosion. Sediment change is significant – lateral erosion and degradation cease when flow no longer transports the sediments. This results from reduction in flow competence, bank resistance, tributary inflow and sediment injection, and armouring. In terms of vegetation growth , 90% of bars and benches below dams were found to have been colonised after dam closure. While this was also related to other changes, it was certainly encouraged by changes in the flow regime due to impoundment. They found that recovery distance is tremendously variable. It may be so great that the river never achieves it.

No. 49. The Colorado River has been significantly impacted in many ways since the construction of Glen Canyon dam (Lake Powell) in 1963. **Dolan, Howard and Gallenson (1974)** have investigated the impact on a 280 km study reach down to the Grand Canyon. The dam is a major sediment trap and eliminator of the flash flooding that is associated with the rivers of the southwest. High flows derived from snowmelt, peaking in May to June, with a second peak in the late summer due to flash floods are a feature of the system. Large quantities of sediment were moved in high flows and as the water receded in the summer much of the sediment was be deposited in the form of bars and terraces: a process of periodic erosion and replenishment of sediment. Under the present regulated conditions the higher terraces are no longer flooded and the lower ones are eroding. Vegetation encroachment has occurred and wind erosion is removing sediment above the lowered water line.

Changes in the flow regime have been dramatic. The pre-dam mean annual flood height was10 times the present median discharge. Floods of more than 100000 ft^3s^{-1} occurred every few years. Sediment surveys of deposits downstream in Hoover dam (Lake Mead) show that the river carries a very high suspended load. Under natural conditions, the river averaged 0.38 million tons of sediment per day. Most deposits along the channel are fine grained terraces, although pebble and cobble bars do occur locally and may underlie the finer material. Floods with low sediment concentrations resulted in erosion of these features, whereas, occasional summer peaks resulted in deposition, resulting in the fluvial terrace morphology of the system. The position of the terraces corresponds to the pre-dam mean annual flood of 80,000 ft^3s^{-1}, and the frequent 12000 ft^3s^{-1} peaks. They occur in low velocity zones and are often associated with tributary entrances where the river is constricted by fan development, causing the formation of rapids and low velocity reverse eddies above and below the falls that create a depositional environment. A line of hardwoods is associated with the higher terraces whereas the lower terraces were unsuitable for any permanent growth.

Under regulated flow conditions there has been a slight increase in median discharge and a great decrease in the number of flood peaks. Diurnal fluctuations are dramatic from 4600 ft^3s^{-1} to 20000 ft^3s^{-1}, (amounting to a fifteen foot stage difference) to meet the hydro-electric power demands. Close to the dam the median suspended sediment load has been reduced by a factor of 200, although this recovers with tributary entrances and erosion of terraces, so that within 100km downstream it is only reduced by a factor of 3,5. Erosion is due to direct water action and the process of >bank slaking= which occurs when the water is low and the groundwater seeps from the terraces. Bed coarsening prevents further erosion in many places. Lower down in the canyon, tributary flows help to restore equilibrium in terms of flow and sediment proportions. Wind erosion of the high terraces is also significant. The Tamarisk shrub has invaded many areas and algal growth has increased in the clear sediment free waters. Associated with this is a change in fauna.

No's 51 and 52. Turner and Karpiscak (1980) have made the link between geomorphological changes on the Colorado river and riparian vegetation change, since the closure of Glen Canyon dam. A summary of the primary impacts is as follows: average annual maximum flows reduced from 2486 m^3s^{-1} to 803m^3s^{-1}; median discharge increased from 210 m^3s^{-1}, average diurnal fluctuation changed from a few centimetres to several metres, median sediment concentration was reduced from 1500 to 7 parts per million. Over a period of 17 years since the dams completion in 1963, various significant geomorphological and associated ecological changes have occurred and will continue to happen. The study concentrates on the stretch that traverses the Grand Canyon.

