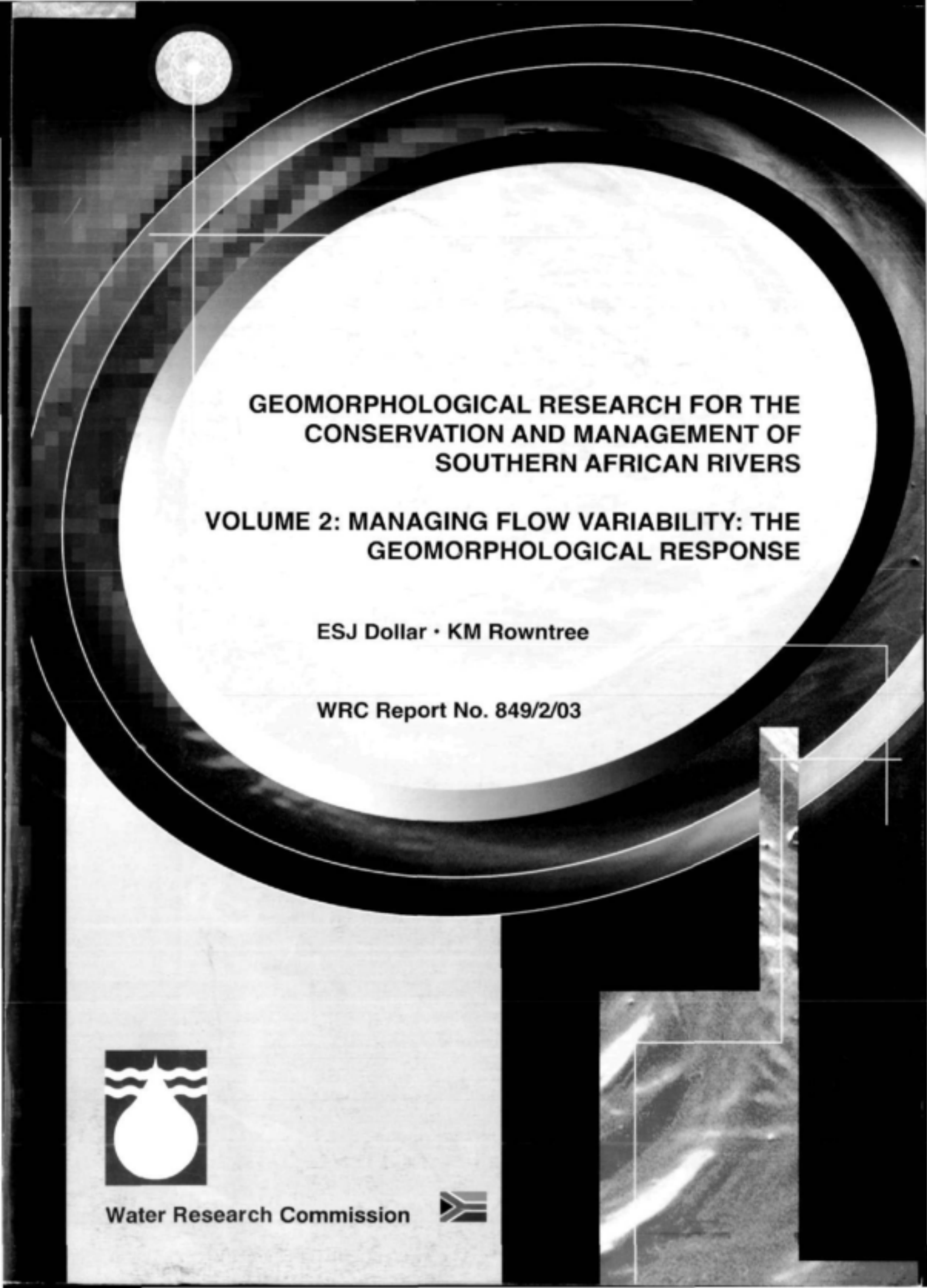

GEOMORPHOLOGICAL RESEARCH FOR THE CONSERVATION AND MANAGEMENT OF SOUTHERN AFRICAN RIVERS

VOLUME 2: MANAGING FLOW VARIABILITY: THE GEOMORPHOLOGICAL RESPONSE

ESJ Dollar · KM Rowntree

WRC Report No. 849/2/03

Water Research Commission

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VOLUME 2: MANAGING FLOW VARIABILITY: THE GEOMORPHOLOGICAL RESPONSE

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.

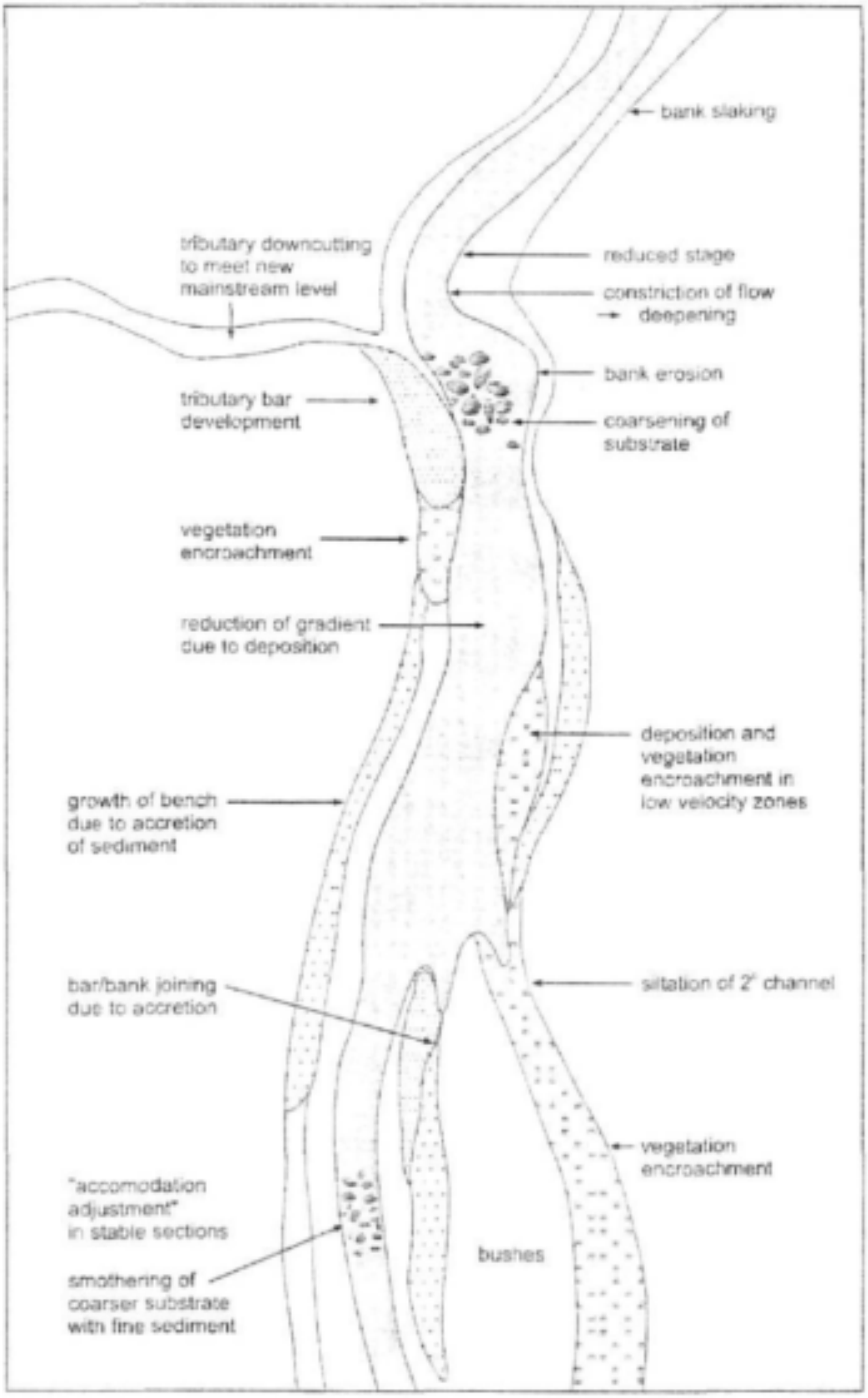

Figure 2.6: *Illustration of morphological change in an impounded river.*

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

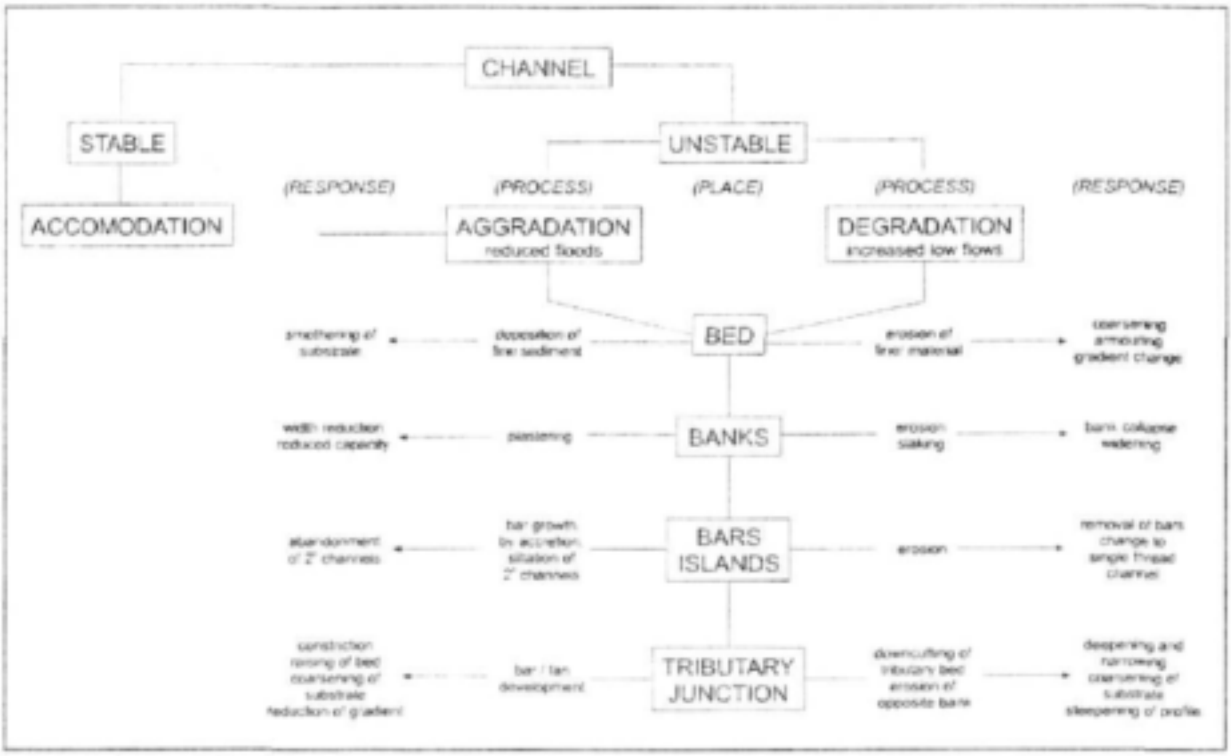

Figure 2.8: Flow diagram for predicting morphological change.

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).

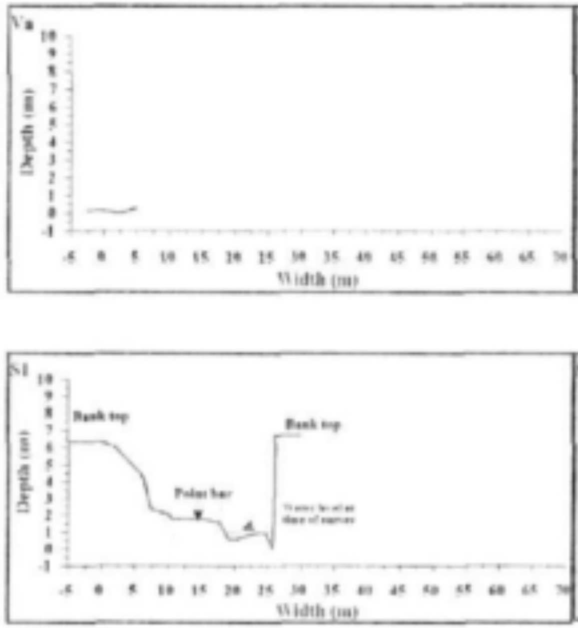

Figure 6.6: *Comparison of two cross-sectional profiles for the upper reaches of the Volkers (Va) and Skoenmakers River (S1) immediately below the point of inflow of the IBT.*

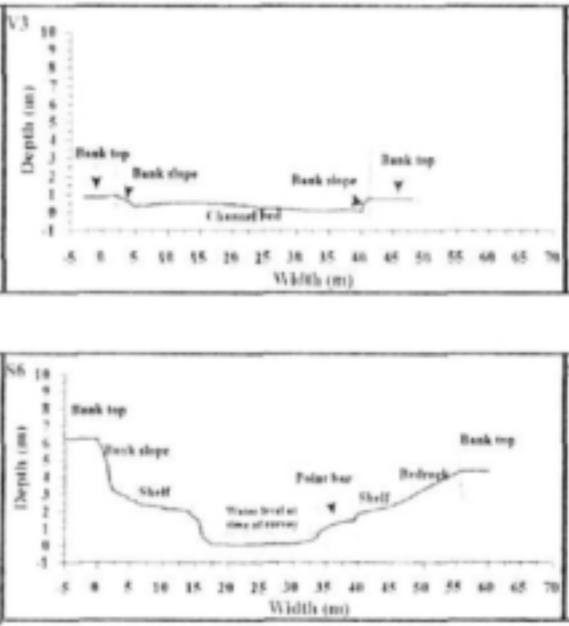

Figure 6.7: *Comparison of two cross-sectional profiles for the middle reaches of the Volkers (V3) and Skoenmakers (S6) approximately 25 km below the point of inflow of the IBT*

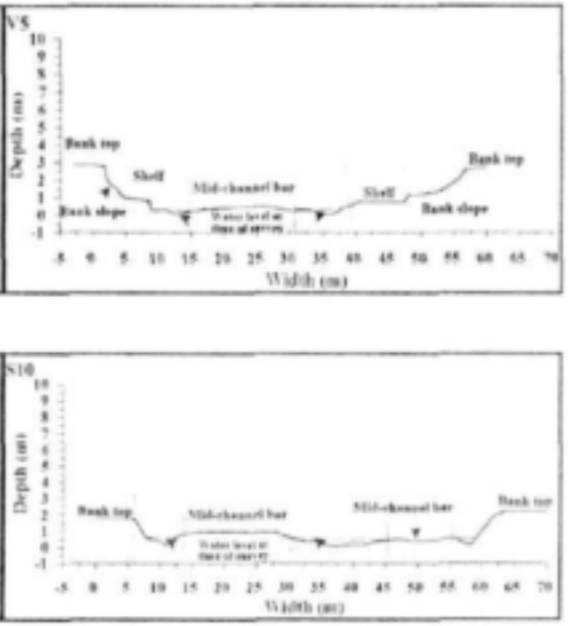

Figure 6.8: *Comparison of two cross-sectional profiles for the lower reaches of the Volkers (V5) and Skoenmakers (S10) approximately 40 km downstream for both rivers*

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.

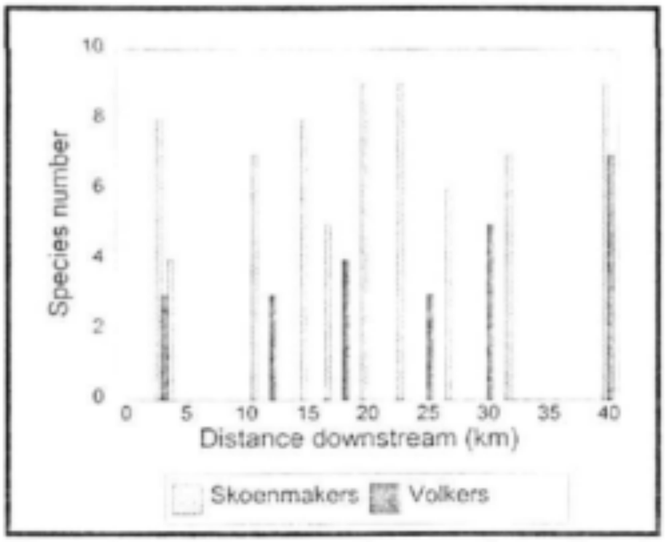

Figure 6.10: *Downstream change in the number of riparian vegetation species for the Volkers River and Skoenmakers River.*

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

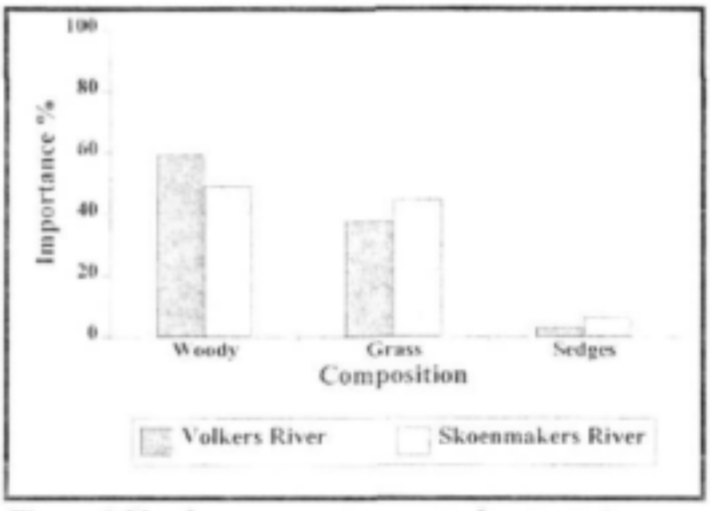

Figure 6.11: *Importance percentage for vegetation types in the Skoenmakers river.*

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.

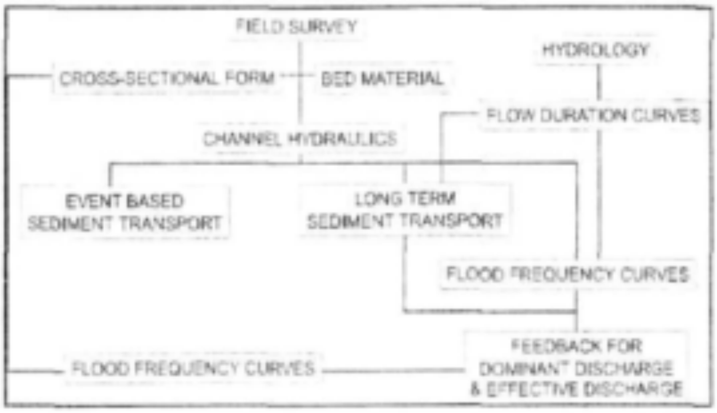

Figure 5.9: *Flow diagram indicating the structure of the research.*

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?

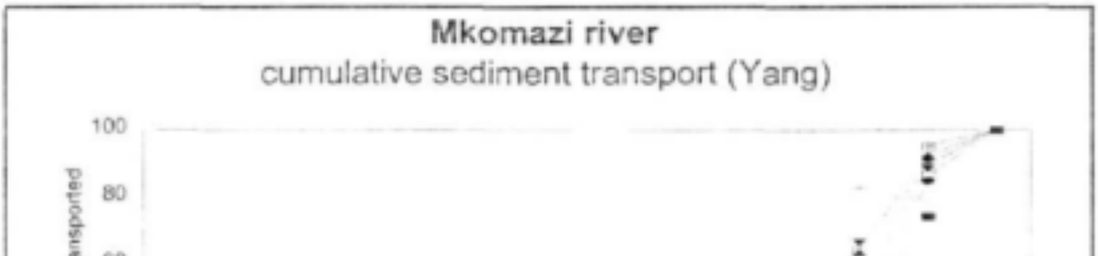

Figure 9.4: *Cumulative sediment transport for the Yang equation for all sites for the Mkomazi River.*

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 THE ASSESSMENT 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.

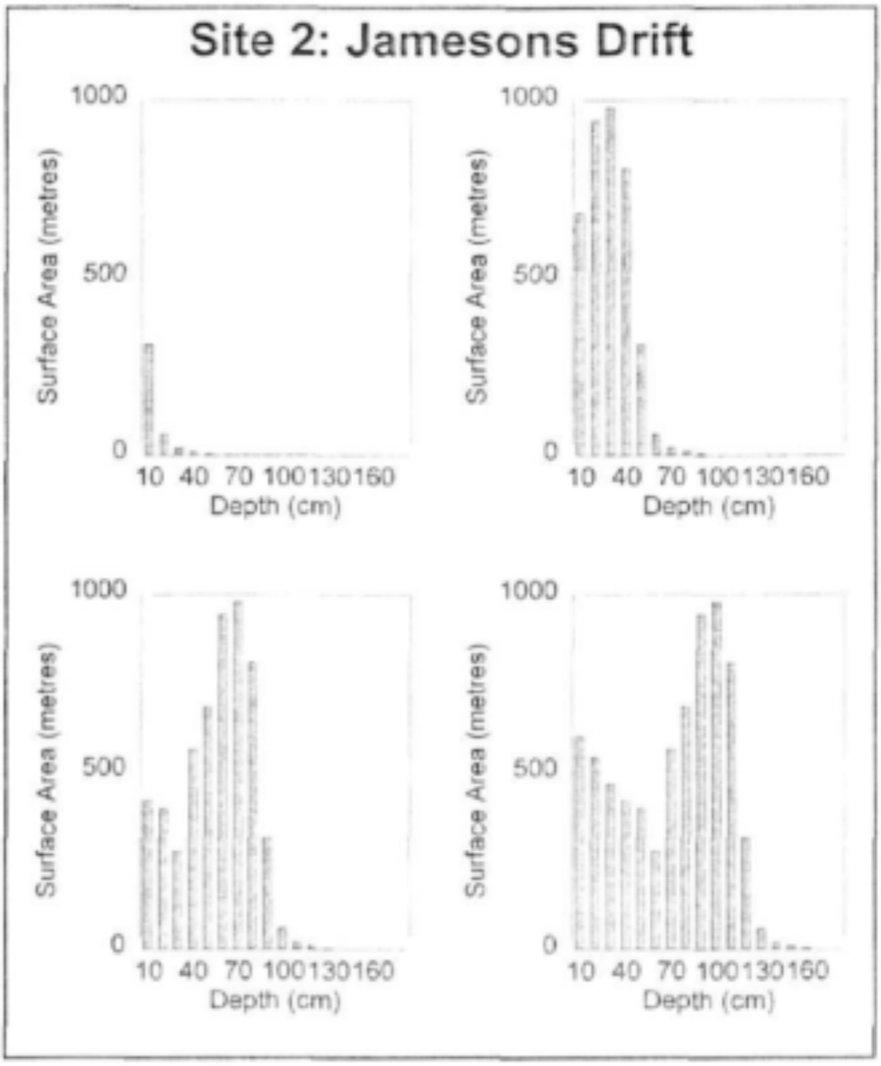

Figure 11.14: *Change in surface area for different depths as discharge increases, Site 2, Jamesons Drift, Tugela River, for discharges of 3,10,40 and 70* $m^3 s^{-1}$.

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.

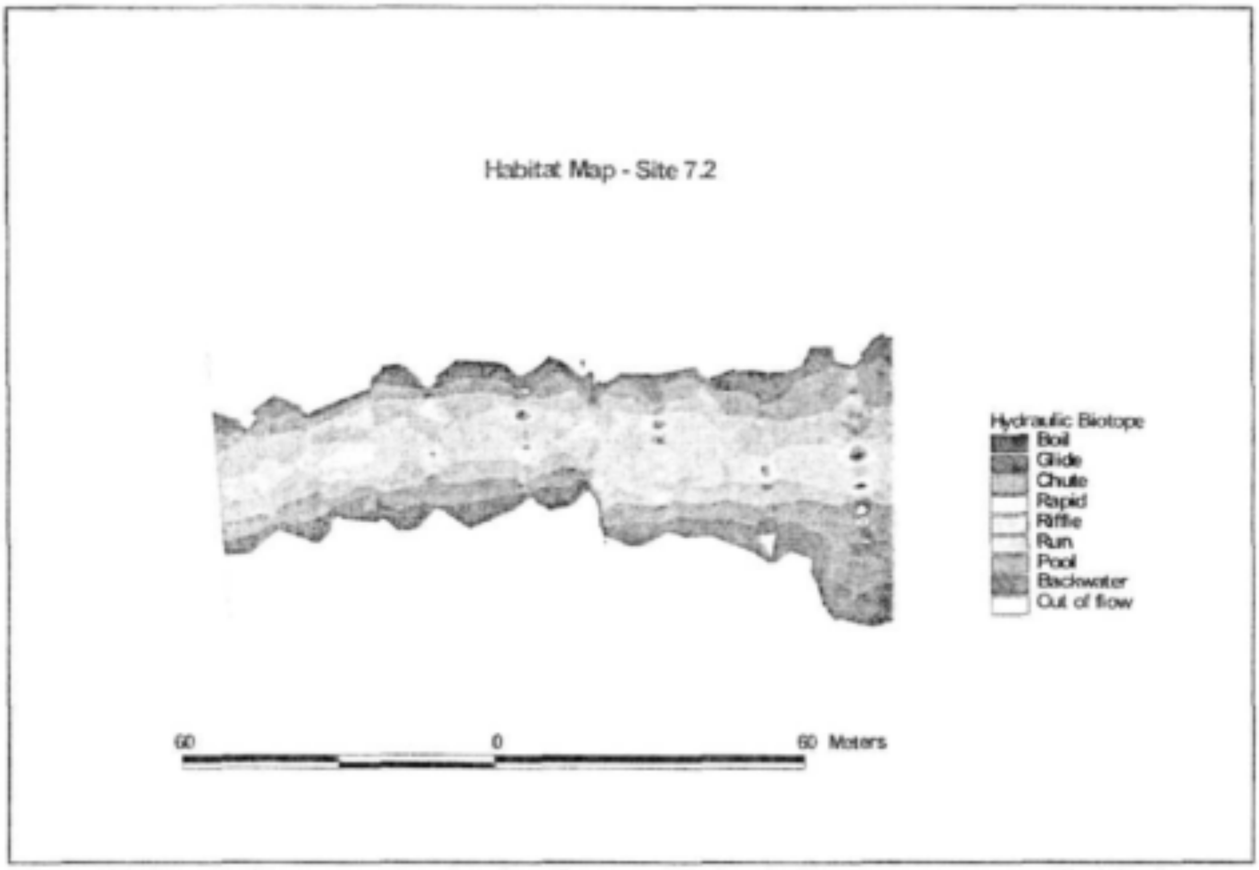

Figure 11.16: *Habitat maps showing distribution of hydraulic biotopes at one specified discharge*

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
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Dr J Boelhouwers	University of the Western Cape
Prof J O'Keeffe	University of Rhodes

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The support of Rhodes University is acknowledged. In addition to employing the project leader, the University provided office and laboratory facilities as well as administrative support. The Geography Department is to be thanked for hosting the project and supporting the research team in many ways.

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 focused 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.

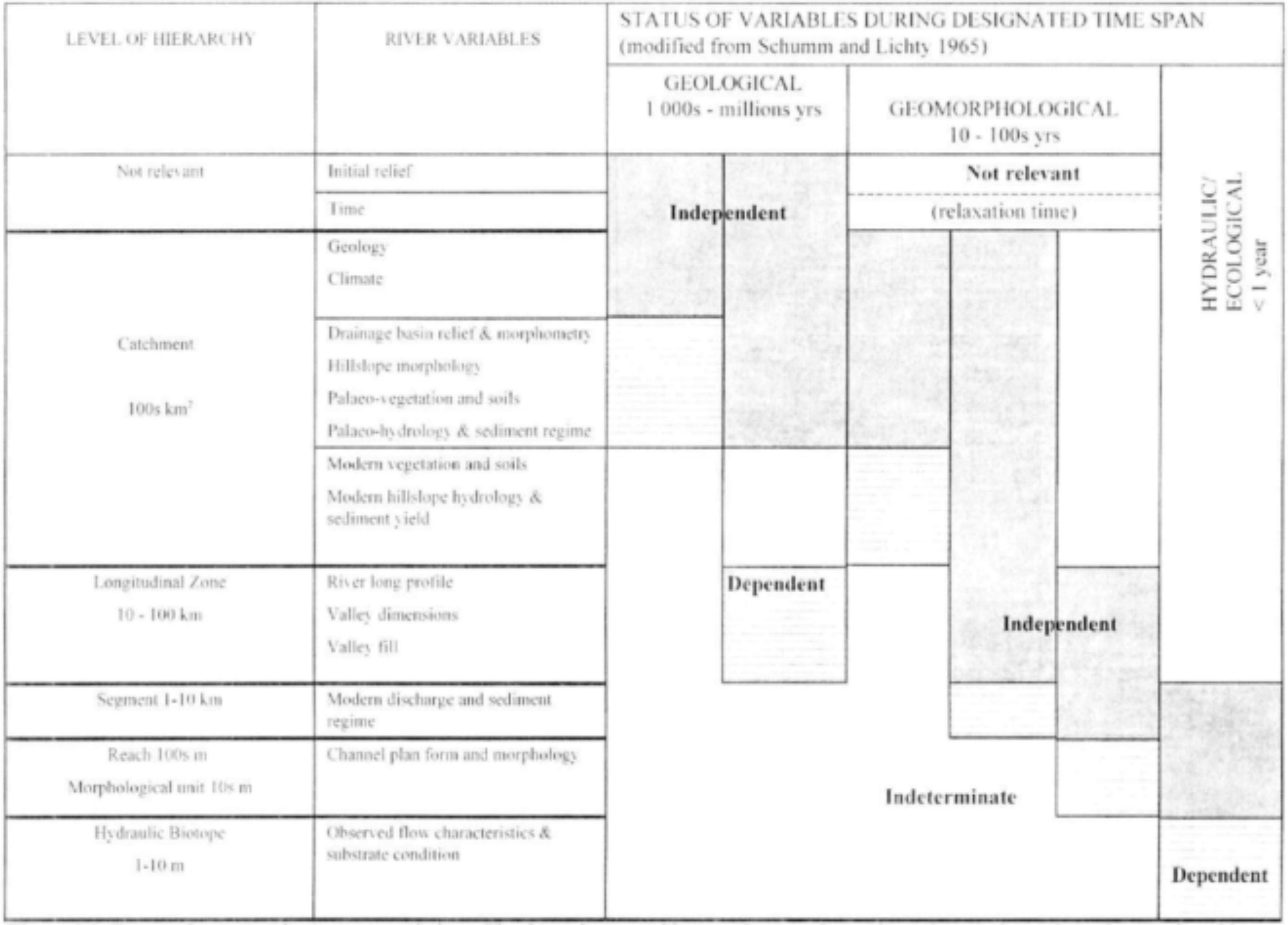


***Figure 1.1:** Time and space scales in geomorphology. The dependent variables are shown as being dependent on those above them in the table.*

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.

Chapter 2: Southern African Fluvial Systems

2.1 Introduction

The environment, landscape and fluvial systems have played a central role in people's lives in southern Africa for thousands of years. However, it is only within the last hundred years that the scientific study of the environment, landscape and fluvial systems has evolved. This chapter will focus on fluvial research work in southern Africa in order to highlight current knowledge in the sub-region and to identify potential areas of weakness. Research into ancient southern African fluvial systems and their environments is addressed first (for a full discussion, see Dollar, 1998a), followed by a review of contemporary research into modern southern African fluvial systems. The chapter closes with an overview of the main characteristics of southern African fluvial systems.

2.2 Ancient southern African fluvial systems

Modern southern African fluvial systems owe their development to the geological template, Jurassic rifting of Gondwana and subsequent creation of new base-levels for erosion. Details regarding ancient fluvial systems have been uncovered through deep mining operations and there is an extensive literature dealing with pre-Gondwana fluvial systems. A good example of this is the Early Archaean (2885 Ma B.P.) Ventersdorp Contact Reef (VCR) which is a sedimentary layer that occurs at the base of the Ventersdorp lavas which rest on the Witwatersrand Supergroup (de Kock, 1941). The fossil river has been mined for gold since 1888 (de Kock, 1941; Chunnet, 1994). The sedimentary rocks of the Karoo Supergroup have also been extensively studied; these are best exposed in the Karoo basin. The basin fill consists of up to 9 000 metres of clastic sediments and lavas. The ages of these sediments range from around 300 Ma B.P. to c.190 Ma B.P. The depositional environments are well documented (cf. LeBlanc-Smith & Eriksson, 1979; Eriksson, 1986; Visser; 1989; Smith, 1995; Smith *et al.*, 1997).

An in-depth review of the post-rifting landscape and the associated fluvial landforms has been admirably achieved by other authors (cf. King, 1963; Fair, 1978; Partridge & Maud, 1987; Dardis *et al.*, 1988; De Wit, 1993; Hattingh, 1996; Maud, 1996). Here, a short review will suffice.

In southern Africa long periods of tectonic stability (African, Post-African I and Post African II erosion surfaces) have been interspersed with periods of tectonic uplift (Miocene and Pliocene) along clearly defined axes that have influenced the macro-level functioning of southern African rivers (Figure 2.1). The main denudational period was initiated shortly after the rifting of Gondwana (c. 180 Ma) and extended to the Late Cretaceous. Major sedimentation peaks in the Eocene, Miocene and Pliocene relate to these periods of maximum relief. Imprinted on these tectonic phases has been the impact of climatic change, with associated periods of wetness and dryness and concomitant changes in vegetation cover, runoff, erosion, weathering rates and environmental change (Dollar & Goudie, 2000). After an extensive period of planation, the African erosion surface developed with flat meandering rivers dominating the southern African landscape (Partridge & Maud, 1987). Two periods of axial uplift in the Miocene and

Pliocene rejuvenated many southern African rivers, hence the incised nature of many coastal rivers (Figure 2.1). The fluvial geomorphology of southern African must be seen within the context of these (polycyclic) macro-processes.

A general trend that emerges from the literature is to ascribe older (usually Mid to Early Pleistocene and older) fluvial changes to tectonic activity and more recent (usually Late Pleistocene to Holocene) fluvial changes to climatic oscillations. Worldwide advances in the study of the Quaternary glacial/interglacials leaves little doubt that climatic change has played a significant part in the evolution of fluvial systems worldwide and also in southern Africa (Maud & Partridge, 1988). Reviews of Late Pleistocene climate change in southern Africa by Partridge *et al.* (1990) and Tyson & Lindesay (1992) present clear evidence for climatic change. The impacts of climate change on landforms have been discussed elsewhere at length (cf. Maud & Partridge, 1988; Partridge, 1988; 1990) and are an important consideration when interpreting modern fluvial processes and landforms.

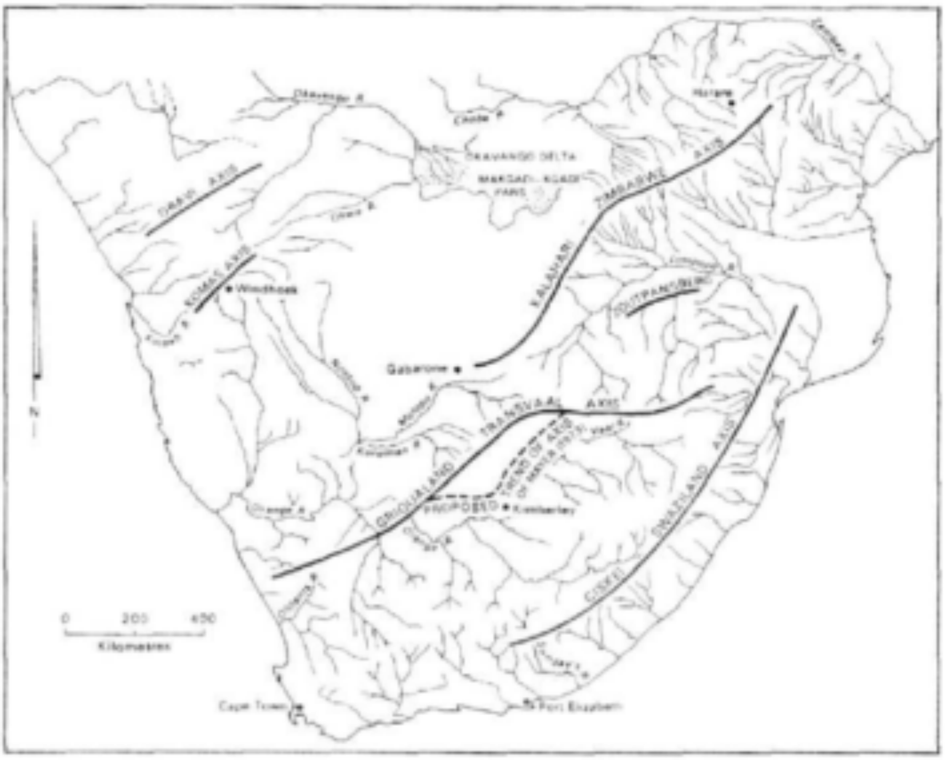


Figure 2.1: Fluvial systems of southern Africa (after Dollar, 1998a).

2.2.1 Palaeoflood hydrology

Of particular relevance to this study is the field of palaeoflood hydrology (PFH). Although this technique has been applied internationally since the 1970s (cf. Baker, 1973), limited attention has been given to the technique in southern Africa (Helgren, 1979; Turner, 1980). The basis of PFH is that certain empirical relationships can be defined between hydraulic and geomorphic variables and channel characteristics. By these means palaeohydraulic conditions can be reconstructed with relative estimates of palaeodischarge, palaeovelocity, palaeogeometry and palaeoform being made within certain confidence limits of the regression line.

Zawada *et al.* (1996) and Zawada (1996; 1997) provide comprehensive reviews of the techniques, methods, potential application and limitations of PFH. Zawada (1997) makes a strong case for the use of PFH to augment the somewhat limited flood record in southern Africa. PFH can provide magnitude and frequency data for floods of variable time scales ranging from 10s to 1000s of years, it augments the flood record and it makes prediction more accurate. Zawada (1994) made the point that the Laingsburg flood of 1981, which was the largest recorded flood (5680 m^3s^{-1}) in the Buffels River for the period of record, could be calculated as a 1 in 10 000-year flood using a log-Pearson distribution or a 1 in 100-400 year flood using a log-normal distribution. Using this as an example, Zawada (1994) points out that the variable predicted return periods using conventional flood-frequency techniques are unreliable, especially for high-magnitude floods, and that PFH provides a useful alternative to extend the record for flood frequency analysis (cf. Smith & Zawada 1990; Smith, 1992a; 1992b).

Zawada *et al.* (1996) provide evidence to show that the Orange River has experienced thirteen major floods with discharges in the range of 10 200 m^3s^{-1} to 14 660 m^3s^{-1} in the last 500 years, whereas the largest gauged flood in the Orange on record is 8 330 m^3s^{-1} at Vioolsdrift in 1974. Similarly, slack-water sediments indicate that a flood of 28 000 m^3s^{-1} occurred in the Late Holocene in the Mfolozi River, nearly twice the size of the largest recorded flood of 16 000 m^3s^{-1} in 1984. Clearly, PFH provides a significant source of information (Boshof *et al.*, 1993). Zawada *et al.* (1996) were able to show that the Orange could be divided into four palaeoflood periods (Table 2.1). They argue that there is a clear relationship between flood magnitude and climate change (cf. Partridge *et al.*, 1990; Tyson & Lindesay, 1992) and that there has been a gradual warming since the end of the Little Ice Age (A.D. 1850).

Table 2.1: *Flood-magnitudes for the Orange River for the last 5000 years (after Zawada et al., 1996).*

Period Number	**Approximate Date**	**Flood Magnitude**
1	5450 B.P. - 1800 B.P.	No flood exceeded 12 800 m^3s^{-1}
2	961 A.D. - 1332 A.D.	No flood exceeded 14 700 m^3s^{-1}
3	1453 A.D. - 1785 A.D.	No flood exceeded 28 000 m^3s^{-1}
4	1785 A.D. to present	No flood exceeded 9 500 m^3s^{-1}

2.2.2 Palaeo-sediment yields

A change in climate, drainage pattern or drainage orientation will result in a change in the sediment yield of a river. It is therefore appropriate to provide a brief discussion on palaeo-sediment yields for southern African rivers. Evidence for changing yields is presented for the Orange River, KwaZulu-Natal and the Eastern Cape.

Table 2.2 presents evidence of a variable but overall declining rate of sediment yield in the Orange River. Dingle & Hendey (1984) suggest that declining sedimentation off the West Coast depocentres can be accounted for by increasing aridity associated with the upwelling of the Benguela Current in the Upper Miocene (Siesser, 1978). Modern values for the Orange's sediment load are 6.5 x 10^6m^3 per annum, but are thought to have been declining since the 1930s (Rooseboom, 1978). Likewise Bremner *et al.* (1991) indicated that the sediment yield from the 1988 Orange River floods were not nearly as impressive as the runoff values. Swart *et al.* (1990) reported that the 1988 flood reached a peak of around 8 500 m^{3}s^{-1}. They suggested that the modest discharges of sediment were related to limited sediment supply to the channel.

Table 2.2: *Sediment yield for the Orange River since the Late Cretaceous (after Dingle & Hendey, 1984 and Rooseboom, 1978).*

Period	**Drainage Area (10^3 km^2)**	**Mean Annual Sediment Yield (10^6 m^3)**
Late Cretaceous	969	10
Palaeogene	517	2.0
Neogene	969	0.3
Present	969	6.5

Martin (1987) has compared modern sediment yields from KwaZulu-Natal rivers to palaeo-yields from the Natal Valley in the Indian Ocean. Using seismic profiles he determined that average modern rates of sediment yield (322 t km^{2}yr^1) are 12-22 times higher than the geological average (14-27 t km^{2}yr^1). It is tempting to explain this higher modern yield as anthropogenically induced, but Davies *et al.* (1977) have pointed out that natural sediment yields have varied by a factor of as much as fifteen between glacial and interglacial periods. Rates for the last 3 Ma are, for example, twice as high as for the previous era of rapid sedimentation.

Illenberger (1992, 1993) suggests that for selected Eastern Cape rivers (Krom, Gamtoos, Van Stadens, Swartkops, Great Fish and Great Kei) modern sediment yields are eight times higher than the geological average of 12 t km^{2}yr^1, but that considerable variation in the geological rates also exist. High modern yields are attributed to poor catchment management practices.

These various results raise the question: are the large increases in modern fluvial sediment yields anthropogenically forced, or do high modern yields form part of a natural fluctuation (cf. Murgatroyd, 1979). Milliman & Meade (1983) make the point that today's river sediment yields should not simply be extrapolated backwards in time, as present-day climates and erosional regimes do not resemble even those of a few thousand years ago.

It becomes clear from the above review that a variable hydrological and sediment regime has occurred since the fragmentation of Gondwana and that the present-day fluvial regime is a recent one. This has significant implications for our understanding of the functioning of modern fluvial systems as the past has left its imprint on modern channels. In order for southern African fluvial systems to be adequately understood, a broader temporal context is required. Untested assumptions about human-induced channel changes should therefore be avoided. Given this context, the following section deals with the current state of knowledge of modern southern African fluvial systems.

2.3 Modern southern African fluvial systems

2.3.1 Introduction

Southern African fluvial systems have undergone considerable changes due to tectonic and climatic influences over the geological past. Modern fluvial systems represent the product of contemporary environmental processes acting on this geological template. This section will review the current state of knowledge of modern southern African fluvial systems.

While the field of fluvial geomorphology is well established in the Northern Hemisphere, knowledge of the physical functioning and processes operating in southern African fluvial systems is still fragmentary. It is only in the last ten years that a concerted effort has been made to elucidate modern channel processes. Ironically, this has been motivated not by a desire to understand the geomorphology for its own sake, but by the recognition by ecologists of the role that geomorphological processes play in driving river systems (cf. Pitman & Pullen, 1989; van Wyk, 1989; Looser, 1989; Bruwer & Ashton, 1989; Palmer & O'Keeffe, 1985;1990; Davies, 1989; Vogt & Moon, 1989). Prior to the 1990s, comments on modern fluvial systems were only made in passing, usually with reference to catchment condition, or flooding (cf. Gevers, 1948; Weiss & Midgley, 1976; Wilson & Dincer, 1976; Alexander, 1979; Beckedahl & Moon, 1980; Beaumont, 1981; Garbharran, 1983; Dix, 1984; Perry, 1985; van Heerden & Swart, 1986).

2.3.2 Channel process studies

The first systematic study of a modern fluvial system in southern Africa was that of the Okavango Delta in Northern Botswana. McCarthy *et al.* (1986; 1987; 1988) were able to show that active channel migration in the Delta was the result of sediment accumulation in the channels, leading to channel aggradation, a reduction in hydraulic gradient and ultimately avulsion. Rates of accretion of up to 50 mm per annum were noted. Channels of the Okavango are thought to be inherently unstable, but these dynamic changes are necessary for the even distribution of sediment through the delta. Channel changes have been occurring throughout geological time, and may also be related to tectonics and changing climatic conditions (cf. Cooke, 1976; Shaw, 1984).

Recent evidence from the Okavango Delta stresses the significant role that vegetation plays in the geomorphic functioning of the system (cf. Ellery, 1988; Ellery *et al.*, 1993; van Coller *et al.*, 1997). Channel margin vegetation assemblages are related to, and impact on, sediment deposition and long-term and seasonal water levels. Erosion-resistant vegetated banks retard water velocities, so that all the sediment introduced into the system is retained. This results in channel aggradation, vegetation establishment and subsequent avulsion (McCarthy *et al.*, 1992). Channel switching is thought to relate to a two phase process of erosion and deposition. Channels that receive their water via seepage and overspill are erosion dominated channels, while channels that receive their water from a direct source (i.e. an active channel) are deposition dominated channels. Once critical thresholds have been attained, channel switching takes place. It is clear that channel avulsion forms part of the natural process of sediment distribution within the Okavango Delta, and that a dynamic relationship exists between discharge, sediment load and riparian and in-stream channel vegetation. McCarthy *et al.* (1991) argue that channel switching indicates that the present channels are attempting to attain an equilibrium condition and that the initial disequilibrium was probably caused by fault movements on the northwestern side of the graben. Without the constant channel switching within the Okavango Delta and the dynamic relationship between the water, sediment and vegetation, the Okavango system would probably become stagnant and moribund (McCarthy, 1992).

A systematic study of channel change in the Bell River in the North Eastern Cape was undertaken by Dollar (1992). He found that change in the form of channel straightening from a meandering to a braided channel (as evidenced by a series of recent meander cutoffs) could be accounted for by increased sediment production to the channel as a result of poor catchment management practices. Triggering mechanisms were argued to be major flow events following periods of extended dryness. This sequence of wet and dry cycles of approximately 18-years was thought to be comparable to Flood Dominated Regimes (FDRs) and Drought Dominated Regimes (DDRs) in Australia (cf. Warner, 1987). Dollar & Rowntree (1995) pointed out that catchment and channel processes were clearly linked and that any disturbance in the catchment would have a concomitant impact on the channel. Rowntree (1991) and Rowntree & Dollar (1996a) also mention the significance of riparian vegetation in maintaining channel stability. Alien woody vegetation on the channel banks may stabilize the banks at low and intermediate flows, whereas at high flows they may aid the process of channel avulsion.

Spatial and temporal changes in the rivers of the Kruger National Park (KNP) have been widely investigated (cf. Venter & Bristow, 1986; Vogt & Moon, 1989; Chunnet *et al.*, 1990; Venter, 1991; Vogt, 1992; Cheshire, 1994; Heritage *et al.*, 1995). Vogt (1992) was able to show that the Sabie River has experienced a number of channel planform changes between the 1940s and the 1980s and that these changes could be related to rainfall periodicities in the catchment as well as changing rates of channel sedimentation and scour. By contrast sediment transport rates were thought to be controlled by antecedent catchment and channel conditions such as drought (Heritage & van Niekerk, 1994; Birkhead *et al.*, 1996). Channel vegetation was considered a major control on channel form. Vegetation density was shown to have increased progressively since the 1940s. Later, Heritage *et al.* (1995) made the point that sedimentation patterns (deposition and scour) in the Sabie River could be related to the 18-year rainfall periodicity in the summer rainfall region (linked to El Niño) which was translated to the flow pattern. Channel change was thought to be related to increased sedimentation in the channel as evidenced by catchment degradation.

2.3.3 Channel forming discharge

Conventional wisdom for alluvial channels is that moderate flow events with a return period of 1 to 2 years are responsible for the maintenance of channel form (cf. Wolman & Miller, 1960; Richards, 1982). Although southern Africa has an extensive literature on flooding, flood magnitude and flood frequency estimation (cf. Alexander, 1976; Kovacs, 1980; 1985; 1988; Kovacs *et al.*, 1985; Begg, 1988; Zawada, 1991), little attention has been paid to determining the magnitude and frequency of flow events responsible for channel form. It is clear that semi-arid rivers exhibit a markedly different flow regime to temperate systems (cf. Baker, 1977) and that the conventional 1 to 2 year channel forming discharge of temperate alluvial channels should not be applied blindly to southern African rivers (Newson, 1996). This theme is expanded in Chapter 3.

An extensive literature search revealed that other than work by Heritage *et al.* (1995) and Wadeson (1989), no work on channel forming discharge has thus far been attempted in southern Africa. Heritage *et al.* (1995) showed that the macro-channel of the Sabie River is inundated once every 20 years. They suggested that the concept of bankfull discharge as applied to semi-arid rivers may be erroneous. The Sabie River is probably in a state of disequilibrium and hence the river may not have had time to adjust its morphology to the current flow regime. In contrast, Wadeson (1989) demonstrated that the bankfull discharge for the Buffalo River in the Eastern Cape did conform to the 0.9 year flood on the partial flood series.

2.3.4 Present-day sediment yield

Although Du Toit had mentioned the problem of siltation of South African reservoirs as early as 1910 (Du Toit, 1910), limited field data is available on modern sediment yield for southern African rivers. Du Toit (1910) ascribed siltation to a combination of high natural levels of sediment load as well as poor agricultural practices. Van Warmelo (1922a; 1922b; 1922c); Mason (1924) and Lewis (1936) mention the problem of reservoir siltation in the Vaal and Orange Rivers, while Warren (1922, p.42) suggested that "... this evil is becoming so pronounced that it would appear that some form of legislation will have to be introduced". Early workers thus recognized the link between reservoir sedimentation and poor agricultural practices (cf. Roberts, 1952).

Rooseboom (1978) has shown that the annual sediment yield from South African rivers is between 100 and 150 x 10^6 tons per annum, but that this figure is declining. Rooseboom & Harmse (1979) indicated that between 1929 and 1969 the average load of the Orange River decreased by more than 50%, while flow reductions during the same period remained insignificant. They argue that these reductions cannot be ascribed to land use, reduction in flows or sediment capture by impoundments but (p.463) "... should be attributed to progressive change in extant material rather than land use."

Le Roux (1990) was able to show that the present-day rate of erosion in South Africa (as a whole) was at least two to three times the rate of replacement by weathering. Rooseboom *et al.* (1992) argue that (p.2.9) "...sediment concentrations and loads in rivers are determined by the availability of sediments rather than by the carrying capacities of the flows". Rooseboom (1992) concludes (p.4.1) "... after more than 20 years involvement with sediment load data for southern African rivers, the main impression which remains is the variability thereof". It is clear that there is extreme variability in the daily, annual and seasonal sediment yields of southern African rivers and that it is risky to draw simple conclusions from limited records. Very little knowledge exists on the impact of 'sediment pulses' through southern African rivers. To the best knowledge of the authors, there are no measured bed load data available for southern African rivers. Bed material is a significant controlling variable, as channel pattern and form has long been associated with bed load and calibre (cf. Schumm, 1977; Church *et al.*, 1987; Ferguson, 1987). This lack of information serves as a major gap in the understanding of the functioning of modern southern African fluvial systems.

2.3.5 Flow regulation and channel processes

The late 1980s and early 1990s saw a growing recognition in southern Africa of the impact of engineering structures on fluvial systems. These related specifically to channel impoundments and inter-basin transfer schemes (IBTs). Initially the focus of research on these regulated rivers was ecological. However, it became clear to ecologists that the physical template for habitats was determined by the flow, channel substrate and banks of the river - the realm of the fluvial geomorphologist. Geomorphologists were increasingly being called on to aid in the process of river conservation and management.

Early work on the geomorphological effects of regulated rivers was undertaken by Dollar (1990) who showed that the building of the Isandile Dam on the Keiskamma River attenuated flood peaks resulting in the build-up of tributary bars at channel junctions and general sedimentation problems immediately downstream of the dam. Work by McGregor (2000) has confirmed this finding. The impact of introducing water from the Wriggleswade Dam to the Nahoon River in the Eastern Cape was shown to have a significant scouring impact on the upper reaches of the receiving channel (Rowntree in Hughes, 1994). Du Plessis (2000; Section C, Vol 1 of this report) has shown how the Skoenmakers River in the semi-arid Karoo region, which is used as a conduit for water transferred from the Orange-Fish-Sundays River IBT, has altered its channel morphology and riparian vegetation structure in response to the imposed flow regime. Other than these four studies, no other published information was available at the time of this review on the impact of flow regulation on channel processes in southern Africa.

2.3.6 River classification and channel processes

Two major bodies of work on river classification have emerged out of the southern African literature since the early 1990s (Figure 2.2). Both systems were borne out of the requirements of ecologists for a physical description for aquatic ecosystem management. The first is the hierarchical classification system of Rowntree & Wadeson (1999), the second is the classification system of van Niekerk *et al.* (1995). These have been extensively reported on elsewhere (cf. van Coller, 1993; van Niekerk & Heritage, 1993; Wadeson & Rowntree, 1994; Wadeson, 1995; van Coller *et al.*, 1995; van Niekerk *et al.*, 1995; Rowntree & Wadeson, 1996; 1997; 1999; Heritage *et al.*, 1997). Here a short review will suffice.

Rowntree & Wadeson (1999) stress the need for a stream classification system that can provide a scale-based link between the channel and the catchment, and that will allow a structural description of the spatial variation in stream habitat. They modified the stream classification system of Frissel *et al.* (1986). Their classification system can be regarded as a hierarchical system, in which each level provides inputs of matter and energy into the lower one, but the lower levels also provide the building blocks of the next higher level. The system therefore provides a systematic framework that links the catchment and channel (Figure 2.2). It is a system that lends itself well to geomorphological assessments at the regional scale and has become the basis of classification for the River Health Programme (Rowntree and Wadeson 2000).

Rowntree and Wadeson, 1993	van Niekerk *et al*, 1995
CATCHMENT	CATCHMENT
	RIVER SYSTEM
ZONE	
SEGMENT	ZONE
REACH	MACRO-REACH
	REACH
	CHANNEL TYPE
MORPHOLOGICAL UNIT	MORPHOLOGICAL UNIT

Figure 2.2 *Hierarchical classification systems of Rowntree & Wadeson (1997) and van Niekerk et al. (1995).*

The second major attempt at river classification was developed by van Niekerk *et al.* (1995). Working contemporaneously with Rowntree and Wadeson, they produced a bottom-up hierarchical classification system based on an extensive study of the rivers of the KNP. Van Niekerk & Heritage (1993) focussed on the Sabie River drawing on earlier work by Vogt (1992), Venter (1991) and Chunnet *et al*. (1990). The Sabie River consists of a macro-channel extending across the width of an incised valley. Cut into the macro-channel are one or more active channels (see Figure 2.3). The active channels are determined by normal flow conditions (i.e. non-flood conditions) while the macro-channel is controlled by high magnitude, low frequency events.

Van Niekerk & Heritage (1993) point out that the geomorphology of the Sabie system reflects the response of the system to a highly variable water and sediment discharge superimposed on a macro-channel controlled by the underlying geology. The implicit assumption is that there are various spatial and temporal levels at which fluvial systems operate, and that these can be 'separated-out' into distinct temporal scales. They suggest that rigid sub-division of rivers using some pre-determined classification system may result in important fluvial processes being ignored. They argue that for a full understanding of the dynamic interrelationships of fluvial systems, a classification system should be built from the bottom up. In this way, implicit assumptions about the river are not imposed from the top and made to fit a rigid classification system.

This bottom-up approach system is well suited to in-depth geomorphological assessments at the local scale. For example Moon *et al.* (1997) were able to use their classification to predict morphological change in the Sabie River, as well as to identify which channel types were likely to undergo habitat changes with altered discharge and sediment loads. They also suggest that this approach should be able to predict the direction of longer-term change which may become ecologically significant.