Prior to dam construction, the confined nature of the channel prevented the development of a floodplain and associated riparian community. The river banks were periodically stripped of plant colonizers. The rivers gradient is under the dominant control of the tributary fans. Since 1963 floods have been dramatically reduced and the flow regime has become much more stable. The co-efficient of variation at Lees Ferry, 26km below the dam has changed from 0.19 (for the 42 year pre-dam period) to 0.06 (for the 13 year post-dam period). The entry of the unregulated Little Colorado River 140km downstream reduces this difference and the pre-and post dam CV=s there are 0.2 and 0.17 respectively. Reduced flooding has provided stability in a previously highly unstable habitat.

In the post dam period, typical daily stage fluctuations are of more than 1.5m and seldom less than 0.3m. A weekly Sunday drop is common as power demands are low then as they are on public holidays. The range of annual flows has reduced greatly: from a low of 5200 hm^3/yr in 1934 and a high of 24500 hm^3/yr in 1929, the post dam range was 2000 hm^3/yr in 1962 to a high of 14500 hm^3/yr in 1965. The general range is 9900-12300 hm^3/yr per calender year. Maximum monthly discharges generally occurred in June as a result of spring snow melt while in the post dam period, the greatest discharges are released in May in response to irrigation and power demands. In the pre-dam period, the maximum mean monthly discharge of 4300 hm^3 was more than 10 times greater then the lowest monthly mean discharge. The post dam maximum/minimum ratio is only 1.8 to 1. The seasonal variability has been removed.

Alluvial deposits are a major feature of this arid river system. The sediment regime has been dramatically altered by the impoundment. A major proportion of the sediment is trapped in Lake Powell and clear water releases have a large transport capacity. However reduced flood peaks do not have the capacity to rework coarse sediment tributary deposits. Essentially there have been four impacts: accelerated erosion downstream of the dam site, followed by armouring of the substrate by coarse material, stabilization of sand bars by vegetation, erosion of talus slopes, benches and bars. This degradation front is likely to move downstream.

No. 50, Kearsley, Schmidt and Warren's (1994) study is very much an applied paper, looking at the effect of Glen Canyon Dam on Colorado River deposits used as campsites in Grand Canyon National Park. The sand bars are characteristic of the pre-dam river morphology and are being eroded under regulated flow conditions. Campsite capacity has been reduced by 44%. While this was not a direct geomorphological approach as it was done via the assessment of available sandy areas for campsites and the change in that availability at different flow levels, it serves as a useful example of the practical implications of geomorphological change due ti river regulation. Campsites changed in terms of erosion of sand, substrate change or invasion by vegetation.

The closure of Glen Canyon dam reduced the annual sediment load of the river below the dam from $6x10^{10}$kg to 8.3×10^{7}kg. The magnitude and frequency of flooding has changed dramatically: the post dam annual peak discharge is controlled by the maximum capacity of the hydroelectric power plant at 940 m^3s^{-1} compared to the natural annual flood of 2180 m^3s^{-1}. Only occasionally is this flow exceeded. While high flows in 1983 served to increase bar size in some areas, they eroded them in other critical reaches. Sediment may accumulate in low flow years, but so does vegetation rendering many sites unusable. A comparison of sites for 1973, 1983 and 1991 was possible, using aerial photograph records. Results showed a 34% increase in sites from 1973 to 1983, but a 48% decrease from 1983 to 1991, giving a net decrease of 32%. 44% of the large campsites were lost to erosion and/or vegetation growth. In the >critical= reaches (ie: high demand zones), there was a loss of campsites during both periods.