2.4 Overview of southern African fluvial systems

It is useful at this point to provide an overview of the main characteristics of southern African fluvial systems. Tectonic uplift during the Miocene and Pliocene rejuvenated many of the eastern sea-board rivers which drain the escarpment. Consequently many of these rivers are incised onto bed rock and have steep and often irregular long profiles. These irregular long profiles consist of sections that are morphologically uniform, these have been termed macro-reaches or zones (Rowntree, 2000; Rowntree *et al.* 2000). Macro-reach breaks are usually associated with changes in lithology, but can also be the result of Miocene and Pliocene tectonic activity. This situation has disrupted the classic downstream gradation of bed material sequence from boulder to cobble to gravel and ultimately to sand. Consequently, sand-bed channels in the lower reaches may often be replaced by bed rock, boulder or cobble on steeper gradients sections.

Many rivers draining the eastern sea-board of South African display complex cross-sections. An active channel which is formed within a larger macro-channel bordered by high terraces commonly occurs (Figure 2.3). The macro-channel has been described in a number of publications (cf. van Niekerk *et al.*, 1995; Rowntree & Wadeson, 1999). Macro-channels develop as a result of incision by the active channel into former terraces that mark the outer boundary of all but the most extreme flood flows. The active channel is the channel which by definition is inundated most frequently and is geomorphologically the most active (Rowntree & Wadeson, 1999). Within the active channel a distinct in-channel bench commonly occurs. There is often no clear flood plain. It is suggested that this channel architecture is a response to the geological template and the variable hydrological regime. This issue will be explored later in this report.

As mentioned earlier, present-day southern African fluvial systems display a highly variable hydrological regime. Walling (1996) has shown that the rivers of southern Africa have the highest coefficient of variation of mean annual runoff, the highest average storage requirement for flow regulation, the highest average annual flood variability and the highest extreme flood index [defined as the standard deviation of the logarithms of the annual peak discharge (Figure 2.4)]. Görgens & Hughes (1982) have shown that the average inter-annual variability of runoff in South African fluvial systems is extremely high. The coefficient of variation (CV) of annual runoff is around 1.13, which is higher than the CV for Australian rivers of 0.7 (cf. McMahon *et al.*, 1992; McMahon & Finlayson, 1995; Brizga & Finlayson, 2000) and considerably higher than the world average of between 0.25 and 0.4. Furthermore, the 18-year periodicity in rainfall characteristic of much of the eastern half of the country is translated to the flow regime, resulting in highly variable short- and medium-term flow regimes.

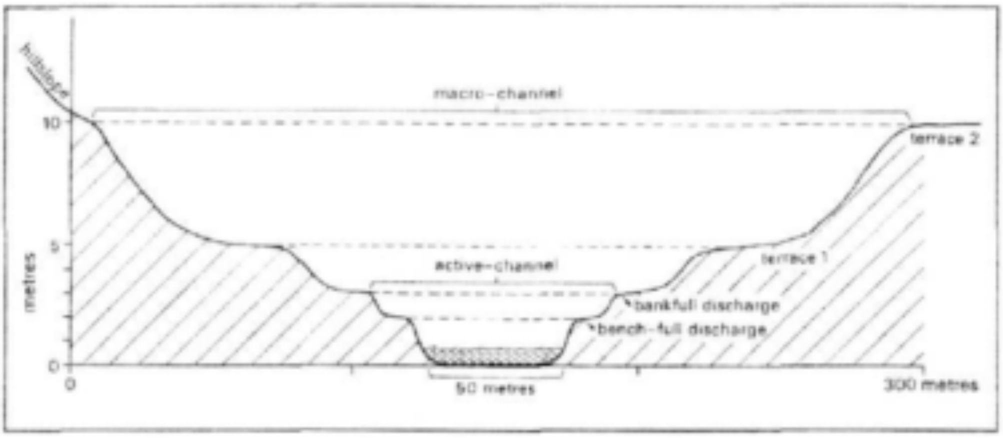


Figure 2.3: *Diagrammatic representation of the macro-channel, active channel, benches, estimated bankfull discharge and terraces.*

It is clear from the above discussion that southern African fluvial systems differ from alluvial systems in temperate climes where much of the conventional wisdom in fluvial geomorphology has been developed. (Recently, however, work from the dryland areas in the United States (cf. Graf, 1988) and a focus on bed rock systems (cf. Tinkler & Wohl, 1998) has gone some way to balance this perspective. Fluvial form is a function of the geological template, channel boundary resistance, climatic inheritance, vegetation and observed discharge of water and sediment. It is inconceivable that all fluvial systems will therefore conform to conventional theory derived from a particular region. Consequently, there is an urgent need to develop appropriate local knowledge.

2.5 Discussion and conclusion

The review has highlighted two important points. First, while the study of palaeofluvial geomorphology in southern Africa is well documented, modern fluvial process studies are limited, and the understanding of modern fluvial systems is fragmentary. In terms of the focus of this report, there is a paucity of information regarding the magnitude and frequency of channel forming discharge and bed material transport in southern African rivers. This is of concern, as effective river management requires information in this regard. Second, southern African fluvial systems differ fundamentally from temperate alluvial systems. If effective river management is to occur, there is a need to develop appropriate local knowledge. This report attempts to contribute to that local knowledge in southern Africa.

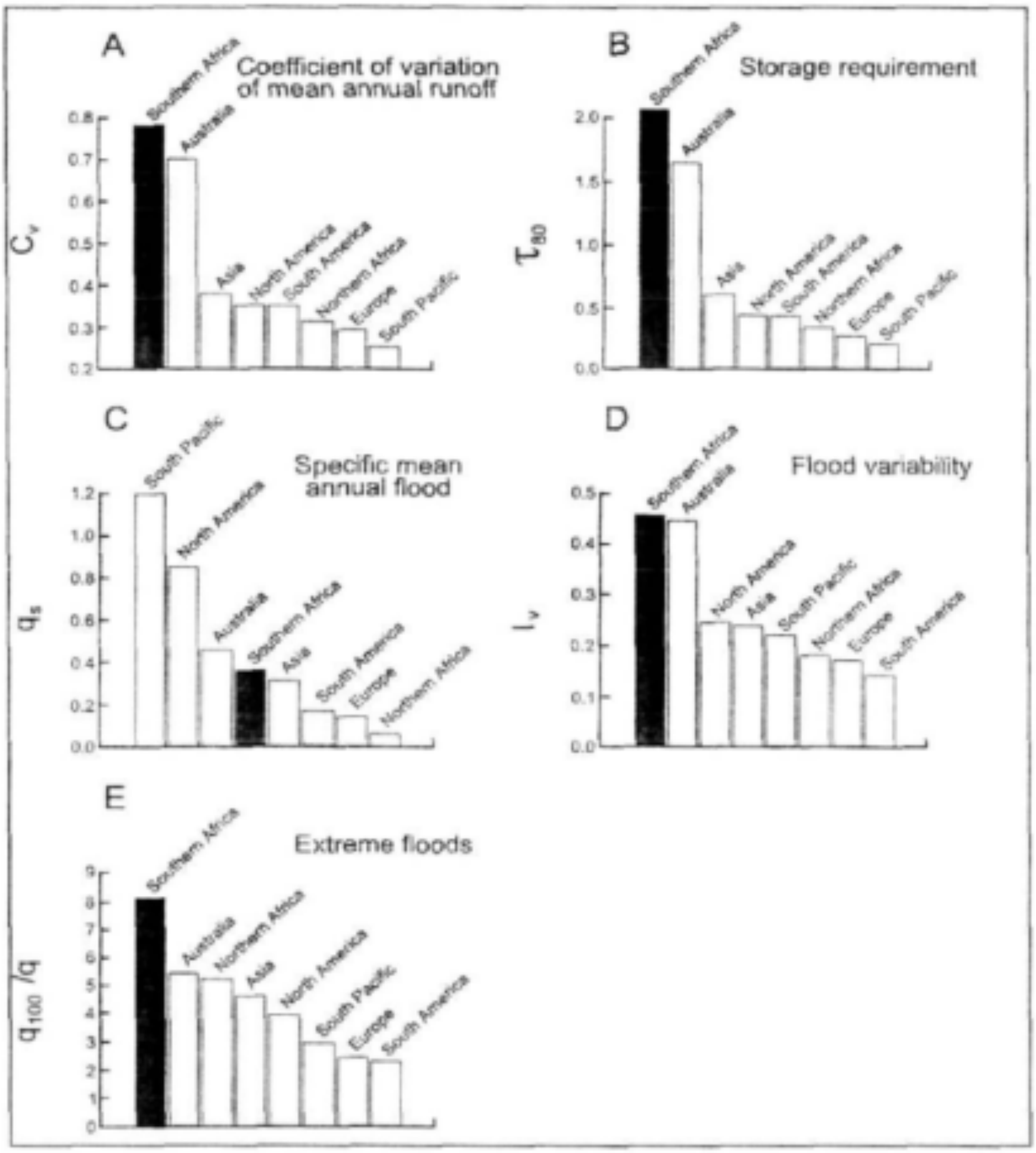


Figure 2.4: *A comparison of the runoff characteristics of rivers of southern Africa with those of other continents (after Walling, 1996). Where a) C_v is the ratio of the standard deviation and the mean, b) τ_{80} is the storage for a constant draughts at 80% of the mean annual flow with a variability of 95% expressed as a ratio of the mean annual flood, c) q_s is the 2.33 year return period flood, d) I_v is the standard deviation of the logarithms of the annual peak discharge, e) q_{100}/q is the ratio between the 100 year flood and the mean annual flood.*

Plate 2.1: *The Mkomazi River in KwaZulu-Natal exemplifies a river with a compound channel characterised by an inset flood bench and macro-channel.*

Plate 2.2: *The lower reaches of many South African rivers show features of rejuvenation as typified by the Mgeni River in KwaZulu-Natal.*

Section B: Long term morphological change: Magnitude-frequency concepts in river management.

Section B is based on the thesis by Evan S.J. Dollar: "**The determination of geomorphologically effective flows for selected eastern sea-Board Rivers in South Africa** " Unpublished PhD thesis, Rhodes University 2001. The full data relating to this research are compiled in the Appendices of this thesis.

Chapter 3: Magnitude and frequency of channel forming discharge

3.1 Introduction

Fluvial sedimentary systems are controlled by the magnitude, frequency and the variability of flow and sediment discharge. The magnitude-frequency debate is concerned with identifying which flows are the most important in controlling channel processes and channel form. Defining these flows is no easy task due to four major issues (Dollar, 2002). First, the relationship between process and form is clouded by the fact that fluvial processes reflect the imprint of past flows. The issue of defining the significant discharges for channel form must therefore take account of the temporal context of earth history. Moreover the historic form affects present processes so that cause and effect becomes and issue of time and scale (see Figure 1.1). Second, the initial conditions necessary for a full understanding of the system are seldom known, so that inheritance factors are poorly accounted for. Third, the issues are scale-dependant, and they require the identification of appropriate descriptors and drivers across a range of spatial and temporal scales. Fourth, variables in natural systems are very difficult to quantify, so it is often necessary to rely on proxies rather than real quantities. Thus the issue of defining the influential discharges is a spatial and temporal one which involves earth history as well as hydraulic understanding and vegetation-sediment-geomorphology interactions. Cause and effect between form and process are difficult to distinguish, and become an issue of time and spatial scale. It is thus almost impossible to reduce a fluvial system to simple physics, except on limited scales and domains (Dollar, 2002). The system has to be simplified by considering the magnitude, frequency and variability of sediment and discharge controlling fluvial sedimentary systems for a specified temporal dimension.

In order to simplify the fluvial system into a physical entity for the purposes of this research, three sets of flow information are required. These are necessary for a geomorphological assessment of in-stream flow requirements (Rowntree & Wadeson, 1997). They are the flows that maintain firstly the spatial and temporal availability of habitat, secondly the substratum characteristics and thirdly the channel form. Rowntree & Wadeson (1997) have suggested the use of the hydraulic biotype to provide the information requirements for the maintenance of aquatic habitat. This idea is explored further in Section C of this report. The latter two information requirements (the maintenance of substratum characteristics and the maintenance of channel form) are fundamentally linked to the magnitude-frequency debate.

The aim of this chapter is to provide a theoretical framework within which the flows necessary for the maintenance of channel form can be appraised. The chapter is divided into two sections. The first section considers the magnitude-frequency debate; the second section reviews environmental flows with specific reference to sediment-maintenance flushing flows.

3.2 The origins of the magnitude-frequency debate

The origins of the magnitude-frequency debate date back to the late 1800s when British hydraulic engineers attempted to construct stable irrigation canals in India. They noted that canals could adjust their boundaries until a stable configuration was attained (the regime channel), and that the geometry of the channel was related to its discharge of sediment and water (Kennedy, 1895; Lacey, 1930). The equations that were developed became known as regime equations (Nixon, 1959; Ackers, 1972; Osterkamp & Hedman, 1977). Later, regime equations were related to natural channels. The thinking behind this was that, in principle, the morphology and dynamics of rivers should be explicable in terms of the laws of physics. This line of thought was later to emerge in the magnitude-frequency debate. This debate centred on the assumption that in alluvial systems channel form can be related to a specific magnitude (discharge) and frequency (return period or duration) of flow (cf. Leopold & Maddock, 1953; Blench, 1957; Lane, 1957; Leopold & Wolman, 1957; Dury, 1959; Dury *et al.*, 1963; Leopold *et al.*, 1964; Woodyer, 1968; Osterkamp *et al.*, 1983). Early researchers sought a physical expression of this flow. Initially, it was argued that the flood plain, shape and pattern of the channel are related to the bankfull condition - the stage at which overtopping onto the flood plain occurs (Wolman and Miller, 1960). The literature came to equate the bankfull discharge with dominant discharge and effective discharge (cf. Wolman and Miller, 1960; Ackers & Charlton, 1970; Gregory, 1976; Pickup & Warner, 1976). These three discharges will be discussed in turn. A discussion can also be found in Rowntree and Wadeson (1999)

3.3 Dominant discharge

The term 'dominant discharge' was introduced by Inglis (1941) as a way of conceptualising the equilibrium between channel form and the long term discharge regime. Dominant discharge was defined as the discharge at which equilibrium between form and discharge is most closely approached and the tendency to change is least. The dominant discharge was conceptualised as the constant flow rate that would produce the same channel morphology as would a sequence of naturally varying flows. Thus dominant discharge was defined by its morphological product rather than by geomorphological process. By the 1970s, the term 'dominant discharge' had become firmly entrenched in fluvial geomorphology and hydraulic engineering literature (cf. Neill, 1968; Bray, 1975).

There are a number of problems with the dominant discharge concept. Pickup & Rieger (1979) argue, as does Kennedy (1972), that to assign a single dominant discharge to a channel is an oversimplification, for to accept the idea of a 'dominant discharge' is to imply that the river is in regime (equilibrium). They argue that instead of a single channel forming discharge, a channel is much more likely to be adjusted to a whole range of flows as well as to the sequential nature of the flows.

Prins & de Vries (1971) suggest that a distinction must be made between dominant discharge as a concept and the determination of dominant discharge. It is clear that the simplified regime can never replace the real regime as far as the reproduction of the morphological characteristics of a river are concerned (Prins & de Vries, 1971). Furthermore, they point out that there could be a number of dominant discharges each related to a different channel characteristic, for example the steady flow that would yield an observed meander length. Thus the accepted notion of dominant discharge is that it is specific for a particular channel morphology, but that the channel morphology is made up of a number of components. Each of these will have their own response to the variable flows and therefore their own dominant discharge. The concept of one dominant discharge for the channel can only hold true if these separate dominant discharges converge towards one value.

3.4 *Bankfull discharge*

The notion of bankfull discharge has existed in the literature for some time (cf. Inglis, 1947), but its use as an independent variable controlling channel form became popular in the late 1950s and 1960s. Wolman & Miller (1960) argued that the flood plain and the shape and pattern of the channel are related to discharges that approximate the bankfull condition. Harvey (1969, p.82) defined bankfull discharge as "... the discharge which just fills the natural stream channel and above which spilling onto the floodplain occurs". The bankfull stage was thus taken as the elevation of the active floodplain, and is a physical measure of the flow capacity of the channel.

Dury (1959; 1961) has shown that the bankfull discharge of many English and American rivers has a recurrence interval of somewhere between 1 and 2 years. This became conventional wisdom (cf. Brusch, 1961; Leopold *et al.*, 1964). Dury *et al.* (1963), however, argued that many rivers in Queensland, Australia, are incised to such an extent that the bankfull stage is well above the mean annual flood and that some sites had not experienced a bankfull stage during the period of record. This suggested that the rivers were still adjusting to a recent climate or tectonic event and may not reach a bankfull stage. It is also possible that Dury was inappropriately applying concepts developed for the British and American context. Hickin (1967) similarly argued that the rivers of New South Wales, Australia, had become deeply incised due to climatic, tectonic and eustatic events, and that for this reason bank top at many sites do not correspond to the natural bankfull stage. Dury (1976) suggested that due to the widespread evidence that streams have incised their flood plains in the mid-latitudes, the feasibility of using the present flood plain level to identify the bankfull stage in these regions should be avoided. Woodyer (1968) suggests that, for this reason, many flood plains may in fact be terraces and argues that channel benches should be used as an alternative.

A consistent definition of what can be considered the bankfull stage is problematic (cf. Kilpatrick & Barnes, 1964; Riley, 1972; Williams, 1978, Rowntree and Wadeson, 1999). Although definitions of bankfull discharge have included morphometric, sedimentary or discharge criteria, more often than not morphometric criteria are used to define the bankfull condition. Rosgen (1996) described bankfull discharge as the single most important parameter in morphological classification. He used bankfull discharge to relate dimensions such as width, meander length, radius of curvature, belt width, meander width ratio and amplitude. He argued that the most consistent bankfull stage determination is obtained from the top of the flood plain. This is the elevation where incipient flooding begins for those flows that extend above the bankfull stage. He argued that it is important that the physical and morphological differences between a low terrace and a flood plain are recognized, since alluvial channels can often have low-level terraces adjacent to the flood plain, easily confused with the bankfull stage.

3.5 Effective discharge

Effective discharge has commonly been used as an expression of dominant discharge. Effective discharge can be defined as the discharge that transports the most sediment over time (Orndorf & Whiting, 1999). In their early work, Wolman and Miller (1960) argued that although the largest flows have the greatest stream power and can do work on the channel boundaries at the greatest rate, they occur only rarely. At the other end of the scale, low flows have such low stream powers that they are incapable of altering channel boundaries, regardless of how often they occur. Moderate flows with moderate stream power can do more work over time and are therefore more efficient than rare high flows (see also Leopold, 1994; Andrews & Nankervis, 1995).

Pitlick & Van Steeter (1998) used duration data and sediment transport relations to determine the effective discharge for the upper Colorado River using the Parker *et al.* (1982) equation. The most effective discharges for the transport of bed load were found to be slightly less than the bankfull discharge and to occur at daily discharges that occurred on average about 2 % of the time or 7 days per year, transporting approximately 30 % of the annual load. More than 80 % of the annual sediment load was carried by the highest 10 % of the flows. This was in agreement with information presented by Ashmore & Day (1988) and Nash (1994) who also showed that the duration of the effective discharge increases with drainage area. Data presented by these authors suggests that for rivers with drainage areas greater than 100 000 km^2 the effective discharge is exceeded about 10% of the time.

Pitlick & Van Steeter (1998) related their findings on effective discharge to the maintenance of aquatic habitat. They argued that aquatic habitats in the upper Colorado River are maintained by flows ranging from about half bankfull up to about the bankfull stage. At the half bankfull stage, gravel transport on a widespread basis is initiated, which is important for flushing fine sediment from the bed. Flows at the bankfull stage carry the majority of the sediment load and erode fine sediment from the side channels. These flows are therefore important for maintaining backwater habitats. Furthermore, these high flows define the upper limit for the onset of bank erosion and the formation of bars and side channels.

Marlette & Walker (1968) adopted a simplified expression of effective discharge as their definition of dominant discharge. They defined dominant discharge as the discharge equating to the water stage above which half the bed sediment transport takes place - this was termed the bed-boundary level. Following earlier authors, they argued that if the bed sediment transport was the dominant factor in determining the channel size and shape, then a channel designed to carry the computed dominant discharge (see Equation 3.1) would be the most stable configuration. The Netherlands Engineering Development Consultants (NEDCO)(Prins & De Vries, 1971) adopted Marlette and Walker's (1968) approach and developed a method for determining dominant discharge using bed load discharge, flow duration data and the stage-discharge curve. A three step computational system was used. First, the monthly river flows were arrayed in ascending order, second, the bed load discharges corresponding to each monthly flow were computed, and third, the bed load discharges were subdivided into class intervals. The dominant discharge (Q_d) is calculated by:

$$Q_d = \frac{\sum_{b=1}^{k} Q_b \, T_b \, n}{\sum_{b=1}^{k} T_b \, n} \qquad \textit{(Equation 3.1)}$$

Q_d	dominant discharge
k	total number of class intervals
b	specific class interval
Q_b	mean monthly or daily water discharge (m^3s^{-1})
T_b	bed load discharge for a given month or day corresponding to Q_b in tonnes per day
n	number of events in each class interval

This model was tested on the Platte and Missouri Rivers. It was found that before flow regulation the dominant discharge of the Missouri River below the confluence was 67 000 cfs. This decreased to 38 000 cfs after regulation. Using a similar procedure, Komura and Gill (1968) calculated the dominant discharge for the Nagara River in Japan. The dominant discharge was calculated as 3000 m^3s^{-1}, this equated to a recurrence interval of 1.43 years on the annual series and a probability of excedence of 70% for the annual peak discharge. Komura (1968) found that the dominant discharge depended on the type of bed material present. Where bed load was predominant, a dominant discharge of 2030 m^3s^{-1} with a recurrence interval of 1.04 years occurred. Where bed and suspended load were equal, a dominant discharge of 3000 m^3s^{-1} with a recurrence interval of 1.43 years occurred, and where suspended load was dominant, a dominant discharge of 3985 m^3s^{-1} with a recurrence interval of 2.78 years occurred.

Although the definition of effective discharge as the discharge that over time transports the most sediment is conceptually satisfying, in real terms significant practical problems hinder the accurate measurement of sediment load. This will be discussed further in Chapter 4.

Statistical measures of dominant discharge

Because of the problems of identifying either the active bankfull level or long term sediment loads, an alternative approach is to use the hydrological record to extract the discharge that occurs at a specified frequency assumed to relate to that of either the bankfull or effective discharge. This requires that empirical studies be conducted on systems where the requisite relationships can be established. Results can then be extrapolated to other systems that lack the necessary morphological or sediment transport data, but have an established hydrological record. Wolman and Miller's (1960) study indicated a strong concurrence between effective discharge, bankful discharge and the 1.5 year flood on the annual series.

As a result of their work the 1.5 year flood (or 0.9 on the partial series) has become widely accepted as representing the dominant discharge for temperate, alluvial rivers.

Rivers in other fluvial environments may not follow the relationships proposed by Wolman and Miller (1960). Pickup & Warner (1976) put them to test using data from the sem-arid Cumberland basin in New South Wales. For the estimation of *effective discharge*, Pickup & Warner (1976) divided the flow into classes, determined the flow duration within each class, and calculated the mean bed load discharge within the class and multiplied it by the duration. A histogram showing the amount of load transported by each class was then constructed. The most effective discharge was taken as the mid-point of the class which transported the most bed load. Their results indicated that a limited range of discharges were responsible for the transportation of much of the bed load. Below this range the flow was not competent to move the bed load. Above it, the reduced flow duration more than offset the higher rate of transport. The return periods for the *effective discharge* lay within the range of 1.15 to 1.45 years on the annual series, while for the partial series the return period lay between 0.20 to 0.40 years. The effective discharge was exceeded or equalled 3 to 5 times a year. This finding was in general agreement with Wolman & Miller's (1960) assertion that a large proportion of the sediment transport is accomplished at flows of low to moderate magnitude, but high frequency. Pickup (1976) suggested that the channel gradients were adjusted to achieve maximum bed load transport at the discharge which over time transports the most bed load.

Analysis of bankfull discharge yielded interesting results. In the Cumberland basin, bankfull discharge did not fall into the typical 1 to 2 year return period. In many channels bankfull flows had a frequency of between 4 to 7 years. Pickup & Warner (1976) argue that due to a bipolar flood frequency curve, the channel capacity is related to the large floods described by the upper limb of the flood frequency curve. They suggest three possible reasons for this situation. First, greater channel capacities may reflect disequilibrium and incision. Second, high bank resistance may completely modify the role of the hydrological regime. Third, the morphology of rivers with a highly variable hydrological regime may be related to less frequent events, as suggested by Harvey (1969). In conclusion, Pickup & Warner (1976) suggest that the bed is shaped by high frequency, low magnitude events that occur on average 2 to 5 times a year. Although these small discharges are capable of transporting bed material, they are not competent to erode the banks. The channel capacity is therefore determined by higher magnitude, low frequency events. Thus Pickup and Warner (1976) identified two groups of 'dominant discharges' - a high magnitude group determining the basic size and shape of the channel and a low magnitude group determining transport capacity and the slope.

Working in the Yampa River basin, Andrews (1980) found that the most effective discharge occurred on average for a few days a year. He also found that the effective discharge and the bankfull discharge were almost identical. He therefore argued that the close agreement between the effective and bankfull discharge would suggest that the channel is adjusted to the flows that transport the largest part of the annual sediment load, this was on average between 1.5 days per year and 11 days per year for the 15 sites in the Yampa River basin.

3.6 *Dominant discharge, bankfull discharge and effective discharge in controlled and semi-controlled systems*

Carling (1988) argues that the Wolman-Miller principle cannot be sustained in non-alluvial streams that are out of equilibrium or are unable to adjust their form freely. He was able to show that the concept could be applied to a sand-bed stream close to the steady state in the sense that, of a range of flows capable of transporting bed material, one class is the most effective in terms of the total mass transported, this being the bankfull condition. This relationship cannot be applied to a coarse gravel-bed stream as high entrainment thresholds are required for bed movement. Overbank flows are often simply not competent to mobilize the bed completely.

Baker (1988), like Carling (1988), therefore argued that the Wolman-Miller principle needs to be adapted for different river types. In resistant bed rock rivers, adjustment cannot occur as easily as in alluvial channels (Harvey, 1984). Such systems are often sediment limited and the excess energy is often dissipated as remarkable intense turbulent phenomena (cf. Baker & Kali, 1998). Often the only flows capable of significant channel alteration in bed rock streams are high magnitude events.

Furthermore, Carling (1988) argued that most channels probably have some slight 'system memory' of past events recorded in the channel form. He argues that for alluvial channels, negative feedback systems and short relaxation times (cf. Allen, 1974) ensure that the system memory is short and that the preferred channel morphology is largely invariant. Thus in alluvial channels the concept of a unique discharge that fills the channel and transports the most bed load (usually the bankfull discharge) has been seen as morphologically significant and equated with 'dominant discharge' (Carling, 1988). It remains untested whether 'system memory' is as short in semi-controlled or controlled bed rock channels or in arid and semi-arid regions.

Gupta (1995) has shown that rivers in the seasonal tropics fall somewhere in-between the arid and temperate categories. Seasonal variability in discharge significantly alters the width-depth ratio and stream power. He argues that the seasonality of the flow produces a nested channel pattern, a large channel for the storm and a small channel for the high discharge of inter-storm periods. This channel architecture is similar to that reported in central Australia (Pickup, 1991) and South Africa (see Chapter 2, section 2.4 of this volume), and suggests activity at widely different and discrete scales. The tropics, located between two anticyclonic belts at about 30° north and south of the equator, are characterised by marked concentration of rainfall within a few months. This seasonality is transferred to the streamflow, and the hydraulic geometry of the river changes dramatically between the wet and dry seasons. Rivers of the seasonal tropics have to adjust to distinct separate periods of high and low flows. Equilibrium of river form requires adjustments to multi-scale discharges. This would suggest that channels in these landscapes cannot be related to a single dominant discharge; rather they are related to a series of discharges.

3.7 Summary and management implications of the dominant discharge, bankfull discharge and effective discharge concepts

It is clear from the above discussion that the literature freely interchanges the terms dominant discharge, bankfull discharge and effective discharge. This leads to much confusion as the concepts are not necessarily interchangeable. The two key questions for geomorphologists are as follows. First, do the bankfull discharge and effective discharge drive the processes that create and maintain the channel morphology? Second, can the effective and bankfull discharges be related to a standard recurrence interval or probability of exceedence? It is possible to argue that the characteristics of the channel dictate the bankfull discharge rather than vice versa. This may be related to the imprint of past climates, or the resistance of the channel boundary to deformation. The resolution of these questions offers the potential to predict channel response to hydrologic regime. It would appear that the usefulness of the dominant discharge approach is probably related to different climatic and channel boundary conditions. Alluvial channels that are free to alter their boundaries may respond to a dominant discharge. There is a case for arguing that there could be different dominant discharges for any characteristic of the channel, for example, a dominant discharge for width, slope, point bars and so on. It may only be appropriate to talk about dominant discharge in terms of maintaining overall channel form if the in-channel characteristics all respond similarly to the said discharge. This is unlikely to be the case, especially in southern African rivers where the hydrological regime is highly variable and structural control on the channel is considerable.

In terms of management implications, it is apparent that the magnitude-frequency debate forms the context within which an understanding of the flows necessary to maintain the channel form and the channel bed can be understood (given the limitations mentioned in the previous paragraph). The use of terms such as dominant discharge, bankfull discharge and effective discharge provides concepts around which the magnitude-frequency debate can move forward. Terms need to be clearly defined and concepts that were developed for certain types of channels should not be applied to others. While it is useful to use the bankfull discharge as a surrogate for effective discharge in alluvial channels, this should not be applied to a river responding to a variable hydrological regime, or a channel that is in disequilibrium or is structurally controlled. For the purpose of this report, the terms bankfull discharge, dominant discharge and effective discharge are defined as follows:

Dominant discharge usually refers to a conceptual discharge without a specific statistical, physical or sediment transport interpretation. For the purposes of this thesis, however, the definition as used by Marlette & Walker (1968) will be applied: the discharge equating to the water stage above which half the bed sediment transport takes place.

Bankfull discharge refers to a unique and measurable physical characteristic of the channel at a particular cross-section. For the purposes of this thesis, it refers to the boundary between the active channel and the macro-channel.

Effective discharge refers to the discharge that over a period of time transports the most bed material load.

3.8 Magnitude-frequency and floods

The concept of geomorphic effectiveness refers to the ability of an event to alter landforms and to the relative persistence of the altered landforms under the influence of processes tending to restore the landscape to its previous condition (Wolman & Gerson, 1978; Hugget, 1994). Miller (1990) has shown that large floods may not be 'effective', and that in order for a flood to be effective, it (p.132) "requires the coincidence of sufficiently large peak flows with a physiographic setting where large values of unit stream power can be applied to valley reaches with erodible alluvial bottomlands". In certain river systems, however, the only flows capable of significant channel modification are rare high magnitude events. The main reason for this is that high levels of applied stress are required to scour perimeter material. In order for modifications to occur, thresholds must be achieved that prevent low to moderate magnitude events from reconstructing the system (cf. Carling & Beven, 1989; Magilligan *et al.*, 1998).

The role of post-flood adjustment is of great significance (cf. McPherson & Rannie, 1969; Beaumont & Oberlander, 1971; Schwartz *et al.*, 1975; Anderson & Calver, 1977; Thornes, 1977; Moss & Kochel, 1978; Harvey *et al.*, 1979), especially the role of re-vegetation. If re-vegetation is rapid, and given a sufficient supply of sediment, the reconstructive process will be rapid. In semi-arid and arid regions, where vegetation growth is limited, high magnitude events may produce irreparable and therefore progressive changes in the channel (cf. Hack & Goodlett, 1960; Schumm & Lichty, 1963; Stuckman, 1969; Cleaves *et al.*, 1970; Burkham, 1972; Clarke, 1973; Costa, 1974; Gupta & Fox, 1974; Stevens *et al.*, 1975; Walsh *et al.*, 1994). In some instances, thresholds of non-recovery may be attained (Tricart, 1961; Brykowicz *et al.*, 1973).

In arid and semi-arid regions, large floods can have significant effects on channel form, both in terms of geomorphological work (sediment transported) and geomorphological effectiveness (landscape impact). Clearly then, climate and hydrology are important parameters determining the effectiveness of floods of differing magnitude and frequencies (Harvey, 1984). Kochel (1988) cites the example of dramatic channel and flood plain modification by large floods in Virginia (cf. Hack & Goodlett, 1960; Williams & Guy, 1973; Johnson, 1983), while hurricane Agnes floods (cf. Moss & Kochel, 1978) produced insignificant change. The response and recovery time from extreme events is of particular significance (cf. Baker, 1973; Thornes, 1976; Baker, 1977; Schumm, 1977; Dietrich & Dunne, 1978; Patton *et al.*, 1979; Hickin, 1983; Meade, 1983; Harvey, 1984; Nanson, 1986; Baker & Pickup, 1987; Schumm *et al.*, 1987; Lewin, 1989; McEwan, 1989; Baker & Kali, 1998).

Costa & O'Connor (1995) have argued that the recognition that some really large floods may not have long lasting effects or cause long-term changes in channel and valley morphology led to the realisation that the absolute magnitude of the event is not the sole factor responsible for the resulting landforms or their perseverance. They have argued that by generating a time - stream power curve, it is possible to integrate the area under the curve to derive the total amount of energy that a flood expends per unit area, thus adding the duration dimension to the effectiveness (Figure 3.1). Using this method, they argue that there are three types of floods that are represented by three types of curves. Curve A (Figure 3.1) represents a flood on a low-gradient river that generates low stream power per unit area. Curve B represents a flood that generates high values of peak stream power per unit area and has a moderate to long duration. Curve C represents a flood which also generates high values of instantaneous peak stream power per unit area, but is short-lived. The floods that are the most effective are those floods that generate high stream power per unit area, but also expend considerable energy.

Of interest to the magnitude-frequency question, particularly in the Southern Hemisphere, is the debate that emerged in Australia about Flood and Drought Dominated Regimes (FDRs/DDRs). The concept was developed to explain the large-scale cyclical channel changes that occurred in many Australian rivers that were out of phase with well documented land use changes (Rutherfurd, 2000). FDRs are periods characterised by episodic catastrophic floods and persistent flood activity with runs of large floods for up to eleven years in a row separated by shorter periods of smaller floods. DDRs are relatively long periods of low flood activity when runs of floods occur for up to six years in a row separated by longer periods of little flood activity. Erskine & Warner (1998) argue that the alternating flood regimes appear to be caused by cyclical medium-term shifts in the location of the summer rainfall belt, with FDRs corresponding to a southerly incursion and DDRs to a northerly retreat. They have argued that rivers respond to the alternating flood regime by bank erosion, channel widening and chute cutting during FDRs, and deposition, channel contraction and chute infilling during DDRs. Erskine & Warner (1998) have pointed out that the alternating flood regime has important implications for understanding the physical functioning of Australian fluvial systems and has considerable management implications. The similarity in climate between southern Africa and Australia brings into question the possible significance of FRDs and DDRs in southern Africa. This has been argued for the Bell River in South Africa (cf. Rowntree & Dollar, 1996b).

Kirkup *et al.* (1998) reject the FDR/DDR hypothesis, arguing that the notion has been overstated and that managing rivers on the basis of FDRs and DDRs, as had occurred in the past, was likely to be ineffective. They argue that the FDR/DDR hypothesis had seriously underplayed the significance of European disturbance on river channels and catchments, while overplaying the significance of climate-driven controls on river channel changes. Brooks & Brierley (1998) have shown that the massive sedimentation that resulted from European disturbance in the Bega catchment in New South Wales (which resulted in significant channel changes) was out of phase with FDR/DDRs. Brooks & Brierley (2000) thus argue that human alteration of channel and catchment conditions and increased geomorphic effectiveness of floods are the principal reasons for changes in channel morphology in NSW.

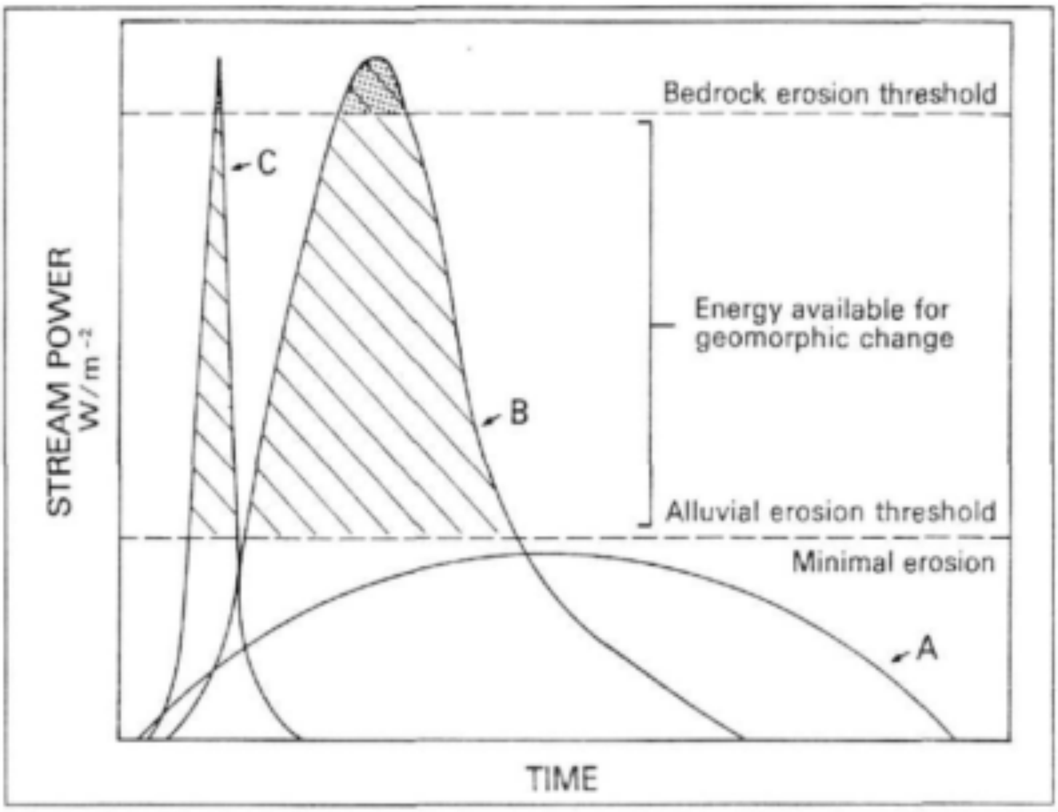


***Figure 3.1**: Conceptual stream power graphs used to determine geomorphic effectiveness of different types of floods (after Costa & O'Connor, 1995).*

3.9 Environmental flows in geomorphology

The final section of this chapter will consider the concept of environmental flows. For a full review see Dollar (2000). The ecological diversity and productivity of channels and flood plains are directly related to the areal extent, complexity and variety of physical habitats. This includes the channel bed, side channels and related habitats, as well as irregularities in the channel that provide cover and refugia from high velocity flows. This variety is dependent on the full range of natural flows, both high and low. Where rivers are impounded, reduced magnitude and frequency of flooding may lead to the accumulation of finer sediment on the channel bed. Where this occurs over long periods of time, the channel may narrow, resulting in increased flood risk and reducing the variety and areal extent of aquatic habitat (cf. Finlayson *et al.*, 1994; Gippel & Stewardson, 1995). The determination of the magnitude and frequency of regulated flows necessary to maintain the aquatic environment in a 'natural condition' is known as *environmental flow determination*. Environmental flows thus fall within the broad magnitude-frequency debate. Determining environmental flows is a complex endeavour. Methods range from simple abstraction of stream flow records to more complex techniques such as the Instream Flow Incremental Methodology (IFIM) (Milhous *et al.*, 1989). Traditionally, there are four main methods for determining environmental flows (Reiser *et al.*, 1989):

- *self-adjusted channel methods* base flows on a statistic determined from the pre-dam flow regime, the assumption being that the pre-dam channel has achieved a form of equilibrium;
- *statistical methods* recommend flows based on a flow duration or flood frequency curve;
- *sediment entrainment methods* recommend flows based on the discharges at the threshold of particle motion; and
- *direct calibration methods* involve the observation of bed movement, sediment transport or changes in fine sediment content by bed gravels.

There is much debate in the literature as to the goals of environmental flows. This is partly a result of the lack of consistency in the terminology employed. The objectives of the recommended flows need to be clearly stated. Terminology such as maintaining the river in a 'natural state' is too broad and can serve no real purpose. The goals must be stated in a manner that permit the identification of a particular discharge and water volume to achieve certain objectives, while accepting that in all cases there will be uncertainty associated with estimates of sediment transport.

Kondolf & Wilcock (1996) argue that when determining an environmental flow a distinction must be made between the ages of impoundments. For recently built impoundments, objectives may be stated in terms of maintaining certain aspects of the existing channel. In such cases, it is prudent to use flows based on the natural hydrograph. For old impoundments, the channel may already have adjusted to the regulated flow regime. Thus, methods for determining a flushing flow, such as using the natural hydrograph or channel geometry, may not be appropriate as they implicitly assume a mutual adjustment between hydrology, channel geometry and sediment transport. Furthermore, the range of flushing objectives are limited by the dam operating rules, release capacity of the reservoir, degree of post-dam adjustment, public safety and legal constraints (McMahon & Finlayson, 1995). In this case, it may only be possible to specify flows that perform some of the objectives, such as removal of fines. Other objectives such as maintaining natural channel geometry cannot be met (Kondolf & Wilcock, 1996; Wilcock *et al.*, 1996a).

Despite these inherent difficulties, the holistic management of rivers requires that an environmentally acceptable flow regime is based on sound scientific principles (Petts, 1996). Traditionally, environmental flows have been based on a minimum flow requirement, but the conservation or maintenance of a system requires a full range of flows. Petts (1996) established that the primary need in environmental flows is underpinned by five scientific principles: longitudinal connectivity, vertical exchanges, flood plain flows, minimum flows and optimum flows. The determination of all of these principles is complex, and requires an in-depth study of the river basin. This in-depth analysis is often lacking and, consequently, models used for determining instream flow requirements are imprecise. Furthermore, Petts (1996) makes the point that ecosystem response to flow regulation, physical habitat alteration and manipulation of biological communities is as yet indeterminate, and the models remain qualitative. Nevertheless, the ecologically sound allocation of instream flow requirements remains a fundamental component of environmentally sound river management. For the geomorphologist, this is essentially embodied in the magnitude-frequency debate.

3.10 Summary and conclusions

The aim of this chapter was to provide a conceptual framework for the magnitude-frequency debate. It has been pointed out that dominant discharge is primarily a concept, while the bankfull discharge and effective discharge are practical ways of determining or defining dominant discharge. Dominant discharge, bankfull discharge and effective discharge cannot, however, be used interchangeably. It has also been demonstrated that these concepts need to be applied with caution in different climatic and geomorphic regions. Nevertheless, they provide a useful means of moving the magnitude-frequency debate forward.

Furthermore, it has been pointed out that the role of floods is of great significance in arid and semi-arid rivers and in rivers that are strongly controlled by bed rock. In these rivers, large floods are often the only flows that can be considered to be effective. This is of particular significance in southern Africa which has a highly variable hydrological regime and strong bed rock influence in the channel boundary. These issues will be taken up in Chapters 9 and 10.

Chapter 4: Geomorphological approaches to bed material transport

"Researchers have already cast much darkness on the subject,
and if they continue their investigations we shall soon know nothing at all about it."
Mark Twain

4.1 Introduction

Schumm (1971) has shown that one of the major factors determining the shape and pattern of a river is its sediment regime. Although bed load constitutes a small fraction of the total sediment transported by a river, the movement of bed load is often responsible for the problems associated with shifting channels, loss of reservoir capacity and with local difficulties that arise in water abstraction (Reid *et al*., 1985; Kondolf, 1995). Morisawa (1985) argues that a river will maintain a channel morphology that is most suited to the transportation of its bed load. Channel pattern has traditionally been seen in part as a function of bed load and calibre. The classification of channels according their bed load characteristics is common (cf. Schumm & Khan, 1972; Schumm, 1977; Miller, 1984; Church *et al*., 1989). Reid & Frostick (1997) argue that a thorough knowledge of bed load transport in a river is essential, as the movement of bed load acts as a regulator of a river's character, geometry, planform, cross-section and long profile.

By inference then, any change in sediment supply or transport will have an impact on the fluvial system. Changes in sediment supply may be in response to tectonic movement, climatic change, major floods, land use change or human modification of the fluvial system (e.g. impoundments, water abstraction). If these changes are transient, they may cause sediment slugs or pulses to move through the system, marked by sedimentation zones in which changes in form and pattern are common (Church & Jones, 1982; Church, 1983). Changes in supply make the situation extremely complex, as supply events may be both spatially and temporally episodic (cf. Nordin, 1963; Ferguson, 1987; Simons & Simons, 1987). Temporal and spatial storage are therefore important determinants of potential channel form and pattern.

Clearly, bed material load in rivers plays an important part in understanding the functioning of fluvial systems, but there are also numerous other factors to consider. These include channel and valley slope, these are often functions of tectonic history (Gregory & Schumm, 1987); perimeter conditions, including vegetation (Thorne, 1991; Rowntree & Dollar, 1999); percentage of silt and clay in the channel banks (Knighton, 1987); human impacts, both direct and indirect (Park, 1981) and, channel forming discharge as discussed earlier. The focus of this chapter will be on bed material transport.

4.2 Basic terminology

The term *load*, as used in sediment transport, refers to the sediment in motion in a river. It is also used to denote the *rate* at which sediment is moved, for example, kilograms per second or tonnes per day. The *load* is further divided into two categories, *bed load* and *suspended load*. *Bed load* is defined as that part of the load moving on or near the bed by rolling, saltating or sliding. Bagnold (1973) defines bed load as those grains that are dispersed upwards from the stationary bed by occasional grain-to-grain and grain-to-bed impacts as the prevailing fluid drag causes them to shear over each other. Upward dispersive stress is balanced entirely by the immersed weight of the moving grain, implying that no net upward-directed fluid stress affects the bed load. Lift on bed grains due to fluid pressure variation around them is described by the Bernoulli equation. Table 4.1 presents a classification of sediment transport.

Of significance to this discussion is the issue of sediment supply. A hydraulically-controlled stream is one that is capable of moving virtually all sizes of material on the streambed. The amount transported is a function of the water's energy. For example, in a sand-bed stream there is virtually an unlimited supply of transportable material on the bed and it can be assumed that whatever is being carried is only limited by the energy of the water. A supply-limited stream is one in which there is a limited supply of transportable material on the bed, and the stream is able to transport more sediment than it is presently carrying. The impact of flow regulation may therefore be different in hydraulically-controlled and supply-limited streams. In a hydraulically-controlled stream, if flows were reduced aggradation would be expected because sediment supply would not change. In a supply-limited stream the capacity to carry sediment is much higher than the amount being delivered to the system; the flows could therefore be reduced and it would still be competent to transport the delivered material without aggradation occurring.

Table 4.1: *Classification and measurement of sediment transport.*

Movement classification	Source classification
Suspended load: is suspended in the flowing water by turbulent eddies. It moves faster than bed load.	*Bed material load:* is the material contributed by the streambed. Can be calculated by hydraulic calculations.
Bed load: moves by rolling, saltation or hopping along the stream bed. It is 'pushed' by the water. This pushing force is correlated with velocity and can be expressed as shear stress.	*Washload:* is always carried in suspension and washes through the system. It is not found in appreciable quantities on the bed. It cannot be determined by hydraulic calculations.

4.3 Particle entrainment

Part of the problem in predicting bed load transport is predicting the initial entrainment and movement of particles (Carling, 1983). Considerable effort has been expended on microscale studies of flow resistance, incipient motion of bed material and bed load transport (Johnston *et al.*, 1998). A particle generally starts to move when the force of the column of moving fluid that intercepts it generates a moment equal to the oppositely directed moment of the immersed particle weight. This is the balance between the fluid forces of drag and hydrodynamic lift, which turns a particle, and the resisting forces of the immersed-particle weight, which keeps the particle at rest (Helley, 1969). When the two opposing forces are just in balance, the fluid is competent to move its bed particles and critical or threshold conditions exist (Andrews, 1983). This assumes that the particle is available for entrainment. The conditions necessary to initiate motion depend on particle size, slope, specific gravity, shape, density, surface roughness, orientation angle, surface packing, exposure to flow and so on (cf. Beaumont & Oberlander, 1971; Miller *et al.*, 1977; Morisawa, 1985).

Reid *et al.* (1997) make the point that most transport equations incorporate a term that defines the critical flow condition for transport. The reliable application of these equations therefore depends on the appropriate specification of these conditions. The conditions under which particle movement ceases are equally important, and are not necessarily the same as those conditions that initiated motion. Most researchers make use of critical shear stress, or critical average velocity (cf. Shields, 1936), while some advocate the use of unit stream power rather than shear stress (cf. Yang, 1973).

Andrews (1983) reports on an investigation to determine the threshold conditions necessary to entrain gravel and cobbles from a river bed composed of heterogenous material. In sand-bed rivers, bed forms have a major impact on transport rates (Bradley *et al.*, 1972; Dietrich *et al.*, 1979). Andrews (1983) was able to show that the presence of bed forms in all types of rivers considerably increases the shear stress necessary to initiate particle motion compared to the critical value for a flat bed. Leopold *et al.* (1964) had already noted that particle spacing exerted more control over movement than did particle size, and they were able to show that little relationship existed between the size of the gravel and the distance moved.

Wilcock (1992) has suggested that where a bed has coarse, mixed-size sediments, all sizes may begin moving over a range of flow conditions that is relatively narrow. A number of authors (cf. Komar, 1987; Wiberg & Smith, 1987) have shown that in the size range of medium sands through to gravel, larger particles of a size distribution are moved at flow stresses less than those required to entrain that size from a uniform bed. This issue will be discussed further in Section 4.4. In the opposite direction, the finer-sized fractions require greater flow stresses than if they had formed under uniform deposits. The complexity of entrainment is infinitely greater under non-uniform bed conditions. It would appear that the bed condition acts as a major controlling factor in determining incipient motion, especially in gravel- and cobble-bed rivers. This is particularly so after a prolonged period of no sediment transport, where the bed material has had time to become consolidated (Reid *et al.*, 1997). The infiltration of fine, cohesive sediments into a framework of coarser sizes can create a powerful cementing effect. Reid *et al.* (1997) have demonstrated from field measurements that negligible transport may occur during the rising stage of the first flood after a long period of stasis. Once the armour layer or bed structure has been broken, transport on the falling stage of the hydrograph may be considerable, thus the conditions for the initiation and cessation of motion can be substantially different. Where floods are closely spaced, however, the bed material remains comparatively loose and offers less resistance to entrainment, such that considerable transport will occur on the rising limb of the hydrograph (Reid *et al.*, 1997). The critical conditions are, thus, to some extent dependent on flow history so that it is possible for bed load transport rates to vary widely, even at the same river stage, or during the same flood event.

Baker & Costa (1987) have attempted to determine the impact of flooding on sediment entrainment and bed load transport and have found that the highest shear stresses (Equation 4.1) and stream power per unit area (Equation 4.2) are not necessarily associated with the largest discharges. High values of stress and power occur mainly in bed rock channels. Large rivers like the Mississippi and Amazon that experience major floods in fact experience relatively low unit stream power as the increase in discharge is accommodated by width adjustments as opposed to depth and velocity adjustments in bed rock rivers (Baker & Costa, 1987). Magilligan (1992) has shown that major morphological adjustments in alluvial rivers do not occur unless mean bed shear stresses exceed 100 Nm^{-2} or stream power per unit area exceeds 300 Wm^{-2}. In bed rock rivers Wohl (1992) has demonstrated that boulder bars only become mobilised at unit stream powers of around 1000 Wm^{-2}. Floods that generate these levels of stream power are thought to have a return period of around 200 years in bed rock rivers.

$$\tau = \gamma RS \qquad \textit{(Equation 4.1)}$$

τ shear stress (Nm^{-2})
γ specific weight of the fluid (9800 Nm^{-3})
R hydraulic radius (m)
S energy slope (m/m)

$$\omega = \left(\frac{\gamma Qs}{w}\right) \qquad \textit{(Equation 4.2)}$$

ω unit stream power (Wm^{-2})
w the channel width (m)

Pitlick & Van Steeter (1998) propose that the key factor in estimating thresholds for sediment transport and channel change is developing appropriate methods of determining boundary shear stress (τ) and critical shear stress (τ_c). Average boundary shear stress is given by

$$\tau = \rho g DS \qquad \textit{(Equation 4.3)}$$

ρ is the density of the water (kg m^{-3})
g is the gravitational acceleration (m s^{-1})
D is the flow depth (m)

In the absence of direct observations of particle entrainment the only practical means of estimating τ_c is to use the Shields criterion where

$$\tau_{critical} = \tau_{ci} = \tau_{ci}^{*}(\rho_s - \rho)gD_i \qquad \textit{(Equation 4.4)}$$

τ_{ci}^{*} dimensionless shear stress
ρ_s density of the sediment (kg m^{-3})
D particle diameter (m)

There has been considerable discussion (cf. Parker *et al.*, 1982; Gomez, 1995) as to the minimum value of τ_{ci}. It is now fairly well recognised that significant motion of the bed, which is characterised by continuous movement of particles and much higher transport rates, occurs at τ_{c50}^{*} (where τ_{c50}^{*} is the critical dimensionless shear stress for the particle size where 50% of the bed material is finer) in the range of $0.045 < \tau_{c50}^{*} < 0.06$ (Wilcock & Southard, 1989; Andrews, 1994; Pitlick & Van Steeter, 1998). At discharges higher than this ($\tau_{c50}^{*} < 0.09$) the transport is so rigorous that gravel-bed forms begin to develop. The impact of bed forms on bed material transport is discussed in Section 4.4. Minimum values of $\tau_{c50}^{*} \sim 0.03$ are required for initiation of transport, but at these levels very few particles of any size are moving and bed material transport rates are very low (Pitlick & Van Steeter, 1998).

Carling & Tinkler (1998) have shown that where large boulders are of the same magnitude in terms of vertical dimension to the depths of normal floods (recurrence intervals in the range of 1 to 5 years), it is questionable whether flow magnitudes experienced over decades or centuries are competent to move them. It is therefore difficult to determine an initial motion criteria for large boulders in shallow, non-uniform and unsteady flow conditions. In bed rock systems, flow is frequently not only non-uniform, but the mode of boulder movement may be by sliding as well as rolling. It is thus clear that empirical and theoretical relationships between the entrainment force and the force resisting motion commonly involve coefficients that are substitutes for the imperfect knowledge of critical parameter values in the force balance. The result of this is that a single coefficient subsumes various physically distinct effects. These findings beg the question whether the classic concept of competence is of relevance in gravel-bed rivers with complex bed forms. The present state of knowledge is certainly incomplete and, as Carling (1983) has stated, insufficient data presently exists for defining a threshold of motion for (large) particles in natural stream flows.

4.4 Bed heterogeneity

The structure of the channel bed has been shown to have a major impact on bed load transport (Brayshaw *et al.*, 1983; Rhoads, 1994b). Where sand-beds occur, most if not all of the bed is available for transport (Ferguson *et al.*, 1989). In gravel-bed rivers where there is a complex bed structure as well as a variable assemblage of grain sizes, the availability of particles for entrainment is complex. Gravel-bed rivers are defined as those in which hydraulic processes are controlled by material coarser than 2 mm in diameter. Gravel-bed rivers are characterised by macro bed forms, pools and riffles and the general absence of smaller scale ripple, dune and antidune features (Hey & Thorne, 1983).

Gravel-bed rivers are commonly armoured (Klingeman & Emmett, 1982; Dunkerley, 1990). Armour refers to a bed where coarse grains have been concentrated over the original sediment mix (Kuhnle &

Southard, 1988). The presence of an armoured layer poses a problem in the calculation of bed load transport (Nanson, 1974). It has been mentioned in Section 4.3 that heterogenous beds can affect the forces acting on a given particle in two significant ways. First, the relatively smaller particles in a mixture are hidden in the turbulent wake of the relatively larger particles and, second, the forces needed to start a larger particle rolling over smaller particles is less than that required to start a smaller particle rolling over larger particles (Bathurst, 1987a). This would suggest that less shear stress is required to entrain a given size particle if that particle is surrounded by smaller particles rather than larger particles (White & Day, 1982; Andrews, 1983; Proffitt & Sutherland, 1983). For bimodal sediments, transport may consist of sand and fine gravel moving in threads between cobbles and boulders.