No. 53. One of the problems associated with regulation in this arid system is related to the rapids: they have become permanent in the absence of destabilizing flows and are causing navigational problems. This particular problem has been investigated by **Graf (1980)** on the Green River, a tributary of the Colorado above Lake Powell. Since the closure of Flaming Gorge Dam in 1962, the maximum release of 170 m^3s^{-1}, has not come close to the 100 year flood of 510 m^3s^{-1}. While the benefits to development have been many, the impact on the river channel has not easily been quantified. One of the obvious effects has been the increase in the occurrence of rapids in the system, due to the reduced water levels/flows which is felt particularly by the many recreational users of the river. Along a 69km stretch of river, there are 55 rapids formed by tributary flash floods, landslides or prehistoric floods on the main stream. A rapid is defined as an accumulation of boulders in the channel where the particles are numerous enough or large enough to break the water surface at mean annual discharges. Conventional sediment movement equations were developed for much smaller sediment sizes, so the author used a hydraulic empirical technique. By calculating the particle resistance based on friction and buoyancy, the downstream force of flowing water against the particle and the ratio of force to resistance as a measure of stability, it was possible to estimate broadly the stability of the largest boulder in each rapid. By establishing the stability of the rapid as a whole by looking at the largest particle it could be assumed that if the force of the water was below the threshold for movement of the largest particle, the feature would be stable. This method can be used to determine what effect a reduction in flood flows will have on the stability of the system.

The overall results can be summarized as follows: 290 miles downstream of the reservoir, the effect of the dam is still significant although the contributing area is 2.7 times that of the regulated catchment.

No's 38 and 39. Hadley, & Eschner (1982) describe the changes which have occurred in the the Platte river system, as a result of extensive regulation. The system has a large catchment area of 223000km^2. Water developments and extensive landuse change have been a feature of the basin since European settlement in the 1860's. The North Platte River has been extensively dammed and has therefore been significantly affected, while the South Platte river is less developed. Most of the rivers flow is derived from snow melt, and a small proportion from rainfall, which ranges from 330 -635mm/annum. Written historic observations on the nature of the river in the early nineteenth century provide a valuable impression of its pre-settlement condition: it was a wide (2km), shallow (0.3-1.8m) river, characterized by annual bankfull spring floods and low summer flows. It was shallow enough to cross in most reaches except during spring floods. It was common for the river to stop flowing in the dry season. The bed material is described as being mostly gravel and sand, (although there are also descriptions of more silty conditions.) whereas today much siltier conditions persist. A current hydrograph of the system shows a reduction in the occurrence of short duration flows and an increase in the magnitude of long duration flows. The flow has become less variable and the baseflow contribution has increased. The impact of the changed flow regime on channel morphology is confirmed by survey comparisons at different dates. By 1951, at Cozad for example, the width had been reduced from 1161m to 204m. This had halved again by 1979. Using maps and aerial photos, it has been possible to measure the considerable reduction in width, which has taken place as a result of in channel bar growth and stabilization.. The 'old channel' was broad and open, with few large islands, whereas by 1938, bank/bar formations stabilised by vegetation, had constricted the channel. In time the number of islands diminished, but their size increased as the secondary channels were abandoned, filled in and vegetated. Low flows and a reduction in floods created favorable conditions for vegetation establishment on previously temporary features. The river has been transformed from a multiple thalweg to a single thalweg stream.

CANADA

In Canada in the late fifties, power producers began to look northwards, beyond the developed regions, to the sparsely populated northern areas, in search of new dam sites for hydro electric power supply . **No. 48, Kellerhals and Gill (1973)** working on the impact of impoundment on some of these northern rivers in Canada, have identified significant impacts at tributary junctions. The Peace River had a highly variable natural flow regime: flows ranged from annual peaks of 3500-9000m^3s^{-1} to lows of 150-250m^3s^{-1}. Regulated releases from Bennett dam have reduced this range to between 2000 and 500m^3s^{-1}. This river channel was maintained by the 1.5 yr flood, but with this removed the new flow is simply being accommodated in the old channel, which is entrenched in stable, resistant bedrock and gravels. In some reaches, deep scour holes on channel bends are filling in, while gravel bars which are exposed above the new high water mark, are aggrading and becoming stabilised by vegetation (balsam, poplar and willows). The sediment load of the river is generally low with little sediment storage, but under flood conditions it carries a small but significant suspended load. After four years, the most significant changes have occurred at tributary junctions, where the unregulated tributaries have built deltas into the main channel, causing distinct breaks in its longitudinal profile. The regime of the main river would normally be in phase with its tributaries but river regulation upsets this condition, so that tributaries may flood when the stage at the junction is considerably lower than under natural conditions. This causes the tributaries to erode their beds to meet the new level of the main stream. A tributary entering the Peace River has eroded its own bed to such an extent that it has exposed foundations of two bridges crossing the tributary.