In many cases, the clast shapes and sizes allow for the consolidation of the clasts into tightly interlocking structures during periods of low flow (Bathurst, 1987b). As noted earlier in Section 4.3, critical tractive forces may be increased by up to three times in this regard. Conversely, on the falling limb of a flood, transport may continue at tractive forces up to six times lower than that corresponding to initiation of motion on the rising stage. Thus Bathurst (1987b) suggests that, due to these factors, transport during storm events can occur at relatively high rates for up to several days after a storm. There may also be an aftermath of relatively high transport rates in subsequent storms (Tacconi & Billi, 1987).

Rhoads (1994b) has shown that flow resistance varies significantly not only between pools and riffles, but also within these distinct morphological features. Rhoads (1994b) has also shown that these differences in terms of shear stress, near-bed velocity and profile averaged velocity can be greater at single locales than the differences between pool and riffles. These differences can also vary with stage. Sediment transport for a river as a whole may be accomplished by a large number of disconnected zones of moving sediment, associated with areas of flowing water with depth and velocity sufficient to entrain and move bed material (which are termed jet zones) (Mosley & Jowett, 1999).

The acknowledgement of the significance of bed microforms and the changing integrity of the armour-layer appears to provide some explanation as to why bed load discharge is often out of phase with changing hydraulic conditions (Reid & Frostick, 1987; Hassan & Reid, 1990; Hoey & Sutherland, 1991). Reid & Frostick (1987) argue that most bed load transport equations are based on the assumption that the bed of a stream will respond to the applied stress in the same way, and that bed load begins and ends at the same threshold value of applied force. Both these assumptions have been shown to be inappropriate (cf. Brayshaw, 1985; Reid & Frostick, 1987). Furthermore, bed load transport equations assume that bed load transport rates will continue to rise as a function of increasing stream energy (stream power or shear stress).

Reid & Frostick (1987) argue that the mismatch between the flood hydrograph and sediment transport rates can be ascribed to the effects of bed microforms and pebble clusters, and the fact that there are significant differences between traction thresholds at the beginning and ending of sediment motion. Pebble clusters are the most common microform in gravel-bed rivers (Reid *et al.*, 1997). In sand-bed rivers these are usually ripples and dunes. Pebble clusters are groups of interlocking clasts formed around exceptionally large bed particles and standing above an otherwise planar gravel-bed. The principal components of clusters have been shown to be an obstacle clast, around which is developed an upstream stoss deposit and a downstream wake deposit (Brayshaw, 1985) (Figure 4.1). Grains in the lee of an obstructing particle suffer considerable reduction in lift and drag forces. Accordingly wake-side clasts are far less susceptible to entrainment than are their exposed counterparts (Brayshaw, 1985). Brayshaw (1985) has further shown that in a number of gravel-bed streams, only 29% of the particles can be considered to occupy reasonably exposed positions - the implicit assumption in treatment of initial motion and bed load transport equations. Furthermore, Brayshaw (1985) argues that between 50% and 70% of bed particles can experience a delay in predicted incipient motion beyond that predicted for more exposed equivalents of like size and shape. Rooseboom & le Grange (1992) have shown that these microforms can increase roughness to such an extent in sand-bed rivers that negligible transport may occur, even during flood conditions.

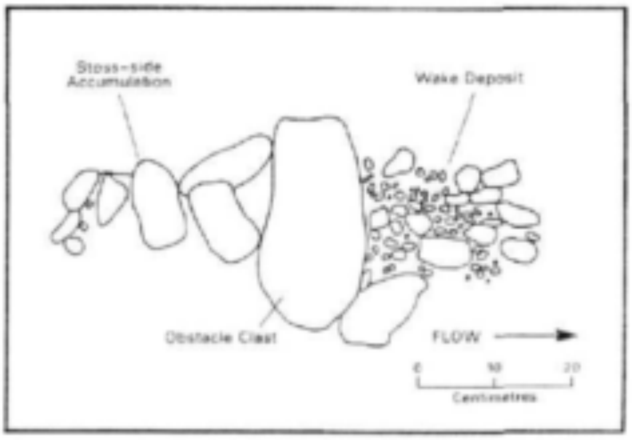


Figure 4.1: *Obstacle clasts (after Brayshaw, 1985).*

Plate 4.1: *Bed structures in a boulder bed reach of the Buffalo River, Eastern Cape.*

4.5 Temporal variations in bed load transport rates

Temporal variability in bed load transport rates under quasi-steady flow conditions were first identified in the 1930s (Carey, 1985; Hoey, 1992). As mentioned in Section 4.3, transient bed load transport conditions are commonly found in many different environments in the field (cf. Lekach & Schick, 1983; Proffitt & Sutherland, 1983; Ashworth & Ferguson, 1989; Ashmore, 1991; Schmidt & Ergenzinger, 1992; Wharburton, 1992; Reid *et al.*, 1998). Short-term variations in bed load transport have been observed in gravel-bed rivers at times of steady streamflow (cf. Klingeman & Emmett, 1982; Carling *et al.*, 1998), while longer-term pulses at uniform flow have also been shown to exist (cf. Pickup *et al.*, 1983; Nicholas *et al.*, 1995). As mentioned earlier, at a given discharge, bed load transport rates for the rising and falling limb of the hydrograph can differ by an order of magnitude, with the rising limb rate being less than the falling limb rate or vice versa (Kuhnle, 1992; Moog & Whiting, 1998).

During the rising limb, availability and mobility of bed material for transport appear to be controlled by the armour layer. These conditions may exist well beyond those producing critical tractive forces. During the falling limb there is generally a reduction in bed load transport as the armour layer is re-established during the waning limb of the flood flow (Gomez, 1983). Reid *et al.* (1985) have suggested that one of the factors that may help explain the confusion surrounding hysteresis effect with the passage of a flood wave is the availability of sediment from one flood to another. This availability need not necessarily be due to the temporal exhaustion of supply (cf. Leopold & Emmett, 1976), but may be due to temporal differences in the resistance of the bed material to movement. Long periods between floods may allow for particle interlocking, thus adding strength to the bed. As a result, the first flood generates significant coarse bed load during the recession limb, only after the rising limb has loosened the structure and winnowed out the fines.

Reid & Frostick (1987) have shown at Turkey Brook, north of London, that the incidence of bed load transport in relation to floods is highly variable. At times bed load may be initiated on the rising limb of the hydrograph, at other times no movement occurs until after the flood peak on the recession limb of the hydrograph. It is clear from the international literature that transport rates do not follow a simple pattern mimicking the flood hydrograph. From a river management perspective, the occurrence of large-scale bed load pulses presents considerable difficulties for any attempt to sample or predict mean bed load transport rates (Goff & Ashmore, 1994). The movement of macropulses has been argued as being a major factor in controlling channel change (cf. Lane *et al.*, 1996). Where bed load moves in the form of pulses, actual transport rates may be considerably lower than predicted rates.

A further complication in bed load transport is that of velocity reversal. Sidle (1988) has shown that during moderate flows, transport competence is greater in the riffle than in the pool and largely sand-sized particles are transported. As flow increases, the hydraulic gradient of the pool-riffle sequence tends to even out and coarse particles become entrained and are subsequently deposited on downstream riffles. Keller (1971) suggested that this phenomenon accounted for the areal sorting of sediments and the maintenance of pool-riffle sequences. Jackson & Beschta (1982) similarly suggest that this results in a 'leap frogging' effect where bed material is moved from riffle to riffle. New evidence has shown that this situation is not necessarily found in all pool-riffle sequences (cf. Knighton, 1998).

A conceptual approach is needed that takes account of the two phase transport process that may occur in coarse-bedded rivers (cf. Beschta, 1981; Jackson & Beschta, 1982; Klingeman & Emmett; 1982; Bathurst, 1987a; Knighton, 1987). *Phase I transport* occurs when the flow is below a threshold for the breakup of the armour layer and bed load consists of the finer fraction of the bed material moving between the coarser fraction (Gomez, 1983; Knighton, 1987). The fractions are small and, consequently, bed load transport equations based on the assumption of a uniform sediment size will necessarily over-predict the observed volume as they assume that all size fractions are mobile when transport begins. In boulder-bed streams, where most transport is Phase I type, Knighton (1987) suggests that over-prediction may be several orders of magnitude.

Phase II transport occurs when the flow exceeds a critical value for the movement of the coarse or armour layer, or bed macroforms. Under these conditions, it is possible for all size fractions to be moved, and therefore sediment supply is unlimited. Parts of the coarse surface layer may be maintained and as a result of the subtle balance derived from the coarse surface material and from the exposure/hiding effect, there is approximately equal mobility for all size fractions. The effect of the non-uniform size distribution is then minimal and predictions of bed load transport can be based on one size diameter without serious error (Knighton, 1987). Phase II type transport equations occur where there is a restricted range of bed material sizes (1-100 mm) and in which sediment moves in events much greater than the thresholds needed for bed load transport (Knighton, 1987). These are likely to be gravel-bed rivers and have slopes of less than 1%.

Much of the research into bed load transport has been conducted in sand- or gravel-bed rivers with a permanent flow. Research into bed load transport rates in ephemeral arid systems has only recently made progress. Laronne & Reid (1993) have reported on data from a bed load trap in Israel which shows that ephemeral rivers can on average transport bed load up to 400 times more efficiently than perennial counterparts. They argue that this increased efficiency is due to the different vertical structure of the stream bed. While perennial gravel-bed rivers have a well-developed armour layer, ephemeral rivers have poorly developed or no armour layers. The lack of an armour layer results in a reduction in size-selective transport, and consequently ephemeral rivers may be more effective bulk sediment carriers (Reid & Laronne, 1995). This leads to the problem of predicting bed load transport in ephemeral streams, as most sediment transport equations are calibrated and designed for sand- and gravel-bed rivers (Reid *et al.*, 1996).

4.6 *Approaches to predicting bed load transport*

There are a number of approaches to predicting bed load transport. These include formulae based on shear stress (e.g. DuBoys, 1879), discharge (e.g. Schoklitsch, 1934), stochastic functions for sediment movement (e.g. Einstein, 1950) and those based on stream power (e.g. Bagnold, 1980). The development of these models are based on certain theoretical considerations that attempt to link bed load transport rates to hydraulic and sedimentological properties, empirical observation and testing to determine the coefficients and constants on the basis of the available data (Gomez & Church, 1989).

The theory behind most bed load transport equations is that there is always a determinant relationship between sediment discharge and a dominant independent variable such as flow discharge, flow velocity, energy slope or shear stress (cf. Yang, 1973; Bathurst, 1987b; Karin, 1998). The preceding discussion has demonstrated that this is not always the case. Part of the problem of relating bed load equations to field conditions is that most bed load equations were developed in the laboratory with uniform sized sediments (Yalin, 1963; Bathurst, 1987a). Rhoads (1994a) has pointed to the significance of the type of flume in determining incipient motion. In a sediment-feed flume, the final equilibrium state is determined by flow and sediment input and is independent of initial conditions. In a recirculating flume, the upstream sediment input depends in part on the initial composition of the bed material. Thus the equilibrium state is not independent of initial conditions. Further important considerations are that all available sizes are assumed to begin to move at the same critical flow conditions, that sediment density is uniform, and that negligible movement occurs below this critical condition.

Furthermore, many field based studies of sediment transport are directed towards assessing sediment related problems, rather than seeking to evaluate theory. Bagnold (1966) states that the dilemma is that no established branch of physics has interested itself in the two-phase flow (fluid-solid) that is involved in sediment transport. It follows that the complexity of two-phase flow cannot properly be tackled until the intricacies of fluid-flow are mastered, fluid turbulence in particular. The complex nature of sediment transport simply cannot be recreated in a flume environment, thus all equations developed for sediment transport estimation remain at best estimates.

Ackers & White (1973) rejected the early preference for using shear stress as the main parameter defining a rivers transporting power. They suggested that the total shear on a deformed bed is in part composed of along-stream components of the normal pressures on the irregular bed profile. Although these pressures may contribute indirectly to sediment motion through suspension, many sediment transport equations separate the bed shear into non-transporting form loss, and shear on the grains. The rate of transport is sensitive to transporting power, and as such inaccuracy in the separation procedure gives rise to large prediction errors. Ackers & White (1973) argue that this factor is important, as very few natural streams have a plane bed. They suggest that because shear stress is not the most rational basis of sediment transport function, stream power should be used instead.

An alternative approach to predicting bed load transport is to use the virtual velocity method. This method uses data of the virtual velocity of the particle movement, dimensions of the active channel layer, and the porosity and density of the bed material (Haschenburger & Church, 1998). Virtual velocity is defined as the total distance travelled by individual grains divided by the measurement interval - typically the total time of competent flow during a flood event. The fundamental equation for the mass transport of bed material is given by:

$$G_b = v_b d_s w_s (1 - p)\rho_s \qquad \textit{(Equation 4.5)}$$

v_b	mean travel rate of the bed material (m h^{-1})
d_s	active depth of the stream bed (m)
w_s	active width of the stream bed (m)
p	fractional porosity of the channel sediment
ρ_s	mineral density of the sediment (kg m^{-3})

Haschenburger & Church (1998) were able to show that the virtual velocity method provided good results and, in general, replicated what is known about sediment transport-flow relations in gravel-bed rivers derived from conventional sampling approaches. In particular, they found that the virtual velocity approach confirmed the sensitivity of transport to stream power that is typical for gravel transport near the threshold for significant transport. Results showed the often quoted disproportionate importance of the highest flows in transport which arises from the non-linear increase in transport with flow magnitude (Haschenburger & Church, 1998).

4.7 *Limitations of bed load transport equations*

Despite over a century of work on bed load transport, a satisfactory, universal formula has yet to be developed. Gomez & Church (1989) note that there are more transport formulae than there are reliable data sets by which to test them. Reid & Frostick (1987) have stated that even the best known predictive equations have not yet been sufficiently developed for universal application to rivers outside the one from which they were derived. They ascribe this to two factors. First, each river has a unique hydraulic and sedimentological character. Second, even where complicated bed arrangements have been acknowledged (cf. Einstein, 1950; Proffitt & Sutherland, 1983), there has been a tendency to seek an *average* response of particles to applied stress. A number of assumptions are made when using bed load transport equations. These include:

- that the flow and sediment properties for the period in question are invariant and can be described with reference to a steady state;
- that the bed load transport is a unique function of tangible and comprehensive flow and sediment parameters; and
- that the maximum possible amount of bed load is being transported. In other words, that the formulae describe an equilibrium state.

Computed results are susceptible to errors stemming from uncertainties in the exact values of the hydraulic variables, in particular velocity, depth and slope, which affect calculations of critical shear stress and stream power (McLean, 1985). Gomez & Church (1989) have shown that sampling errors and conceptual errors may produce errors of up to an order or two of magnitude. Most bed material is transported by runoff events in which flows are very unsteady in nature, yet the effect of flow unsteadiness on the rate at which sediment is transported remains poorly understood. Despite this, all bed load transport equations assume steady uniform flow. Furthermore, formulae are derived from a restricted data base. This has resulted in a proliferation of bed load formulae rather than a consolidation of existing knowledge. The traditional approach has been to calculate the transport rate for a single characteristic grain size, for example, the median. This can lead to poor results in bimodal bed rivers (Wilcock, 1998).

As mentioned previously, where a heterogenous bed occurs, only the highest flows are capable of moving the entire bed. Even where moderate events occur, only partial sediment transport occurs with some sizes in motion and others not. Under these conditions the transport rate for the moving size fraction is not directly comparable with the rate for a uniform bed material of the same mean size as those fractions within the bed material. As a result, equations assuming a uniform bed material size will overestimate the observed rate since they assume that once any transport begins, all size fractions are in motion. One way of overcoming this problem is to apply the transport equation separately to each bed material size fraction and sum the resulting partial transport rates to give the total rate. Additional problems are then encountered as the relative effects of the different size fractions in impeding or promoting each others' movement and for the effect of bed armouring need to be taken into account (Reid *et al.*, 1997). Little progress has been made in this regard.

4.8 Comparison of bed load transport equations

Yang (1973) applied the following criteria for evaluating sediment transport equations: the equation should be theoretically sound; it should be dimensionally homogenous; it should be thoroughly verified by both laboratory and field measurements that cover a wide range of variations in both flow and sediment conditions; the parameters used in the equation can be obtained from both laboratory flumes and natural streams without much difficulty; and the computations should be simple and straightforward. Due to the large number of sediment transport formulae available, it is instructive to select a formula most appropriate to the physical conditions of the bed. The suitability of the formulae should be judged on the generality of the basic assumptions used and, most importantly, by comparison of the bed load discharge prediction with measurement. A number of comparisons for accuracy of different formulae have been made. These include White *et al.* (1975); Alonso (1980) and Yang (1984). Most bed load transport formulae were developed for sand-bed rivers and as such should not be applied outside of these conditions (Vanoni, 1964; Graf, 1971; Simons & Şentürk, 1977). Fewer equations have been developed for gravel- and boulder-beds, those that exist have been reviewed in White *et al.* (1975); Bathurst *et al.* (1987) and Gomez & Church (1989). The modification of popular sediment transport models to fit local conditions is common (cf. Misri *et al.*, 1984; Smart, 1984; Bathurst, 1987a; Diplas, 1987; Phillips & Sutherland, 1989; Shih & Komar, 1990).

Many attempts have been made to verify bed load transport equations. However, one of the problems is that the various approaches can only be tested in relation to one another (Reid *et al.*, 1997). Three major problems with verification were identified by Gomez & Church (1989):

- Most attempts at verification have been based on comparing the calculated bed load transport rate with the bed load transport rate measured in a flume or a natural stream (Carson & Griffiths, 1989). Relatively few verifications refer to channels outside the sand- to fine-gravel range. The performance of these formulae has therefore not been assessed with respect to the range of grain sizes for which they were ostensibly derived.
- There is considerable overlap of data employed in the development of many subsequent evaluations (cf. Ackers & White, 1973; White *et al.*, 1975; Yang, 1973). The formulae which are most reliable were developed on the basis of relatively extensive data.
- There has been little attempt to select test data which refer consistently to the hydraulic and sedimentological conditions that the data specifically purport to describe (i.e. steady flow and equilibrium transport conditions).

Gomez & Church (1989) selected ten formulae for testing. These were divided into two categories, those applicable to sand-bed and those applicable to sand- and gravel-bed rivers. The sand-bed river equations tested included Schoklitsch (1934; 1950) and Meyer-Peter & Müller (1948). The sand- and gravel-bed equations included DuBoys-Straub formula (Straub, 1935), Einstein (1950), Ackers & White (1973), Bagnold (1980) and Proffit & Sutherland (1983). Gomez & Church (1989) found that the equations of Bagnold, Einstein and Ackers & White perform best. (For the purposes of this report, the Yang, Ackers & White and Engelund & Hansen equations were used. Justification for the use of these equations are given in Chapter 8). Only the Einstein equation consistently under-predicts the river data. Most of the formulae over-predict, possibly as a result of the failure to account for surface coarsening in reducing the rate of transport of fine material in gravel-bed rivers with low, overall rates of transport. Similarly, they fail to take account of the fact that the whole discharge may not be available or utilised for sediment transport (Gomez & Church, 1989). This effect is realised in two ways. First, no account is taken of the resistance afforded by bed forms. Second, the use of average hydraulic variables (e.g. average velocity) which relate to the entire cross-section fail to take into account the fact that only a portion of the bed may be active at any given time.

The complexity of the bed load transport process is such that little real progress has been made in the field (Carling *et al.*, 1998). Part of the reason for this is that modellers have not taken sufficient notice of the role of process in bed load transport. Ashworth *et al.* (1992 p.1895) make a plea for "the need for larger research teams, pooled equipment and expertise, and a focus on taking intensive and representative spatial and temporal hydraulic and bed load measurements using a rigorous research design".

4.9 Bed material transport and river management

Many of the problems associated with river management are related to an inadequate understanding of the role of bed material transport in rivers. Changes in the sediment load and/or bed type in rivers usually have complex, long-lasting biological consequences (Kondolf & Wolman, 1993; Trimble, 1997). Surficial bed-material size is often the primary influence on benthic invertebrate community composition and density. Bed sediment influences habitat suitability for fish, and to a lesser extent for invertebrates that live on or in the bed (ASCE, 1992).

Human impacts may change the relationship between channel hydraulics and bed sediment size. While short-term temporal variations in bed-material type are common, longer-term temporal variations in bed type occur infrequently. If sediment loading is greater than capacity, channel morphology or bed type may change. In coarse-bedded channels, such as boulder-cobble or cobble-gravel-bed streams, interstitial voids provide important habitat - the hyporheic zone. If these interstitial voids are filled or covered by finer material, such as sands and silts, their habitat value is greatly reduced. Human activity has been shown to result in hyporheic interstitial sedimentation (ASCE, 1992). It is clear that sediment management is an important component of river management. It is only recently, however, that sediment management has been considered a part of an environmental flow (Milhous *et al.*, 1994).

Van Steeter & Pitlick (1998) have shown that flow reductions in the Colorado River have resulted in significant channel narrowing, as well as reductions in side-channel areas. Discharges that approximate the bankfull stage are necessary for a clean loose substrate, critical to the reproductive success of Colorado squawfish. Narrowing of the channel represents significant losses in potential fish habitat. They found that sediment accumulation on the bed can degrade the quality of the spawning bars and fill the interstices in the bed where organisms live. These can only be winnowed out by moving the protective gravels around them (Pitlick & Van Steeter, 1998).

Wilcock *et al.* (1996a; 1996b) have shown how flow regulation in the Trinity River has reduced the mean annual flood from 525 to 73 m^3s^{-1} and the 2 year flood from 484 to 30 m^3s^{-1}. Concurrent increases in tributary sediment yield resulting from road construction and timber harvesting have created a sedimentation problem. Little transport of the bed material occurs in the river at flows less that 85 m^3s^{-1}, and no transport of bed material coarser than 1 mm occurs at typical post-dam minimum flows of 4 m^3s^{-1} (1961-1978) and 8.5 m^3s^{-1} (1978 onwards). This has resulted in the encroachment of riparian vegetation and a narrowing of the active channel. The active channel has narrowed by 20 to 60% of its pre-dam width, resulting in a straightened channel and reduced topographic variability (Wilcock *et al.*, 1996b).

4.10 Conclusions

The preceding discussion has demonstrated the significance of bed material and bed material transport in fluvial systems. It has been shown that bed material transport is a complex process which is difficult to model accurately, particularly in coarse grained, heterogenous beds under unsteady flow conditions. Very little real progress has been made either in gaining an understanding of the process itself, or in the development of realistic sediment transport models that can be applied to natural systems (Carling *et al.*, 1998). Furthermore, as long as the physics of bed load transport remain incompletely understood, there is no reason to believe that any of the available bed load transport formulae will result in accurate results (Gomez & Church, 1989).

Nonetheless, when faced with a practical geomorphological problem such as recommending flows that will perform a specific sediment transport task (e.g. entraining gravel or maintaining a riffle), the application of highly simplified, imprecise sediment transport models calibrated using empirical data is often the only practical path forward. The transport equations should therefore be seen for what they are, an approximation of the truth over a limited range of conditions, within the bounds of professional practice. It is within this context that the bed load transport equations were utilised in this research.

Chapter 5: The research problem: aims, objectives, study area and overview of research design

5.1 Introduction

The magnitude frequency concept provides a logical approach to setting geomorphological flows for the Ecological Reserve. This will allow us to address a number of relevant questions. What is the magnitude and frequency of flows which do most work transporting channel sediments? How are these flows related to channel form? Can we use channel form as an indicator of channel forming flows? What is the geomorphological consequence of changing the magnitude-fequency spectrum through flow regulation.

The aim of this research was therefore 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.

5.2 Research Objectives

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

Field surveys of cross-sectional data and bed material class for sites in 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.

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

Morphological features identified on channel cross-sections were related to hydrological data to explore the relationships between bankfull discharge, dominant discharge and effective discharge. The results of this analysis can guide interpretation of channel morphology in terms of geomorphologically effective flows.

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

It was necessary to develop a conceptual understanding of the importance of different flows for South African fluvial systems so as to contribute 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.

5.3 Selection of representative rivers

Three South African rivers were selected for research. These were the Mkomazi River in KwaZulu-Natal, the Mhlathuze River in northern KwaZulu-Natal and the Olifants River in Mpumalanga. These rivers all drain the eastern sea-board of South Africa. Because of significant uplift in the Miocene and Pliocene (c. 15 M and 2M years BP respectively), the dominant process over the geological time scale has been valley incision. No true meandering occurs in these systems. The Mkomazi River is a cobble-bed river with strong bed rock control and remains one of South Africa's least disturbed rivers. As yet, there are no impoundments along the course of the river, but this is due to change soon (Louw, 1998a). The Mkomazi provides an opportunity to study a relatively un-impacted system and therefore forms the main research component of the study. The Mhlathuze and Olifants Rivers on the other hand are highly regulated systems. The lower Mhlathuze River has a regime sand-bed channel which flows over Quaternary alluvium. In contrast, the upper Olifants River has a highly impacted cobble-bed river, with strong bed rock control. The rivers also formed part of an Ecological Reserve assessment (Louw, 1998b; Louw, 2000). These rivers therefore provided an opportunity to test the methods developed for the un-impacted Mkomazi system on two regulated systems - the Mhlathuze and Olifants systems are therefore the application systems.

5.3.1 The Mkomazi River

5.3.1.1 Regional setting

The Mkomazi River drains an area of approximately 4387 km^2 in KwaZulu-Natal (Figure 5.1). The Great Escarpment forms its headwaters and it exits into the Indian Ocean at the town of Umkomaas. The upper catchment geology is fairly simple, with Karoo sequence Elliot and Clarens sandstones capped by Drakensberg lavas. The upper-middle catchment is dominated by Tarkastad mudstones and dolerite, while the Ecca and Beaufort Group dominate the middle catchment. The lithology produces clay and clay loam soils, which are only moderately erodible (Midgley *et al.*, 1994). According to the Surface Water Resources of South Africa (WR90) (Midgley *et al.*, 1994) the estimated 'natural' sediment yield from the catchment is around 155 t/km^2/yr for the upper, middle and lower-middle catchment. The lower catchment produces an estimated 175-190 t/km^2/yr. The middle and lower parts of the catchment display a more complex geology. The catchment lithology here forms part of the Natal structural and metamorphic province, consisting of granites and gneiss. The terrain is faulted, and structural control on the channel is considerable. The geology has produced an upper catchment with steep relief, while the middle catchment can be classified as undulating. Steep relief in the lower catchment is a function of the underlying lithology.

The distribution of rainfall is reasonably consistent throughout the catchment, ranging from nearly 1300 mm per annum in the headwaters to around 1000 mm per annum in the middle and 900 mm per annum in the lower parts of the catchment. Catchment land use is mainly grazing and commercial forestry (wattle, pine and eucalyptus). Under natural conditions, the catchment vegetation would be dominated by pure grassveld and temperate and transitional forest and scrub, with false grassveld and coastal tropical forest dominating the middle and lower catchment. Overgrazing and high population densities in the upper-middle and lower parts of the catchment probably produces an increased sediment yield, although this remains untested.

Hydrological charcteristics were obtained from Midgley *et al.*, (1994) The Mean Annual Runoff (MAR) of the Mkomazi is 1089 million cubic metres. Most of the runoff is generated in the upper part of the catchment, with the lowest 33% of the catchment contributing only 14% of the total MAR. The Mkomazi catchment is in the summer rainfall region of South Africa, and consequently most of the discharge occurs during the summer months (December to March). The winter is characterised by low flows (April to October/November). The average coefficient of variation (CV) for the catchment is 0.41. The upper part of the river has a more variable regime, with a CV of up to 0.74. The Mkomazi has experienced a number of large floods. These are usually related to cut-off low pressure systems and appear to have an average return period of 20 to 50 years. Chapter 6 provides more information in this regard.

5.3.1.2 Identification of macro-reaches

The long profiles of many South African rivers display a diverse form (Rowntree & Dollar, 1996a), seldom with a uniform concave profile. This is in part a function of tectonic history and climate change, but also of variable lithology. Major breaks of slope are often coincident with changes in channel type, bed material and reach type (Rowntree & Wadeson, 1999). It is therefore instructive to subdivide the long profile into morphologically uniform reaches - these have been termed macro-reaches (Rowntree, 2000). This provides the basis for site selection and for extrapolation of sites from one reach to another (Rowntree, 2000). Two methods for delineating macro-reaches have commonly been used for South African rivers. The first is a technique developed by Rowntree & Wadeson (1999) which delineates reaches based on the percentage gradient change as measured off a 1:50 000 topographical map - generally, where gradient changes of greater than 50% occur, a reach break is denoted. A second technique is to use the CUSUM plot to identify major breaks of slope. This technique is similar to the previous technique in that it sums the cumulative percentage slopes thus making the major breaks of slope easily identifiable. For the purposes of this report, both techniques were used to identify the breaks of slope and good agreement was found between the two. Four macro-reaches (Figure 5.2) were identified for the Mkomazi River. Table 5.1 presents the characteristics of each macro-reach.

5.3.1.3 Identification of sites

Within each macro-reach, sites were selected that were considered to best represent the reach morphology. Difficulties of access to the river constrained site selection. Thirteen sites were chosen for analysis and where possible each site was surveyed using at least three fixed-point cross-sections, but at a number of sites only one or two cross-sections were surveyed where it was considered that these were sufficient to characterise the site. A stage-discharge relationship was generated for each cross-section by repeated calibration surveys. The bed material transport modelling for each site relied on hydraulic information based on the stage-discharge curves. It was therefore necessary to limit the amount of cross-sections at each site to maximise efficiency. It is considered that the surveyed cross-sections adequately represent the sites, and in total twenty-eight cross-sections were surveyed for the Mkomazi. Chapter 7 will discuss the site surveys in more detail. Details of all sites, including the cross-sectional data, sketch map and photograph, can be found in Dollar (2001).

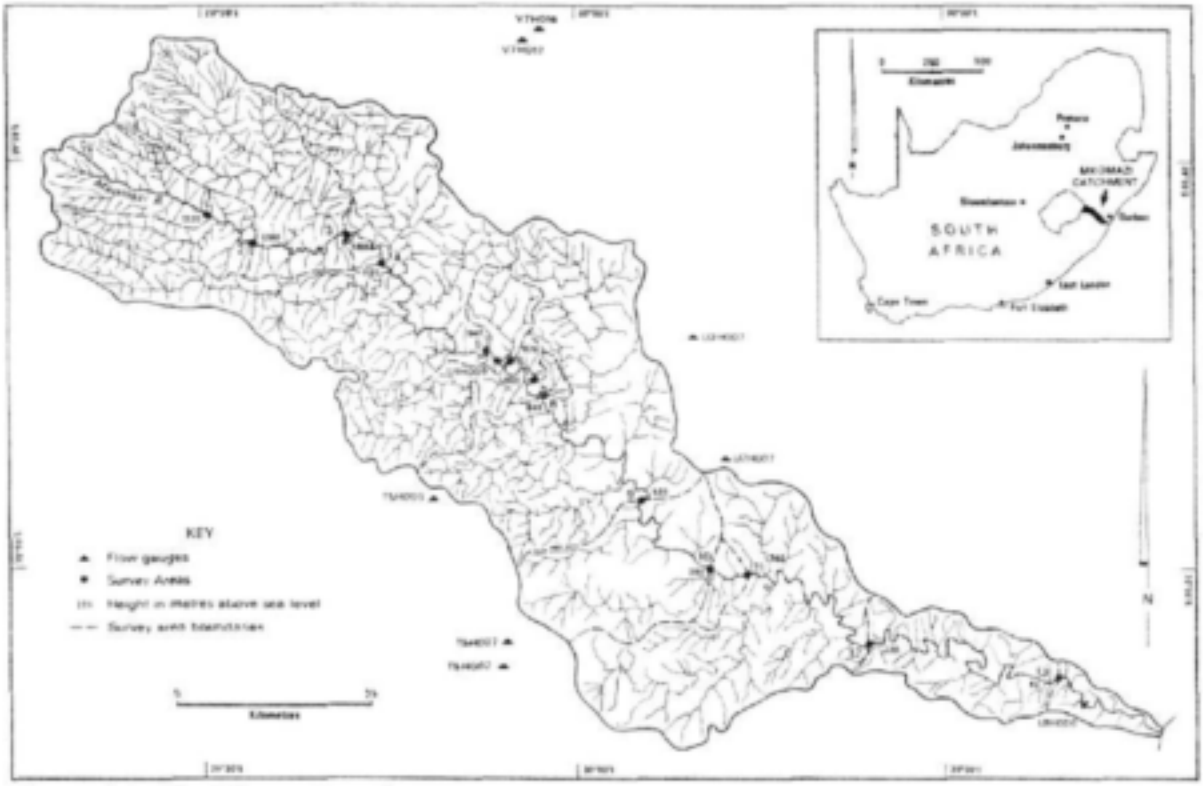


Figure 5.1: The Mkomazi catchment

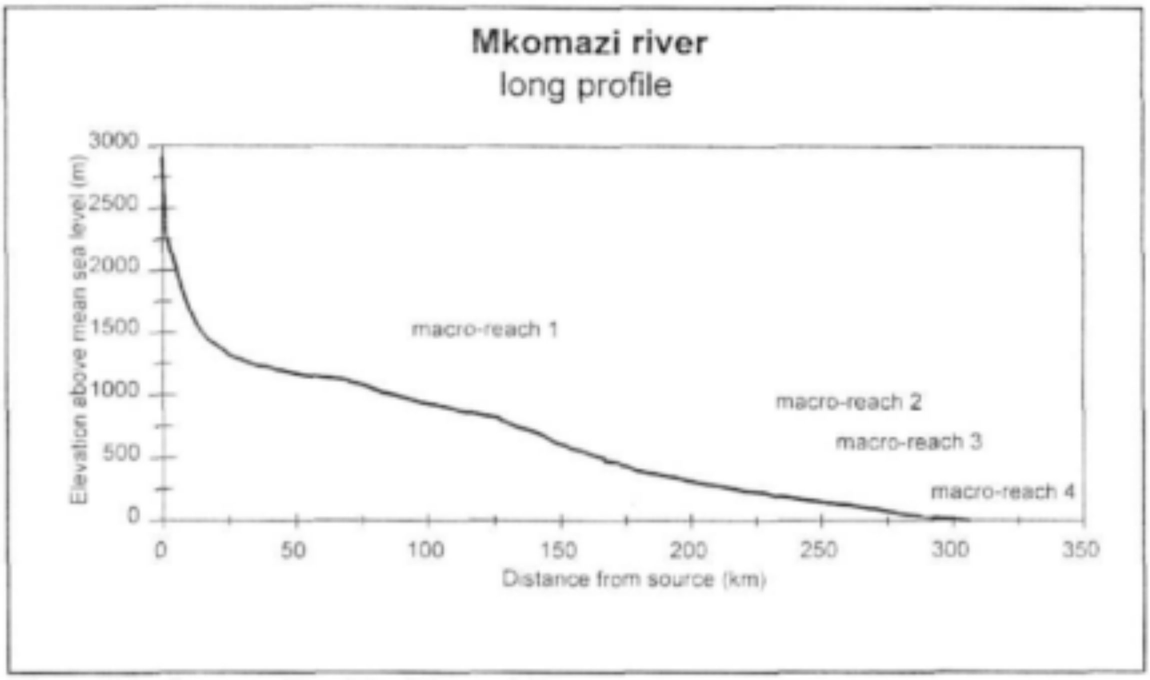


Figure 5.2: Long profile of the Mkomazi River.

Table 5.1: Characteristics of the Mkomazi River.

Macro-reach	Characteristics	Average Gradient	Geology	Site numbers
1 (2850m to 1020m)	Confined valley. Low population density. Cobble-bed foothills to mountain stream zone with cobble-bed channel characterised by plane beds, step pool morphology, rapids and pools. Floodplains generally absent, but lateral depositional bench features occur.	0.0073	Shales and mudstones with dolerite intrusions	1, 2, 3, 4
2 (1020m to 840m)	Confined to semi-confined valley. Moderate population density with extensive cultivation. Irregular channels with infrequent islands, cobble-bed foothills zone with gravel- and cobble-bed river. Pool-riffle or pool-rapid morphology, locally bed rock controlled. Narrow floodplain of sand and gravel may be present.	0.0046	Shales and mudstones with dolerite intrusions	5,6,7
3 (840m to 400m)	Confined to semi-confined valley, cultivation on floodplain areas. Commercial farming of timber and livestock. Mainly single channel with well developed lateral bars. From 620 metres the channel goes into a gorge with an anabranching channel. Mixed pool-riffle or pool-rapid morphologies in lower gradient reaches, bed rock or boulder/large cobble dominated channels in steeper sections. Rapids, cascades and bed rock controlled pools common.	0.0213	Shales and mudstones with extensive dolerite intrusions	8,9
4 (400m to sea level)	Confined to semi-confined valley. Many small 1st and 2nd order tributaries. High rural population densities. Anabranching channels common, foothill zone has mixed alluvial bed rock channel, pool-riffle morphology, sand or gravel bars.	0.0037	Instrusive granites with sedimentary sequences	10,11,12,13

5.3.2 The Mhlathuze River

5.3.2.1 Regional setting

The Mhlathuze River drains an area of approximately 4209 km^2 in northern KwaZulu-Natal (Figure 5.3). The Mhlathuze rises at about 1280 metres around Babanango and discharges into Richards Bay harbour. The geology of the area is complex, with faulting and thrust faulting impacting on the traverse of the river. The upper catchment geology is dominated by Dwyka tillite. The lower part of the upper catchment consists mainly of Natal Structural and Metamorphic province rocks such as granite, quartzite and basaltic lava. The middle catchment consists mainly of sedimentary rocks of the Ecca group, with Vryheid, Volksrust and Pietermartizburg formations occurring. The lower catchment is dominated by Quaternary sands. Weathering of the quartzites, tillites and granite produces mainly sand-sized material, resulting in a predominantly sand-bed channel. The highly faulted middle terrain affects considerable structural control on the channel. The impact of this can be seen in the numerous orthogonal turns on the river.

Estimated sediment yield from the sub-catchments range from 27 t/km^2/yr to 216 t/km^2/yr with an estimated average sediment yield of 160 t/km^2/yr (Midgley *et al.*, 1994). Catchment land use includes commercial wattle, pine, eucalyptus and sugar cane production.

Mean annual rainfall distribution in the catchment varies from 870 mm in the upper and middle catchment to around 1100 mm in the lower catchment. The Mhlathuze forms part of the summer rainfall region of South Africa. Most of the rainfall (and hence discharge) occurs during the summer months (December to April), however the seasonal distribution of flow is not as marked as for the Mkomazi River.

The Mhlathuze has been impounded by the Goedertrouw Dam since 1979. The Goedertrouw Dam is an 81-metre high earthfill embankment dam with a maximum surface area of 12 km^2 and a maximum storage capacity of 321×10^6m^3. This dam has had a significant impact on the flow regime of the Mhlathuze River. The virgin MAR of the Mhlathuze River has been estimated to be 362 million cubic metres, but the construction of the Goedertrouw Dam has reduced the MAR to around 217 million cubic metres per annum (Hughes & Smakthin, 1998). It has also resulted in the attenuation of flood peaks and higher flows (van Bladeren, 1992). This will be discussed in greater detail in Chapters 6 and 10.

The Mhlathuze has a very high CV of 0.934 (Midgley *et al.*, 1994). This is due to the geographical location of the Mhlathuze catchment in northern KwaZulu-Natal, an area subject to heavy and prolonged rains due to the frequent (once every 20 years or so) occurrence of cut-off lows which result in large floods. These cut-off lows are specific types of low-pressure systems which are strongest in the upper troposphere and are associated with strong uplift and the occurrence of widespread rain on their eastern sides (Tyson, 1986). The northern parts of KwaZulu-Natal are particularly prone to this meteorological phenomenon. (The Mkomazi catchment which is further south, is also impacted on by cut-off lows, but not as frequently.)

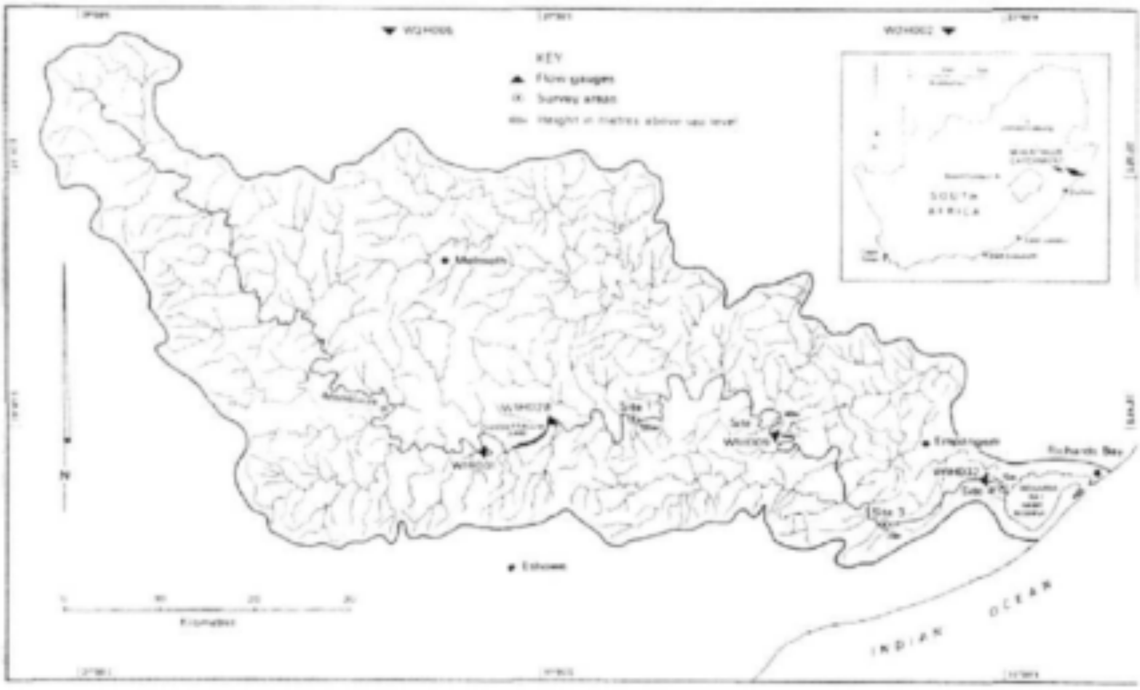


Figure 5.3: *The Mhlathuze catchment.*

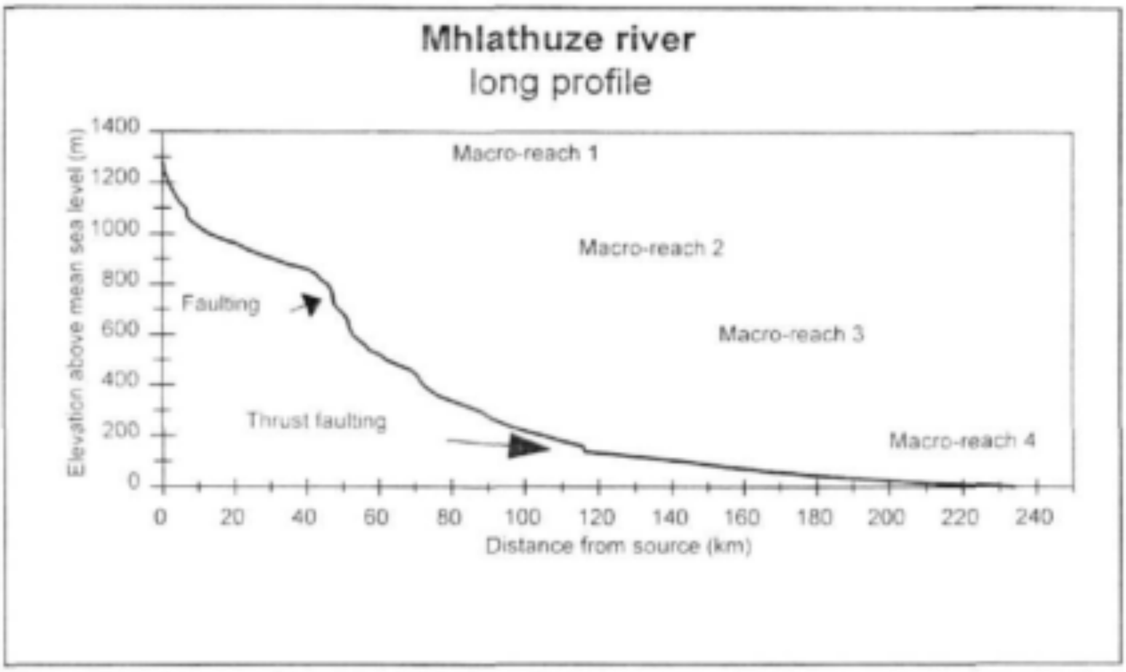


Figure 5.4: *Long profile of the Mhlathuze River.*

Table 5.2: *Characteristics of the Mhlathuze River.*

Macro-reach	Characteristics	Average gradient	Geology	Site numbers
1 (1280m to 1080m)	Confined valley with a mountain stream and a bed rock and cobble-bed channel. No floodplain is present but lateral depositional features occur in a few places.	0.0373	Dwyka tillite	0
2 (1080m to 820m)	Confined valley with no floodplain present. The topography is undulating.	0.0126	Natal structural and metamorphic province rocks including granite, quartzite and basaltic lavas	0
3 (820m to 180m)	The boundary between macro-reach 2 and 3 is coincident with the faulting of the sedimentary and volcanic rocks. The gradient is generally steep and is associated with resistant lithologies and periods of tectonic re-adjustment. The reach, although steep, displays a remarkable number of depositional features.	0.0215	Sedimentary rocks of the Ecca Group, including Vryheid, Volksrust and Pietermaritzburg formations	0
4 (180m to sea level)	The boundary between macro-reach 3 and 4 is coincident with thrust faulting of sedimentary rocks associated with the Natal structural and metamorphic province. Rapid gradient changes are common in this macro-reach as a result. Below the Goedertrouw Dam, remarkable changes occur in channel type from a pool-rapid channel type to a sinuous single thread channel. Channel narrowing and vegetation encroachment is evident. The depositional features that are common in macro-reach 3 are no longer evident.	0.0096	Sedimentary and intrusive rocks associated with the Natal structural and metamorphic province	1,2,3,4

5.3.2.2 Identification of macro-reaches

Four macro-reaches were identified using a combination of the CUSUM plot and the percentage gradient change. Table 5.2 displays the characteristics of each macro-reach. Figure 5.4 displays the long profile of the Mhlathuze River.

5.3.2.3 Identification of sites

Four sites were selected to represent the macro-reaches. The terms of reference of the Ecological Reserve assessment were that all the sites should be located below Goedertrouw Dam (Louw, 1998b)(Figure 5.3). Site 1 is approximately 25 kilometres below the dam. No major tributaries join the Mhlathuze between the dam wall and Site 1. Site 2 occurs some 35 kilometres downstream of Site 1. Between Site 1 and Site 2, a major tributary, the Mfule River joins the Mhlathuze. The Mfule also has a sand-bed channel. Site 3 is a further 35 kilometres downstream of Site 2. No major tributaries join the Mhlathuze between these two sites. Site 4 is approximately 15 kilometres downstream of Site 3, just upstream of a major tributary input, the Nseleni. Site 4 is an artificial channel that was cut by the Port authorities at Richards Bay to accommodate the development of Richards Bay harbour (Dollar, 1998b).

Site 1 has multiple channels with different water elevations. This necessitated the surveying of six cross-sections to ensure accurate hydraulic calculations. Sites 2, 3 and 4 were simple sand-bed channels, and were therefore only represented by one cross-section at each site. Site details, including the cross-sectional data, sketch map and photograph of each site, can be found in Dollar (2001).

5.3.3 The Olifants River

5.3.3.1 Regional setting

The Olifants River is a highveld river that drains the Gauteng and Mpumalanga provinces of South Africa before entering Mozambique to the east and exiting into the Indian Ocean (Figure 5.5). For the purposes of this report only the upper Olifants catchment will be considered. The upper Olifants River above Loskop Dam drains an area of approximately 10 841 km^2. The upper Olifants catchment has three main stems, the Wilge to the west (4356 km^2), the Klein Olifants to the east (2391 km^2) and the Olifants proper (4094 km^2). The upper Wilge, Olifants and Klein Olifants drain a flat, gentle relief plateau underlain by Vryheid formation Karoo sequence rocks. In the middle parts of the catchment the channels are incised into the ancient basement rocks of the Transvaal sequence (mainly Pretoria group quartzite, shales and granite, Rooiberg group rhyolite and sandstones) and the Bushveld Igneous Complex (BIC). The geology of the area has a considerable impact on the structure and flow direction of the river. The country rocks are intruded by dolerite and diabase dykes and sills. The flat relief and basement geology in the upper parts of the catchment are associated with shallow, sandy soils, while the undulating relief in the lower parts of the catchment is associated with moderate to deep clayey loam soils. The soils are only moderately erodible. The grassveld and false grassveld produces a good vegetation cover. This results in moderate to low estimated annual sediment yield for the catchment of approximately 45 t/km^{2}yr^1 (Midgley *et al.*, 1994). The gross channel structure and planform is to a large extent determined by bed rock. A number of lineaments and faults cross the river, forming local gradient changes. Where the river is incised onto the more resistant lithologies, significant structural changes occur in the channel and in the long profile. Resistant bed rock outcrops create local downstream steepening, but also result in an upstream decrease in gradient, reducing channel energy and creating areas for sediment accumulation. A number of knick-points and abandoned plunge pools along the course of the Olifants attest to the incised nature of the channel. Mean annual rainfall in the catchment varies between 600 and 700 mm, with mean annual potential evapotranspiration ranging from 1500 mm in the east of the catchment to around 1700 mm in the west.

The hydrology of the Olifants River is described in terms of the three main-stem tributaries for virgin conditions. This is because there is insufficient information on the operation of the dams, water abstraction for irrigation, return flow from effluent treatment works and land use change impacts to model the present-day conditions. The Wilge River (Site 4) has an MAR of 167 million cubic metres, with a CV of 0.73. The Klein Olifants (Site 3) has an MAR of 81.6 million cubic metres, with a CV of 0.72. The Olifants proper (Sites 1 and 2) has an MAR of 449 million cubic metres, with a CV of 0.70. The Olifants system falls in the summer rainfall area of South Africa. Consequently, most of the discharge occurs during the summer months (November to February). The high CV indicates that the Olifants is a highly variable system, with high magnitude, short duration storm events which are concentrated in rapidly rising and receding flow events (Hughes, 2000).

The Wilge River is impounded by two major dams, the Bronkhorstspruit Dam and the Premier Dam. The Bronkhorstspruit Dam is a 30-metre high arch/earthfill combination dam nearly 80 kilometres upstream of Site 4. It was completed in 1950 and has a surface area of nearly 9 km^2 and a capacity of 59.4x10^{6}m^3. Downstream of the Bronkhorstspruit Dam is the 9-metre high Premier Dam. It is a concrete gravity dam which was completed in 1909 with a surface area of 0.60 km^2 and a capacity of 5.036x10^{6}m^3. Site 4 is approximately 40 kilometres downstream of Premier Dam.

The main Olifants stem is regulated by two dams, the Witbank Dam and the Doornpoort Dam. The Witbank Dam is a 9-metre high earthfill dam with a very small capacity and surface area. Just downstream of the Witbank Dam is a much larger dam, the 9-metre high earthfill Doornpoort Dam, with a capacity of 5.7x10^{6}m^3 and a surface area of 0.10 km^2. The Doornpoort Dam was completed in 1924. Site 1 was 15 kilometres downstream of Doornpoort Dam.

The Klein Olifants River is impounded by the 27-metre high concrete buttress Middelburg Dam. The dam has a surface area of 4.7 km^2 and a maximum capacity of 48.4x10^{6}m^3. Site 3 was approximately 45 kilometres downstream of Middelburg Dam.

Site 2 was the lowest site on the Olifants system and, at this point, the river is regulated by all five impoundments. These impoundments have been in place for some time (over 50 years) and have had a major impact on the flow regime of the Olifants system.

5.3.3.2 Identification of macro-reaches

Four macro-reaches have been determined for each of the three main-stem tributaries of the upper Olifants catchment (Figures 5.6 to 5.8). The macro-reaches were determined from an analysis of the long profile, geology and gradients from the 1:50 000 topographical sheets and the 1:250 000 geological maps. A CUSUM plot was used to determine the major breaks of slope for each of the three main-stem rivers of the upper Olifants. Tables 5.3 to 5.5 display the characteristics of each macro-reach.

5.3.3.3 Identification of sites

The analysis of the Olifants formed part of an Ecological Reserve assessment (Louw, 2000). The terms of reference of the Reserve assessment were that one site be located on the Wilge River, one site be located on the Klein Olifants and two sites be located on the Olifants River (Figure 5.5). The four sites were surveyed with a minimum of three cross-sections per site. All the chosen sites are located at the lower end of the upper Olifants catchment. Site 1 represents a single thread sinuous channel reach. Site 2 is in a reach classified as pool-rapid but is transitional to single thread sinuous. Site 3 and Site 4 are pool-rapid channel types. Site details, including the cross-sectional data, sketch map and photograph of each site, can be found in Dollar (2001).

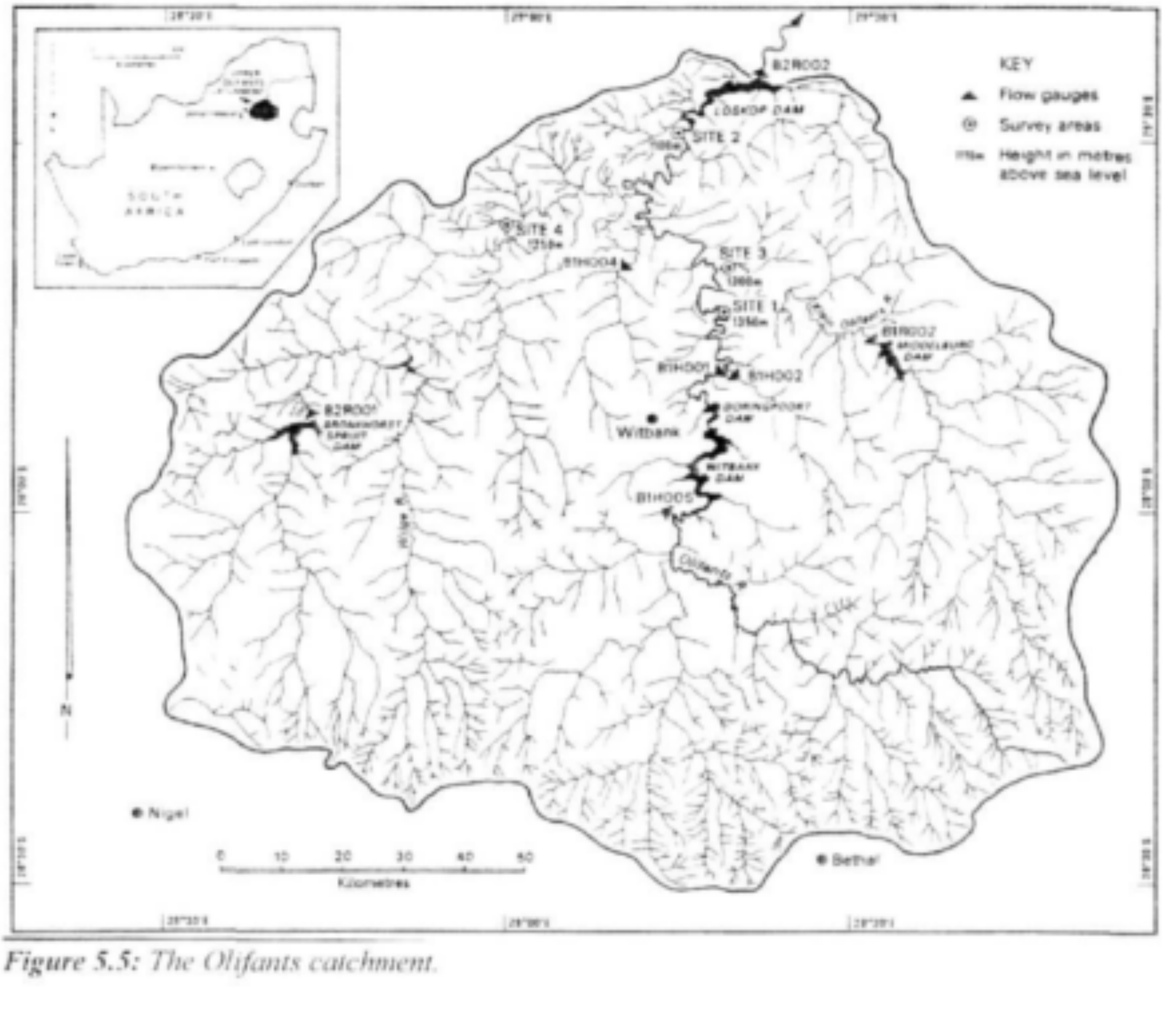


Figure 5.5: The Olifants catchment.