No. 23, Bray, and Kellerhals (1979) give some more information about the impact of WAC Bennett dam, a few years after Kelerhals and Gill's (1973) study. 1800km downstream of the dam, spring peak flow (about 9000 m^3s^{-1}) reduction by 3000 - 6000 m^3s^{-1} has resulted in a stage reduction of 2-4m. Flow regulation reduces summer peak water levels by 0.6m for a stretch of 80 km at the delta, 1200km downstream, which is highly significant on this flat land. Winter flows immediately downstream of the dam increased by a factor of 10, (dam releases are 1500-2500m^3s^{-1}) and by a factor of 5 to 8 at Athabasca lake. At the lake there have been problems with ice-jams associated with the high winter flows, causing uncharacteristic flooding and associated silt deposition. They also note the growth of deltaic tributary deposits in the main channel. Where the tributaries have a steep gradient with coarse gravel bedload and a high transport capacity and are relatively close to the dam, this phenomenon is apparent. For example, 35km downstream, at Farrell Creek, a bridge 300m upstream from the confluence on the tributary has become unstable due to exposed foundations. Further down, the eroded material forms a large delta in the main channel.

No. 37, Buma and Day's (1977) work on of the impact of Deer Creek Reservoir (30ha), Deer Creek, southwestern Ontario is a very detailed study, only possible in such a small system (catchment area approximately $10km^2$). The climate is mild with an average temperature of 8° C; rainfall is high with an average 940mm per annum and evapo-transpiration rates of 530mm. The river flows through an alluvial floodplain of sand and silt. Channel downcutting due to sustained clear water releases was the major impact below the dam. Detailed examination of nine sites over a period of five years, within 3km of the dam wall, failed to produce any general trends. A summary of the site results are presented in the table below.

***Table B:** Summary of Buma and Day's 1987 study.*

	D/S	DESC.	BANK	BED	THALWEG	X_SECTION
1	63 m	straight, stable bed, meandering thalweg	r/b eroded by 0.458-0.610m		moved from L to R and partially back	increase in x-sectional area
2	127 m	at a tributary junction	r/b eroded 0.214m, l/b aggraded 0.153m	bottom level reduced by 0.153	minor movement	no change in x-sectional area
3	254 m	straight	r/b eroded by 0.61m; l/b aggraded slightly.	channel bottom degraded	deepened by 0.122m	small increase in x- section.
4	256 m		minor change	bar adjacent to left bank bottom, in 1971 and 1975		little change
5	317 m	in a meander	r/b eroded 0.458m; equal aggradation on l/b	rapid downcutting 0.305-0.458m of material removed	shifted laterally by 0.915m	x-sectional area increased
6	1.3 34k m	straight reach	r/b eroded; l/b aggraded	downcutting up to 0.458m	migrated from left to right bank - 1.312m	Increased x-sectional area.
7	1.6 51k m	in a meander	minor r/b aggradation 1971-1974; substantial erosion,1975; l/b showed a tendency to erode - up to 0.61m	large bottom shape variations	fluctuation over 0.122m vertically, and 0.610m horizontally from left to right	overall increase in x-sectional area
8	2.0 32k m	straight reach cut into floodplain	degradation of up to 0.61m in some places on r/b; with the l/b aggrading by	steady rise of up to 0.244m	thalweg shifted from left to right about 0.305m	Cross sectional area maintained. Overall channel

			0.214m			shifting in a westerly direction.
9	2.2 22k m	close to confluence with Big Creek,	l/b eroded 0.6m; r/b 0.458m.	Bed rose 0.763m in 71-72;rose in 75 by 0.305m	shifted back and forth laterally 1.83m	slight increase in cross sectional area

In Canadian papers there seems to be a strong concern for lowering of the groundwater table on floodplains in impacted systems, because of it=s impact on vegetation succession, related to the presence of permafrost/climatic concerns which as outlined by Gill, 1973 is complex.