Table 5.3: *Characteristics of the Olifants River.*

Macro-reach	Characteristics	Average gradient	Geology	Site numbers
1 (1780m to 1670m)	No information is available.	0.0223		0
2 (1670m to 1570m)	The reach has low relief, and this is reflected in the channel type which is mainly sinuous single thread. At the lower end of the reach, the Doornpoort and Witbank Dams are underlain by Selonsrivier formation sandstone and quartzite. The channel is partially controlled by bed rock. Bank erosion is a significant source of sediment.	0.0026	Permian age Vryheid formation interbedded sandstones and shales	0
3 (1570m to 1230m)	The country rock is intruded by diabase (metamorphosed dolerite) and diabase dykes and sills which strike across the Olifants resulting in significant gradient adjustments. These sandstones have been deformed. There are numerous structural controls on channel form and pattern, including faults and joints. The Olifants has exploited lines of weakness which has determined the traverse of the channel. Variable rock hardness has resulted in a pool-rapid channel type. The more resistant lithologies producing rapids and creating hydraulically controlled upstream pools.	0.0098	Mogolian age Wilgerivier formation sandstone, dolerites and diabase	1
4 (1230m to 1000m)	There are a number of knick-points along this stretch (one being Kanongat). These are likely structural knick-points (rather than tectonic or cyclical knick-points), but have served to allow the Olifants to adjust to different base-levels. The boundary between macro-reach 3 and macro-reach 4 is probably such a knick-point. Given the nature of the bed rock, the channel type is pool-rapid.	0.0047	Mogolian age Wilgerivier formation sandstone, dolerites and diabase	2

Table 5.4: *Characteristics of the Wilge River.*

Macro-reach	Characteristics	Average gradient	Geology	Site numbers
1 (1770m to 1430m)	The channel structure of the Wilge River is controlled by the underlying bed rock, and its post-depositional formation such as faulting and weathering along joints. The gorges are incised into Wilgerivier sandstone and quartzite.	0.0223	Wilgerivier sandstone and quartzite	0
2 (1430m to 1360m)	This reach is underlain by Vaalian age Pretoria group sediments consisting of quartzite, shales and subgraywackes. Also present is diabase. This is reflected in the channel type for the reach which is sinuous single thread.	0.0004	Pretoria group quartzite, shales and subgraywackes and diabase	0
3 (1360m to 1170m)	This reach is underlain by Mogolian age Waterberg group sediments consisting of Wilgerivier sandstones. There are numerous structural controls on the channel form and pattern, including faults and joints. As the river traverses the Wilgerivier sandstones, lines of weakness have been exploited which have determined the direction of the channel. Structural control of the channel in this macro-reach is considerable. Variable rock hardness has resulted in a pool-rapid channel type. The more resistant lithologies producing rapids and creating hydraulically controlled upstream pools.	0.0003	Wilgerivier sandstones	4
4 (1170m to 1090m)	This reach is underlain by Waterberg group Lebowa granites. Granite is extremely resistant to weathering and very little jointing occurs, hence the flatter topography. Sinuous single thread channels dominate together with mixed anabranching channels.	0.0001	Lebowa granites	0

Table 5.5: *Characteristics of the Klein Olifants River.*

Macro-reach	Characteristics	Average gradient	Geology	Site numbers
1 (1700m to 1630m)	No information is available.	0.0117		0
2 (1630m to 1585m)	No information is available.	0.0037		0
3 (1585m to 1440m)	The reach is one of low relief and strong bed rock control. The channel type is mixed, ranging from sinuous single thread to pool-rapid. Bank erosion is an important source of bed material.	0.0035	Selonsrivier sandstone and quartzite as well as diabase	0
4 (1440m to 1250m)	Macro-reach 4 is underlain by Wilgerivier sandstones and quartzite as well as diabase and diabase dykes and sills. This has resulted in a pool-rapid channel type.	0.0049	Wilgerivier sandstones and quartzite as well as diabase dykes and sills	3

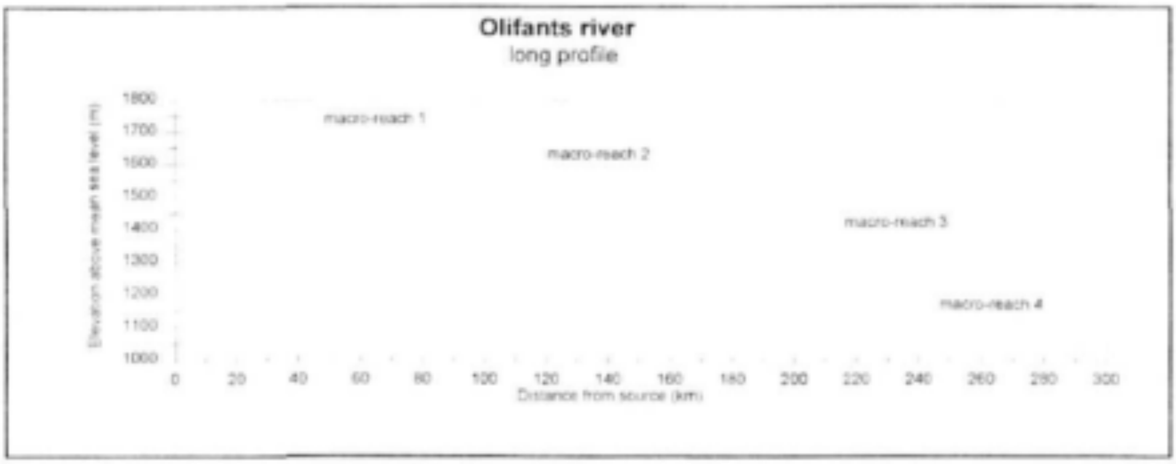


Figure 5.6: *Long profile of the Olifants river.*

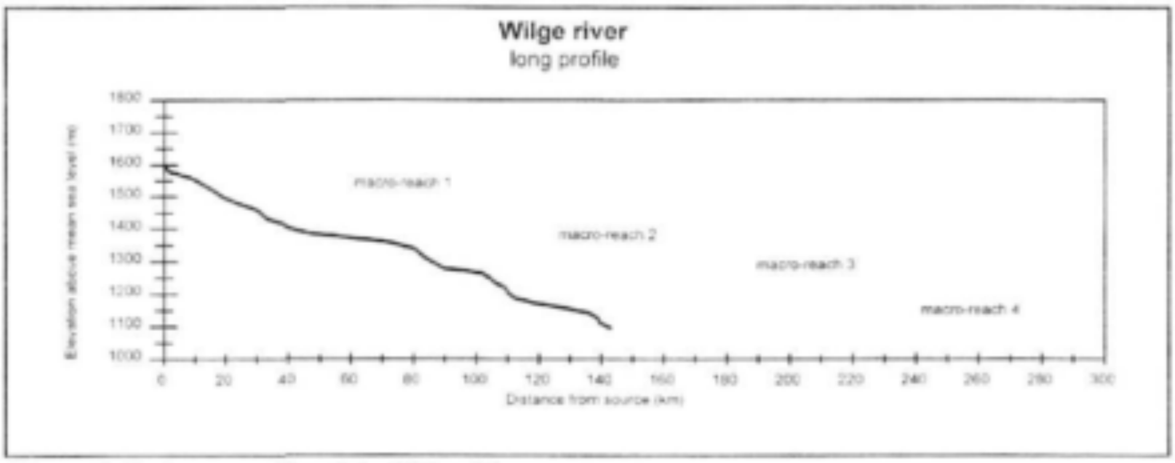


Figure 5.7: *Long profile of the Wilge River.*

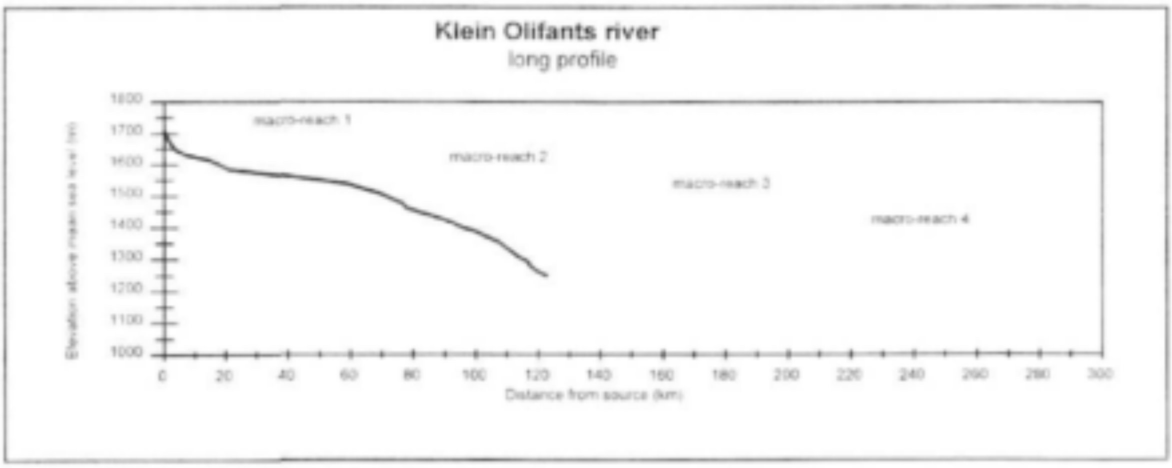


Figure 5.8: *Long profile of the Klein Olifants river.*

5.5 *Research design*

The research has two major foci: the research system (the Mkomazi River) and the application systems (the Mhlathuze and Olifants Rivers). The method and results sections are presented in this context. Figure 5.9 presents a flow diagram which illustrates the project research design. The Mkomazi River was used as the main study river, where the techniques to determine the magnitude and frequency of channel forming flows were developed. The Mhlathuze and Olifants Rivers were selected for pragmatic reasons, but also to test the methods developed for the Mkomazi on two impounded systems.

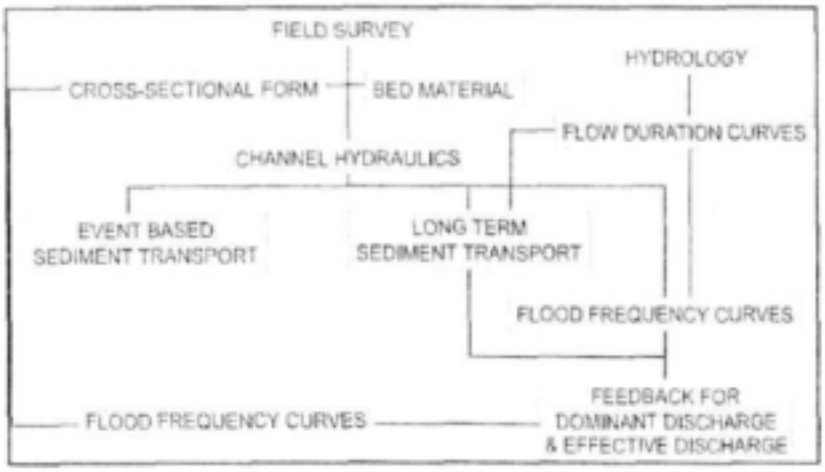


Figure 5.9: *Flow diagram indicating the structure of the research.*

The remainder of this section is structured as follows. Chapter 6 presents the methods and results of the hydrological data that were used in this research. Daily time series were required at each site to generate flow duration curves and flood frequency curves. These were used in conjunction with the information from the field survey of channel cross-sections, bed material characteristics and hydraulic computations for each of the rivers (Chapter 7) to generate bed material transport rates (Chapters 8). The generation of bed material transport rates allowed for the determination of effective and dominant discharge for each cross-section for each site for each river. This was then related back to cross-sectional form and hydrology. The synthesised results are presented for the Mkomazi in Chapter 9 and for the Mhlatuze and Olifants in Chapter 10. The implications for the development of magnitude and frequency concepts and their application to environmental flows are discussed later in Chapter 12 (Section D).

5.6 *Summary and conclusions*

The preceding discussion has presented an overview of the rivers that were selected for analysis. The rivers represent examples of different channel types that occur in the southern African landscape. These channels reflect a range of rivers, from an un-impacted semi-confined cobble-bed channel (Mkomazi), to a highly impacted, alluvial, single-thread channel (Mhlathuze), and a highly impacted semi-confined bedrock-controlled channel (Olifants). The sites selected within each river were systematically chosen to be representative of different channel types associated with particular macro-reaches. The rivers were surveyed and studied in a manner that would achieve the stated research objectives The following five chapters present the methods and results of the research.

Chapter 6: Hydrological analysis

6.1 Introduction

A hydrological analysis was used to generate representative daily time series for each of the selected sites on the Mkomazi, Mhlathuze and Olifants Rivers. These daily time series were used as input to the bed material transport model (Chapters 9 and 10). As a large volume of daily data was generated for 21 sites, it is impractical to display all the information within the body of the report. Much of the data are presented in Appendices B to D of Dollar (2001).

There are two main sources of hydrological data in South Africa. The first is primary data from gauging weirs controlled by the Department of Water Affairs and Forestry (DWAF), and the second is secondary data from the Surface Water Resources of South Africa 1990 (WR90) (Midgley *et al.*, 1994). WR90 provides virgin monthly modelled data based on the Pitman model for quaternary catchments and therefore serves as a useful reference for total flow volume and monthly flows.

6.2 The Mkomazi River

6.2.1 Data availability

There are two streamflow gauges for the Mkomazi with flow records dating from 1960: an upper gauging station, U1H005, gauging 1744 km^2 and a station close to the mouth, U1H006, gauging 4349 km^2. These records are stationary and are of good quality. The data used in all cases can be considered to represent natural flow conditions in the catchment. There is a problem with extreme high flows, especially at the lower station which has a very low Discharge Table Limit (DTL). U1H005 has a DTL of 637.8 m^{3}s^{-1} and has been overtopped only once since 1960. U1H006 has a DTL of 226 m^{3}s^{-1} and has been overtopped 35 times since 1962. The high flows must therefore be treated with circumspection. Simulated monthly flow data for virgin flow conditions are available for a 70 year period (1920-1990) from WR90. WR90 has divided the Mkomazi catchment into 12 quaternary sub-catchments. These quaternary catchments were used to check and calibrate the daily data generated for each of the sites. These details will be discussed later in the chapter.

The daily flow duration curves for U1H005 and U1H006 clearly indicate the similarity in the hydrological regime of the two sites (Figure 6.1). However, U1H006 demonstrates a slight increase in the maintenance of low flows during drought periods compared to U1H005 (flows equalled or exceeded more than 90% of the time). Analysis of the seasonality of the flows demonstrates that these differences are more pronounced during the dry months of the year. This is an indication that, at the lower end of the Mkomazi, the regime is more base-flow driven. By inference then, the upper end of the Mkomazi is probably more flashy. This assumption was used to estimate the shape of the target daily flow duration curves for the study sites.

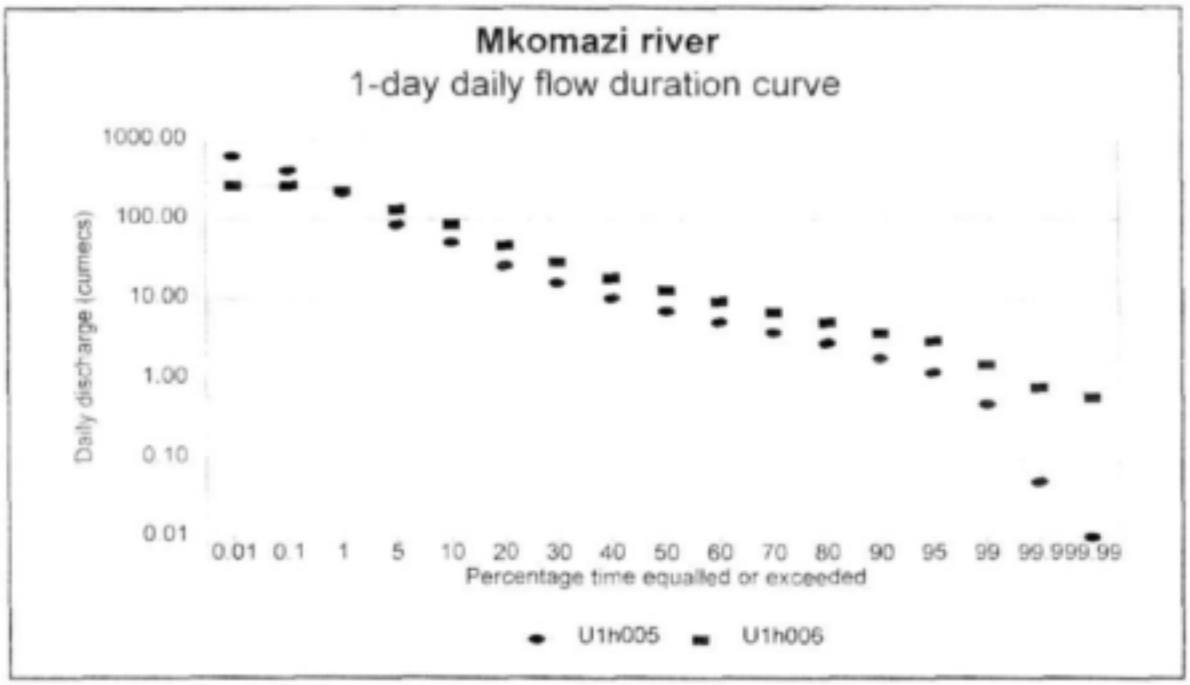


Figure 6.1: *1-day daily flow duration curves for U1H005 and U1H006.*

6.2.2 Selection of appropriate calibration stations

This section describes the data and techniques used to generate the representative daily streamflow time series at each of the thirteen selected sites for the Mkomazi River. Figure 5.1 shows the location of the flow gauging stations in relation to the sites selected for analysis. There are a number of ways to generate a daily time series at a particular station, including stochastic and deterministic modelling. However, since these models require detailed information such as catchment soil types, vegetation and antecedent soil moisture indices, which was not available for the Mkomazi catchment,a different approach was adopted.

The technique used is an adaptation of that 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. Figure 6.2 displays the technique in graphical form. The technique involves identifying the percentage point position of the source site's streamflow (Figure 6.2b) on the source site's flow duration curve (Figure 6.2a), and then reading off the flow value for the equivalent percentage point from the target site's flow duration curve (Figure 6.2d). The weighted average of the target site flow value is then assumed to be the target site's flow value. The technique is based on two steps:

1. the generation of source flow duration curve tables for source and target sites;
2. the simulation of the time series using target flow duration curves for each site.

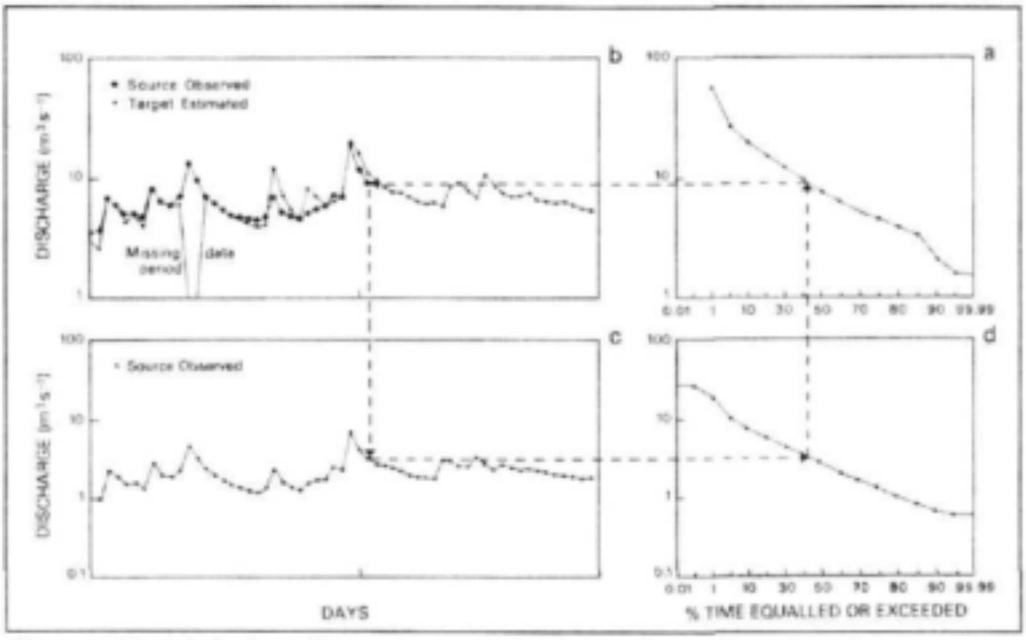


Figure 6.2: *Method used for generating daily time series from flow duration curves (after Hughes & Smakthin, 1996).*

6.2.3 Generating target flow duration curves

6.2.3.1 Regionalising the flow data

In order to run the model, source daily time series and target daily flow duration curves were required. The daily time series for U1H005 and U1h006 were used as the source daily time series. The target daily flow duration curves were more problematic. They were generated using the following technique:

Twelve gauging stations in and around the Mkomazi were selected for analysis. These stations were chosen on the basis of their length and reliability of record, and proximity to the target sites. Daily flow data were obtained from DWAF and were imported into the hydrological package *HYMAS* (Hughes & Smakthin, 1996). For each of the twelve stations, a 1-day daily flow duration curve was generated. The flow duration curves were then regionalised to compare the shape of the 1-day curve with the shape of the 1-day curves for the Mkomazi gauging stations. The average daily flow (in cubic metres per second) was thus calculated with equation 6.1:

$$\text{Average daily flow } (ADF) = \frac{(MAR * 1000)}{(365 * 24 * 3.6)} \qquad \text{(Equation 6.1)}$$

MAR Mean Annual Runoff in million cubic metres.

and regionalised using equation 6.2:

$$\frac{Q}{ADF} \qquad \textit{(Equation 6.2)}$$

Q discharge for a given point on the flow duration curve in cubic metres per second.

Using this method, it was possible to determine which of the 12 selected flow stations produced similar shaped flow duration curves to those of the Mkomazi River. Figure 6.3 demonstrates that the curves generated for stations U7H007, V2H007, V2H005, V7H016, V7H017, T5H002 and T5H007 all plot very close to U1H005 and U1H006 between the 1% equalled or exceeded and the 90% equalled or exceeded flows. For the purpose of this study, the low flows (those flows equalled or exceeded 90% of the time or more) are of little consequence, as these do not generate sufficient stream power or shear stress to have any impact on channel form or bed material transport. The high flows are of greater significance. Simulating high flows in South Africa is problematic as South African flow gauging stations are very poorly calibrated for high flows and are often overtopped, resulting in poor flood peak estimates. Those stations that plotted with a different shape (T5H003 and T5H005) to the two stations for the Mkomazi were excluded from further analysis.

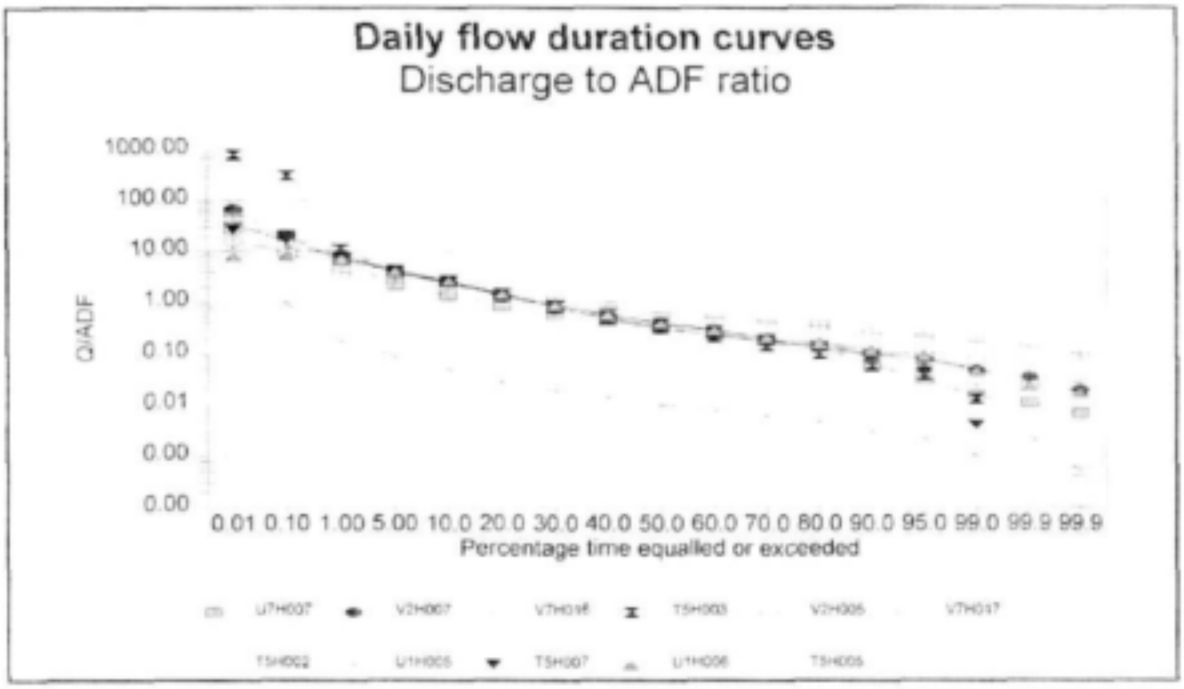


Figure 6.3: *Daily flow discharge to average daily flow for 11 gauging stations.*

6.2.4 Generating target daily flow duration curves

Once the percentage points of the 1-day daily flow duration curve were determined for each of the regional stations, the ratio between each percentage point and the lower percentage point was calculated. For example, for station U7H007, the 0.10% Q/ADF is 19.86, and the 0.01% Q/ADF is 57.96. This gives a ratio of 2.92 , i.e. the flow equalled or exceeded 0.01% of the time is 2.92 times the size of the flow equalled or exceeded 0.10% of the time (Table 6.2). This gave an indication of the relative sizes of the flows in relation to one another. However, it is clear from the evidence presented in Figure 6.3 that although the curves from each of the flow stations overlap between the 1st and 90th percentile, the two stations that gauge the smaller catchments and have a lower mean daily flow, also have a 'flashier' hydrological regime as measured by the coefficient of variation (CV) (Table 6.1). This is also reflected in the ratios between the percentage points between the 1% and 0.1% and the 0.1% and 0.01% equalled or exceeded range. This would suggest that in this region, smaller catchments in the upper parts of the drainage basin have a 'flashier' type hydrological regime, while the lower parts of the systems tend to be more base flow dominated with a less 'flashy' high flow regime.

Table 6.1: *Flow gauging stations around the Mkomazi catchment.*

Station	River	Years	MAR ($10^6 m^3$)	ADF (m^3/s)	Coefficient of variation	Area (km^2)
U7H007 (Beaulieu Estate)	Lovu	1964-1999	23	0.74	0.60	114
V2H007 (Broadmoor)	Hlatikulu	1972-1999	32	1.02	0.54	109
V7H016 (Drakensberg)	Ncibidwane	1976-1999	48	1.53	0.44	121
V2H005 (The Bend)	Mooi	1972-1999	115	3.65	0.46	260
V7H017 (Drakensberg)	Boesmans	1972-1999	138	4.37	0.43	276
T5H002 (Nooitgedacht)	Bisi	1960-1974	154	4.88	0.38	867
U1H005 (Camden)	Mkomazi	1960-1999	636	20.15	0.47	1744
T5H007 (Bezweni)	Mzimkulu	1956-1978	957	30.35	0.36	3586
U1H006 (Delos Estate)	Mkomazi	1962-1999	1033	32.76	0.45	4349

2.2.4.1 Generating the scaling factor for the target daily flow duration curves for sites 1 to 10

The target daily flow duration curves needed to be adjusted to accommodate the flashier nature of the upper catchment as well as the base-flow driven nature of the lower catchment. In the *HYMAS* model, the target daily time series is accommodated by utilising a scaling factor. To generate the daily time series for sites 1 to 10, the source flow data was taken to be the daily series for U1H005, as these sites were closer to U1H005 than U1H006. For sites with an MAR less than 70, the average of the ratios for U7H007, V2H007, V7H016 and U1H005 were used to downscale (sites 1 to 4) the target daily flow duration curve for the 0.1 and 0.01 percentiles. For the 1 to 99.99 percentiles, the target daily flow duration curve was downscaled using the ratio of the site's MAR to the MAR of U1H005. The MAR of each site was calculated using the available data from the quaternary catchments from WR90 and the catchment area for each site (measured using the 1:50 000 topographical map).