AFRICA

No. 38, Kinaway, *et al* (1973) give a comprehensive overview of the impact of the High Aswan dam on the sediment balance in the Nile. River flow in the Nile is completely regulated by the High Aswan dam. The dam has a total capacity of 164 km^3 (30 km^3 for silt, 90 km^3 for live storage and 44 km^3 for flood control). Only when the reservoir is at full capacity does excess flow overflow naturally. The Nile used to transport 80% of the total sediment load of some 125 million tons in the flood season, from July to October. The suspended load becomes negligible when the discharge drops below 200 million m^3/day. Estimates were made that the silt deposited on the floodplain so vital to agriculture, equaled only 12% of the total load of which, the essential nutritive azote factor amounted to only 0.13%. This was to be compensated for with calcium nitrate fertilizer. Immediately below the HAD (7km), degradation has been checked to a certain extent by the old Aswan Dam. The river channel is mainly a single thread, 500-600m wide on average, but sometimes divides into two or three branches where it is up to 1.5km wide. Depth at high water is up to 20m in pools, and 5-6m over bars, or 1-1.5m at low levels. Since 1964, there has been a reduction in water levels due to bed degradation. Initially the rate of degradation was rapid, but gradually reduced as the channel became armoured.

No. 39, Shalaby (1986) gives a more up to date summary of the impacts of the HAD, with an assessment of the change in flows and sediment regime. Before the construction of the HAD, discharges passing Aswan were highly variable. The flows which ranged from 720 -13000 m^3s^{-1}, now have a range of 930-2600m^3s^{-1}. Total annual flow to the Mediterranean which used to average 40km^3yr^{-1}, are reduced to 2-3km^3yr^{-1}. Degradation has been a major impact ranging from 1-10m at various points, with average bed level drops of 0.25 to 0.7m, over a distance of 540km. The subsequent water level drop ranges from 0-1m depending on the discharge.

No. 9, Hammad's (1972) study is an investigation of the sediment relationships after the closure of the dam. The dam traps the rivers whole sediment load. Recovery below the dam is no where near the original value amounting to only 5% of pre-dam values. Degradation begins with the movement of fine particles, leaving a plane bed of coarser material or a rippled bed of coarser materials, which tends to happen at the end of a degrading sequence. Coarsening of bed material increases roughness and reduces flow velocities further. Suspended flood material consists of fine sand (30), silt (40%), clay (30%). Bed material is largely coarse sand. . This is due to coarsening of the bed downstream

No.76. According to **Davies (1996)** in the Zambezi valley, downstream of Cahora Bassa the natural flow regime of the river has been substantially altered. The greatest impact has been on the floods which are vital to the maintenance of the floodplain. The channel is changing from a braided stream where islands are temporary, to an anastomosing, or single thread channel, with large islands which are aggrading and stabilising and being inhabited and utilised by the local population.

AUSTRALIA

Walker (1979) and **Jacobs (1994)** have assessed the impact of water resource developments on the Murray-Darling system in Australia. Being the biggest system in the country its correct management is of importance to the whole country. The Murray (the principal stream), flows through well watered mountainous terrain for 350km, the remaining 2200km flows through semi-arid desert. It is difficult to generalize about the hydrological behaviour of this river because the flows are so variable. (Walker, 1985) The system is regulated by a variety of structures: in total there are 4 major reservoirs, 16 weirs, and 5 barrages. This intensive regulation has been a response to the tremendous variability of the system (Walker, 1979). With the exception of Menindee Lake on the Lower Darling, 2 weirs on the lower Murrumbidgee river, and the largest and newest Reservoir - Dartmouth Dam on the Mitta Mitta River, all the other structures are on the Murray River. Although much of the system is unregulated due to a lack of suitable reservoir sites and shortage of finance, flow is estimated to have been reduced to a third of its natural volume by the time it reaches the rivers mouth. This is attributed mainly to increased irrigation demands in the last 30 years (Jacobs, 1994).

According to both authors, the main influences of impoundments have been: a change in the seasonal distribution of flows due to irrigation requirements where winter flow is reduced by storage, and summer flow increased as water is released for irrigation. Flow regulation has been used to ameliorate the impact of floods, and there has been a trend towards the reduction of average flows in the middle of the river. Severe bank erosion has been experienced in some areas (for example, below lake Hume) because of the sediment free releases.

Jacobs (1994), describes the processes which operate below two of the reservoirs . Dartmouth Dam (no. 34), the largest in the system on the Mitta Mitta river has capacity of $3906 \times 10^6 m^3$ and stores water for irrigation. Releases of $115m^3 s^{-1}$ are designed to correspond with the channel capacity below the dam, while a minimum release of $2.3m^3 s^{-1}$ ensures that the river is never dry. During the construction phase, the downstream river bed became silted up and algaefied, with an associated bio-diversity reduction, for up to 50km below the dam. It has been flushed out subsequently by irrigation releases and at one site only 10% of the bed is now composed of sand/silt. Algal growth is still a problem due to the intensive agricultural production in the valley. As is particularly common with irrigation type releases bank erosion downstream has occurred, which has been counteracted by anti-erosion measures. The nature of irrigation demands has resulted in a reversal of flows: the winter flow is stored and released in the dry summer period when irrigation demands are greatest. The first major tributary enters the system 25km below the dam.

Downstream of Hume Reservoir (no. 35) for a distance of 80km to Yarrawonga weir the channel is still adjusting to the changed flow regime, 52 years after the reservoir was built, and 32 years after it was enlarged. Lake Hume is situated where the Murray emerges from the mountains onto the plains and is not ideally suited to the delivery of irrigation flows, because the alluvial channel is easily eroded. Bank erosion is high due to maintained irrigation releases. The mainstream river and its anabranches are widening, with the bed deepening in the upstream section, and becoming shallower downstream. More anabranches are developing as fallen trees (due to undermining of banks) divert the flow and capture part of the remaining stream flow. Expensive erosion controls and >desnagging= measures have been instituted too rectify some of the problems caused by bank collapse, with associated debris jams. The systems wetlands have also been degraded. *The process of anabranching is typical of a river which has* *reduced its flow velocity and is therefore depositing its load to form a braided, anabranching channel.*

A detailed investigation carried out by **Sherrard and Erskine (1991)** investigates the impact of Mangrove Creek Dam on Mangrove Creek (no 31). The stream has a catchment area of $420km^2$, while the the dam has a catchment area of $100km^2$. Most of the catchment is still under natural vegetation. Average annual rainfall at the dam is 1200mm and annual evaporation 2400mm. The study reach which extended for 16km below the dam, consisted of a sand bed stream, laterally confined by bedrock valley sides. This was further divided into three reaches, according to morphological characteristics: the upper reach (dam to Warre Warren Creek), characterized by a low bankfull sinuosity with a meandering thalweg and a narrow, constant width, sand bed channel; the middle reach (Warre Warren to Dubbo Creek), a wider more active sand bed, with a higher sinuosity and channel expansion at bends; the lower reach (Dubbo Creek to Mangrove Mountain station), a constant width sand bed channel, narrower, deeper and straighter than upstream.

Readings taken at the gauge below the dam are a reflection of the size of the unimpounded catchment which at this point is only $4km^2$. Discharge had been reduced by 70%. At the end of the study reach, (Mangrove Mountain gauging station) the effect is not as drastic as the proportion of unregulated catchment has increased. Flows of more than 10% duration have been reduced by 50%, while more frequent flows have been reduced by 29 - 36%. Overall the change in flood frequency curves has been significant. At both stations the upper limb of the bi-linear flood frequency curve has been eliminated, thereby restricting floods to the lower limb with a recurrence interval of less than a year. The resultant reduction of channel capacity is supported by a study by Pickup and Warner (1976) conducted in a neighboring creek, which found that the larger events are responsible for determining channel capacity, but the smaller more frequent events carry most of the bedload and therefore control the channel form. The largest flood (peak instantaneous discharge of 34 800 Mld^{-1}) recorded at the dam station has been reduced by an order of magnitude to1710Mld^{-1}, with a recurrence interval of only 1.08 years. Overall there has been a reduction in larger floods of 80% and further down at Mangrove Mountain, larger floods have been reduced by 54-66%. There the largest flood recorded after impoundment, had a recurrence interval of only 1.2 years on the pre-dam flood frequency curve.

With such substantial changes in the hydrologic regime of the river, significant second order impacts were clearly recognizable. The most severely impacted section was a 1km stretch below the spillway, where a new complex morphology with alternating reaches of aggradation and degradation developed. Aggradation was caused by a concrete causeway and by sediment wedges deposited by incoming tributaries. Cross sections show that a very narrow channel with a capacity of 205 Mld^{-1} had developed. Aggradation on the unincised portion of the pre dam channel caused the development of a 0.4m high bench, which became well vegetated For one kilometre downstream of the dam, channel width contracted by 50% and mean depth increased by 53%, while mean velocity decreased by 8%. At Mangrove Mountain, bankfull width had been reduced by 7-15% due to oblique accretion. Mean depth and bed elevation were unchanged, which could be attributed to the different channel type and the smaller reduction in flows and sediment loads. In the middle and upper reaches the reduction in channel width was significant, particularly where the channel was not confined by bedrock. Second order impacts included stabilization by vegetation of bars and bank attachment of mid channel bars. Trenches were dug to determine the composition of the bars and a distinct break was identified between the coarse basal sand and overlying finer bench sediment which corresponded to the dam closure time. According to Erskine(1986a) bench construction of this sort marks a phase of channel recovery by contraction. This discovery was confirmed by a comparison of pre and post impoundment aerial photos of the channel, which verified extensive bar development since impoundment. The entrance of Warre Warren Creek , halfway along the study reach, with a catchment area of $50km^2$ provides a significant sediment input where it enters Mangrove Creek which at this point only has an effective catchment of $39km^2$.

Erskine (1985) studied the the Hunter River, New South Wales, Australia, which was dammed for water conservation and flood mitigation by Glenbawn reservoir (no. 32) with a capacity of $228 \times 10^6 m^3$, and a 1214ha surface area. It has a sediment trap efficiency of 99%. There has been no overflow since completion in 1958 and all releases have been artificially controlled. Reduced runoff since 1959 amounts to the volume lost to evaporation. Flow records below the dam show a truncation of high flows ($>8 \times 10^6 m^3 d^{-1}$); reduced frequency of intermediate flows ($>7 \times 10^5 m^3 d^{-1}$) and an increased frequency of low flows. Seasonally, there has been a decrease in the frequency of all discharges, the other eight months reflect the pattern described above. The biggest flood ($7.83 \times 10^6 m^3 d^{-1}$) recorded since 1959 has only been marginally bigger than the maximum capacity of the dam valves. This equates with the pre dam flood with a probability of accedence of 87%. Concrete bars and bedrock immediately below the dam have limited scour, while the stable nature of the channel banks, vegetated by willows whose roots form a dense mat on the bank foot have only allowed minor changes in bankfull width, cross sectional area, and mean depth of less than 10%. This can be described as >accommodation adjustment,= (Petts, 1984). Site four just below the entrance of Rouchel Brook is an exception, where there has been 45% contraction, and 69% deepening, as well as lateral migration onto the floodplain with reworking of sediment.

Bed material size change has been most marked at site four where there has been a progressive coarsening of bed material. This would be the influence of an unregulated tributary introducing coarse sediment which the mainstream is incapable of moving. The armouring on the bed was investigated by sampling the surface and sub-surface layers and by determining the mobility of the bed material at various flows. There was little sediment finer than 8mm in the surface sample, but 22-38% of the sub-surface sample was finer than 8mm. The presence of algal growth on the coarse fraction suggested that the sediment had not been moved in a while. The regulated water releases were not competent to move coarse sediment, but were able to winnow out fines. This is a typical impact of a flood retention reservoir where high flows are eliminated. Associated with the absence of >flushing flows,= has been the encroachment of willows onto bars and bank feet, which have had to be cleared manually to maintain the conveyance capacity of the channel.

No. 33, Benn and Erskine (1994) have investigated the complex response of the Cudgegong River, to the construction of Windamere dam in 1984. It is a large capacity storage dam, with a full supply level storage capacity of $368 \times 10^9 l$, regulating a catchment area of $1070 km^2$. It meets irrigation demands for a 120km stretch downstream and provides water for the townships of Mudgee and Gulgong. The dam has spilled only once since construction for a three month period in 1990. It has a sediment trap efficiency of 95% plus. The channel is confined by bedrock which prevents meandering and forms a pool -riffle gravel-bed stream with occasional bedrock outcrops in the bed and banks.

The first Order impacts to the system are significant. Flow duration curves indicate a truncation of high flows greater than $3 \times 10^9 l\ d^{-1}$ and an increase in duration of lowest flows with discharges less than $30 \times 10^9 l\ d^{-1}$. The 10% duration flow has been reduced from $260 \times 10^9 l\ d^{-1}$ to $130 \times 10^9 l\ d^{-1}$. The 80% duration flow before the dam was built was $6 \times 10^9 l\ d^{-1}$, after 1984 that flow is estimated at $21 \times 10^9 l\ d^{-1}$. As would be expected with an irrigation dam the large and moderate flows are reduced and baseflow increased.

Despite the significant change in flow regime, channel pattern change has not occurred due to lateral confinement by bedrock valley sides. Channel cross sectional change has been monitored at 6 sites, 1.6km apart, as well at the 2 gauging stations, with the following results:

- 6 sites exhibited < 5% width contraction,
- 2 sites exhibited > 15% width contraction

- cross sectional area of the channel decreased by more than 10% at 6 out of 8 sites, mostly by width contraction (5 sites)
- width contracted at 2 sites
- 5 sites degraded by 13 - 31%.
- 2 sites showed aggradation of 5 -18%

This range of responses has been termed complex by Petts (1984) and overall the morphological change can be described as accommodation adjustment, because there has been no major morphological alteration.

Bed material samples at nine sites show the dominant response in this system to be aggradation and a decrease in bed material size due to incompetence of flows. Two sites show substrate coarsening: this is associated with unregulated tributary sediment input, tributary bar development and channel constriction, which would cause higher velocities capable of moving the finer fraction of sediment through those reaches. This was confirmed with bed material mobility estimations. Using Neill's (1968) criterion, cited in Benn and Erskine, 1994, the competence of the maximum regulated flow was determined as 2.3×10^{n} l d^{-1} and it was found that regulated flows do not exceed the threshold of motion at any of the other cross sections. Competence is so low that armouring has not even occurred.

Four new tributary bars were identified as having developed since closure of the dam. Floods in the tributaries in 1986 and 1990 generated sediment loads which were deposited in the mainstream and became permanent in the absence of sufficient mainstream flow to destabilise them. Vegetation has further stabilised these features. Bench development is shown at three of the sites since dam closure, the most extensive one occurring at site five, where an armoured gravel bar formed the nucleus for the deposition of finer sediment, which regulated flows did not have the capacity to move. The bench is 0.3m high and 12m wide and has been invaded by a dense stand of *Casuarina*. This is a means of channel contraction which allows the channel to adjust to post dam flows. According to Erksine and Benn, the response here is from a flood dominated to a drought dominated regime and is identical to that proposed by Erskine and Warner (1988) in response a rainfall regime change. The regulated system is comparable to a natural regime change.

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