To generate the daily time series for sites 5 and 6, the source flow data was taken to be the daily series for U1H005, as U1H005 is within two kilometres of each of these sites. The ratios for U1H005 were used to downscale the target daily flow duration curve for the 0.1 and 0.01 percentiles. For the 1 to 99.99 percentiles, the target daily flow duration curve was downscaled using the ratio of the site's MAR to the MAR of U1H005. The MAR of each site was calculated using the available data from the quaternary catchments from WR90. For sites 7, 8, 9 and 10 the same technique was used, but the scaling was in the upward direction. In this way, daily time series were generated for sites 1 to 10 for the Mkomazi River. Figure 6.4 displays two examples of the daily time series for the Mkomazi River. Figure 6.5 displays examples of the 1-day daily flow duration curves for four sites for the Mkomazi River.

6.2.4.2 Generating the scaling factor for the target daily flow duration curves for sites 11 to 13

To generate the daily time series for sites 11 to 13, the source flow data was taken to be the daily series for U1H006, as these sites are closer to U1H006 than U1H005. For sites draining greater than 70 MAR, the average of the ratios for V2H005, V7H017, T5H002, T5H007 and U1H006 were used to downscale the target daily flow duration curve for the 0.1 and 0.01 percentiles. For the 1 to 99.99 percentiles, the target daily flow duration curve was downscaled using the ratio of the site's MAR to the MAR of U1H006. The MAR of each site was calculated using the available data from the quaternary catchments from WR90. In this manner, daily time series were generated for sites 11 to 13 for the Mkomazi River.

Table 6.3 presents the flows for the 1-day daily duration curves that were used to generate the daily time series for each site. The daily time series for all sites are available in Dollar (2001). (Appendix B).

6.2.5 Flood frequency analysis

The daily time series generated for each site were used to generate flood frequency curves using the annual and partial series. Standard techniques were applied (cf. Dunne & Leopold, 1978; Gordon *et al.*, 1992). The cutoff for the partial series was taken as the smallest annual flood for the period of record. It must be noted that the flood frequency analysis was based on mean daily flows and not the peak flows. Instantaneous peak flows are not available as these flows often exceed the Discharge Table Limit (DTL) of the flow gauging stations, as previously explained. However, it is argued that given the focus of the research and the importance of modelling bed material transport, average flow conditions better represent long-term sediment transport patterns. This does not negate the significance of instantaneous peak discharges, these will be dealt with in Section 6.2.6. It is not practical to display all the data for the flood frequency analysis. Examples of the analysis are provided in Figures 6.6 and 6.7. Full details are presented in Appendices C and D of Dollar (2001).

Table 6.2: Regional flow gauging stations around the Mkomazi catchment.

Station	U7H007		V2H007		V7H016		V2H005		V7H017		T5H002		U1H005		T5H007		U1H006	
MAR	23.18		32.27		48.3		115.25		117.9		153.8		635.58		937.1		1033.17	
ADF	0.74		1.02		1.53		3.65		3.37		4.88		20.15		30.35		32.76	
CV	0.598		0.518		0.442		0.461		0.429		0.383		0.468		0.36		0.446	
%	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*	Q/adf	Ratio*
0.01	57.96	2.92	66.79	3.25			29.18	1.53	35.77	2.37	16.41	1.79	31.22	1.53	57.37	3.47		
0.1	19.86	3.1	20.54	2.42	11.71	1.38	19.11	2.38	15.07	2.07	9.16	2.38	20.39	1.95	16.51	2.44	8.03	1.16
1	6.41	3.01	8.49	2.11	8.49	2.25	8.02	2.09	7.28	1.98	3.84	1.27	10.471	2.5	6.76	1.68	6.92	1.74
5	2.13	1.59	4.04	1.61	3.78	1.58	3.84	1.55	3.67	1.56	3.04	1.32	4.18	1.67	4.13	1.56	3.98	1.54
10	1.34	1.65	2.5	1.95	2.39	1.86	2.48	1.8	2.35	1.77	2.31	1.58	2.51	1.94	2.65	1.79	2.59	1.83
20	0.82	1.41	1.28	1.76	1.29	1.65	1.38	1.59	1.33	1.56	1.46	1.38	1.29	1.65	1.48	1.68	1.42	1.64
30	0.58	1.38	0.73	1.52	0.78	1.57	0.87	1.52	0.85	1.48	1.06	1.33	0.78	1.56	0.89	1.53	0.86	1.56
40	0.42	1.33	0.48	1.51	0.5	1.45	0.57	1.48	0.57	1.42	0.79	1.29	0.5	1.45	0.58	1.44	0.56	1.42
50	0.32	1.35	0.32	1.41	0.34	1.45	0.38	1.41	0.41	1.4	0.62	1.23	0.35	1.38	0.4	1.42	0.39	1.38
60	0.23	1.32	0.22	1.31	0.24	1.33	0.27	1.33	0.29	1.45	0.51	1.18	0.25	1.35	0.28	1.49	0.28	1.38
70	0.18	1.31	0.17	1.29	0.18	1.33	0.2	1.33	0.2	1.31	0.43	1.24	0.18	1.36	0.19	1.43	0.2	1.32
80	0.13	2.2	0.13	1.36	0.13	1.36	0.15	1.44	0.15	1.22	0.34	1.33	0.14	1.54	0.13	1.93	0.15	1.36
90	0.06	1.96	0.1	1.28	0.1	1.31	0.11	1.77	0.12	1.16	0.26	1.19	0.09	1.51	0.07	1.55	0.11	1.26
95	0.03	2.09	0.08	1.59	0.08	1.51	0.09	1.57	0.11	1.32	0.22	1.3	0.06	2.48	0.05	11.02	0.09	1.96
99	0.01	1.38	0.05	1.4	0.05	1.43	0.05	2.01	0.08	1.28	0.17	1.22	0.02	9.6	0.004	-	0.05	1.06
99.9	0.01	1.6	0.03	1.75	0.04	1.29	0.02	1.37	0.06	1.11	0.14	1.41	0.002	5			0.02	1.33
99.99	0.01	-	0.02	-	0.03	-	0.01	-	0.06	-	0.09	-	0.000	-			0.01	-

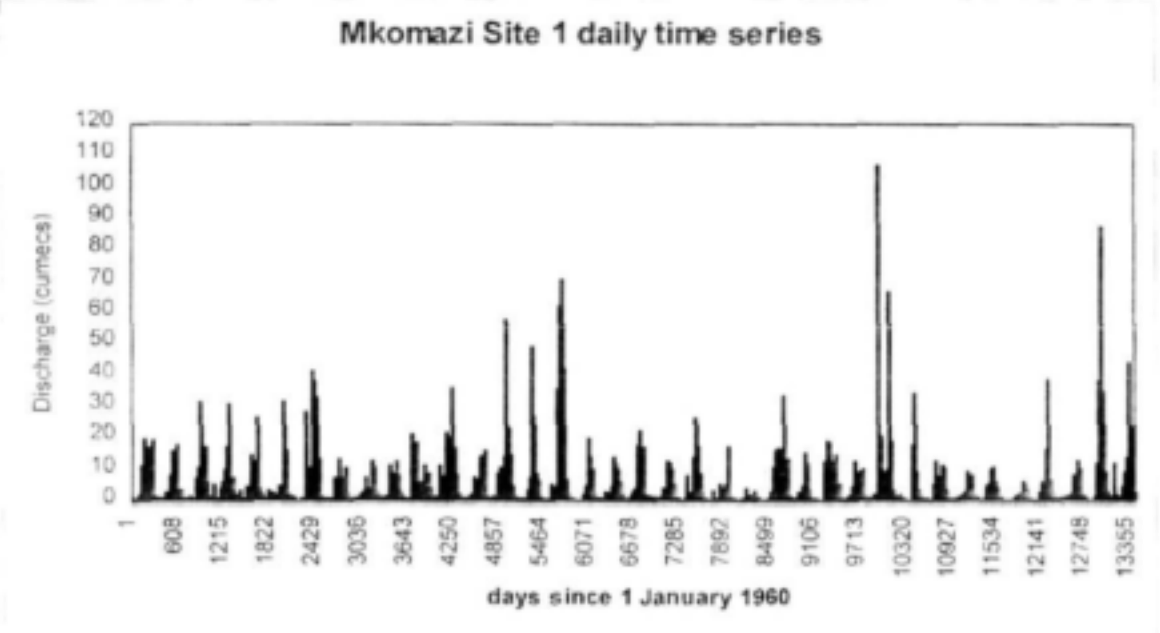
* Ratio refers to the ratio between the upper flow class and the lower flow class. For example, for U7H007, the Q/adf for flow class 0.10 is 19.86 and the Q/adf for the 0.01 flow class is 57.96. Thus 57.96/19.86 is 2.92.

Table 6.3: *Flows for the 1-day daily flow duration curves generated for the daily time series.*

MAR	635.6	1033.2	67.15	121.51	355.6	374.56	633.63	640.39	681.31	698.31	910.25	949.63	975.63	1026.88	1032
%	U1H005	U1H006	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13
0	629.4	263	102.772	183.404	436.522	459.907	622.337	634.909	672.627	691.185	900.23	939.01	964.89	1015.57	1021.13
0.1	411.07	263	47.143	84.13	216.1	227.677	406.756	414.973	439.625	451.951	588.38	613.74	630.64	663.77	667.41
1	211.04	226.605	19.561	34.909	99.585	104.92	208.593	212.907	225.449	231.77	301.74	314.74	323.41	340.4	342.26
5	84.28	130.502	9.271	16.013	47.197	49.725	83.437	85.123	90.18	92.708	114.842	120.062	122.672	129.197	130.902
10	50.57	85.006	5.563	9.608	28.319	29.836	50.064	51.076	54.11	55.627	74.805	78.206	79.906	84.156	85.006
20	26.03	46.501	2.863	4.946	14.577	15.358	25.77	26.29	27.852	28.633	40.921	42.781	43.711	46.036	46.201
30	15.79	28.418	1.737	3	8.842	9.316	15.632	15.948	16.895	17.369	25.008	26.145	26.713	28.134	28.418
40	10.12	18.227	1.113	1.923	5.667	5.971	10.019	10.221	10.828	11.132	16.04	16.769	17.133	18.045	18.227
50	7	12.81	0.77	1.33	3.92	4.13	6.93	7.07	7.49	7.7	11.273	11.785	12.041	12.682	12.81
60	5.07	9.25	0.558	0.963	2.839	2.991	5.019	5.121	5.425	5.577	8.14	8.51	8.695	9.158	9.25
70	3.76	6.692	0.414	0.714	2.106	2.218	3.722	3.798	4.023	4.136	5.889	6.157	6.29	6.625	6.692
80	2.77	5.051	0.305	0.526	1.551	1.634	2.742	2.798	2.964	3.047	4.445	4.647	4.748	5	5.051
90	1.8	3.718	0.198	0.342	1.008	1.062	1.782	1.818	1.926	1.98	3.272	3.421	3.495	3.681	3.718
95	1.19	2.947	0.131	0.226	0.666	0.702	1.178	1.202	1.273	1.309	2.593	2.711	2.77	2.918	2.947
99	0.48	1.501	0.053	0.091	0.269	0.283	0.475	0.485	0.514	0.528	1.321	1.381	1.411	1.486	1.501
99.9	0.05	0.766	0.006	0.101	0.028	0.03	0.05	0.051	0.054	0.055	0.674	0.705	0.72	0.758	0.766
100	0.01	0.578	0.001	0.002	0.006	0.006	0.01	0.01	0.011	0.011	0.509	0.532	0.543	0.572	0.578

Table 6.4: Highest extreme flood peaks on record for the Mkomazi River (modified after van Bladeren & Burger, 1989 and van Bladeren, 1992).

Year	Catchment area (km^2)	Equivalent current research site	Discharge (m^3s^{-1})	Period under review	Maximum depth (m)	Return period (years)
1959	1744	5 and 6	1490	1931-1990		20-50
1975	1744	5 and 6	2010	1931-1990		
1987	1744	5 and 6	2770	1931-1990	5.28	50-100
1988	1744	5 and 6	1230	1931-1990		
1959	3177	9	2470	1931-1990	3.55	20-50
1959	3339	11	3480	1931-1990	8.79	50-100
1987	3339	11	6030	1931-1990	11.42	>200
1989	4349	12 and 13	2618	1931-1990	4.31	36818
1856	4375	12 and 13	7250	1856-1990	11.91	>200
1868	4375	12 and 13	5820	1856-1990	11.01	100
1917	4375	12 and 13	3570	1856-1990	8.55	20-50
1925	4375	12 and 13	6100	1856-1990	10.61	100-200
1959	4375	12 and 13	5510	1856-1990	10.69	50-100
1976	4375	12 and 13	2880	1856-1990	8.99	
1987	4375	12 and 13	6830	1856-1990	10.78	



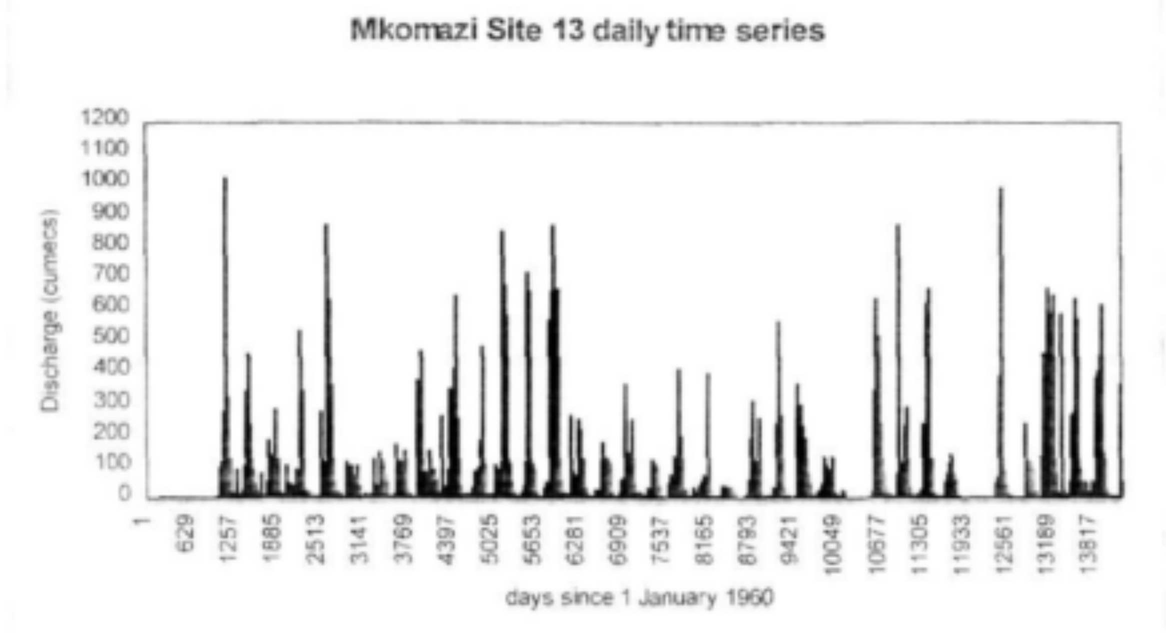


Figure 6.4: *Synthesised daily time series for sites 1 and 13 for the Mkomazi River.*

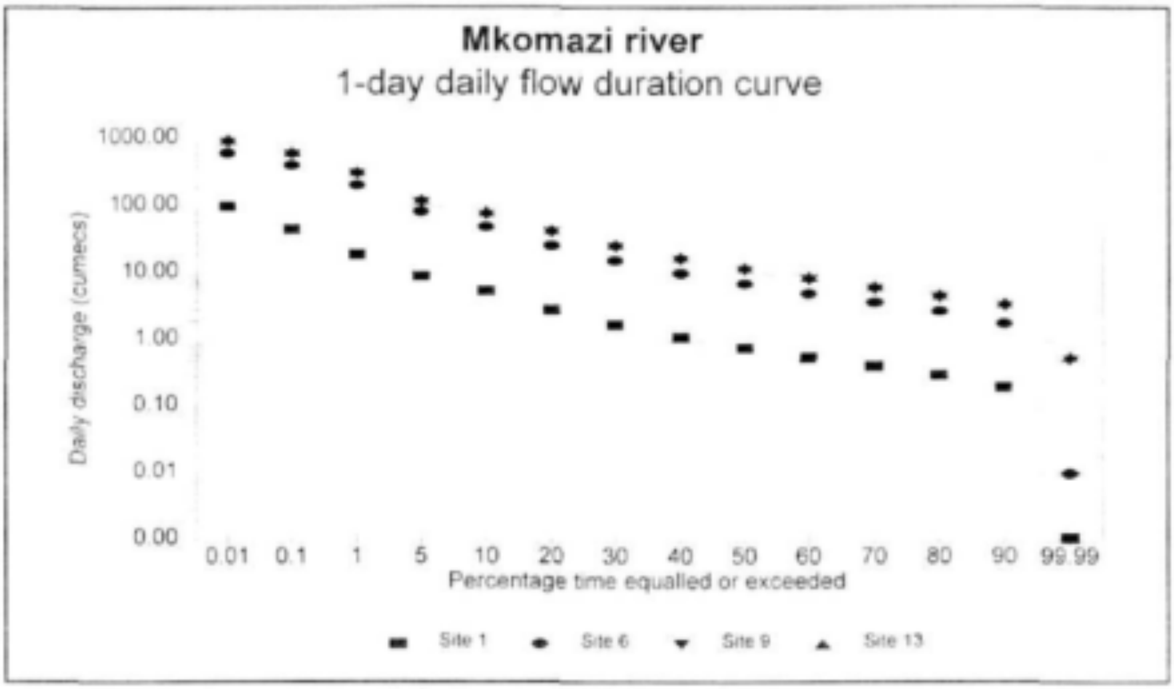


Figure 6.5: *Synthesised 1-day daily flow duration curves for sites 1, 6, 9 and 13 for the Mkomazi River.*

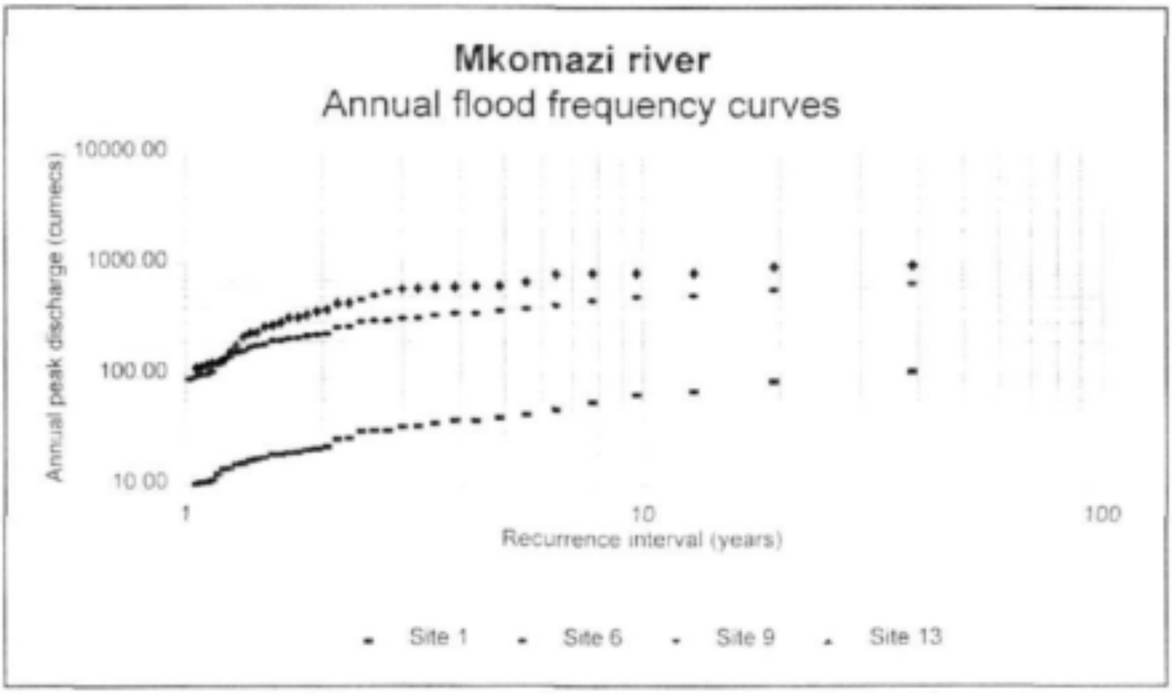


Figure 6.6: *Annual flood frequency curves for sites 1, 6, 9 and 13 for the Mkomazi River.*

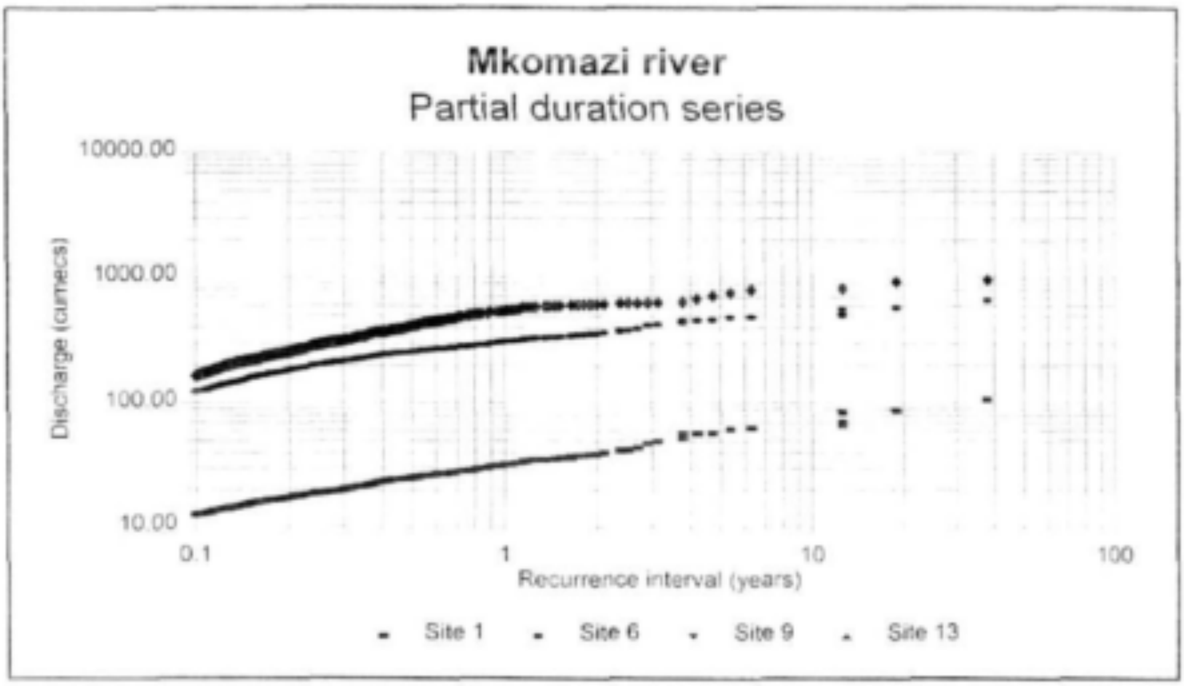


Figure 6.7: *Partial duration series flood frequency curves for sites 1, 6, 9 and 13 for the Mkomazi River.*

6.2.6 Historical flood records

Historical flood records for the Mkomazi River have been compiled by van Bladeren & Burger (1989) and van Bladeren (1992). These records were compiled using a combination of historical records, hydraulic modelling using the slope-area method and cross-sectional data. Table 6.4 presents the data in summary form. Van Bladeren (1992) demonstrated that the inclusion of the historical record has a significant impact on the frequency distribution of the gauged data. Results indicate that calculating historical flood data may provide more realistic flood estimates. These records serve as useful information and will be utilised in the discussion of results.

6.3 The Mhlathuze River

6.3.1 Data availability

Synthesised daily hydrological data was available for the Mhlathuze River. The data was generated by Hughes & Smakthin (1998). Here, a short review of the context of the data is provided. There were two streamflow gauging stations available for the Mhlathuze River, the first is at the site of the Goedertrouw Dam which was completed in 1979. Prior to the building of the dam, a flow gauging station, W1H006 (Normanhurst), had data ranging from 1964 to 1973, but also contained long periods of missing data. After the construction of Goedertrouw Dam, the present gauging station, W1H028, was re-opened. This has data from 1980 to the present-day. A second gauging station, W1H009 (Riverview) has data from 1963-1991 (see Figure 5.3). These latter two stations were used by Hughes & Smakthin (1998) to generate virgin and present-day daily time series for the four sites identified for the Mhlathuze River.

To generate the virgin time series, Hughes & Smakthin (1998) calibrated the model to achieve mean annual volumes and monthly distributions that were similar to those presented in WR90 and the pattern of daily flow variation to the station W1H009. To simulate present-day conditions, the model was calibrated against water use data supplied by the local water authority, Mhlathuze Water.

6.3.2 Hydrological regime of the four Mhlathuze sites

Eight daily time series were generated for the four Mhlathuze sites, four daily time series for the virgin conditions and four daily time series for the present-day conditions. This information is available in Appendix B of Dollar (2001). Examples of the virgin daily time series data are given in Figure 6.8 and examples of the present-day daily time series in Figure 6.9. The virgin 1-day daily flow duration curves are presented in Figure 6.10, while Figure 6.11 displays the present-day 1-day daily flow duration curves.

6.3.3 Flood frequency analysis

Results of the analysis of the virgin time series and present-day time series for the annual series are presented in Figures 6.12 and 6.13 respectively. The results of the analysis of the virgin time series and present-day time series for the partial duration series are given in Figures 6.14 and 6.15 respectively.

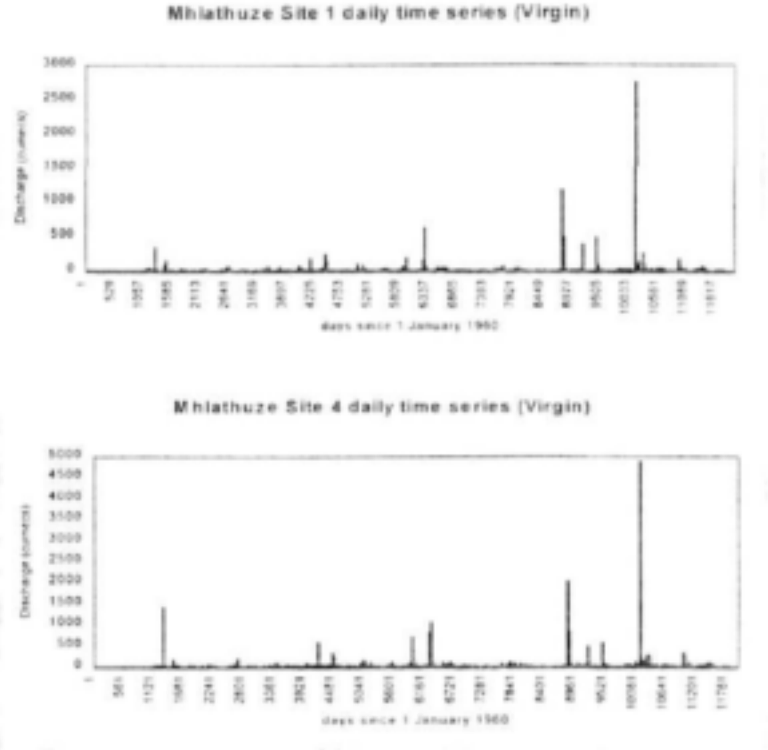
6.3.4 Historical flood records

The Goedertrouw Dam has been shown to have a significant effect on flood peaks downstream of the dam. Van Bladeren (1992) has shown that the September 1987 inflow flood to Goedertrouw Dam was 3760 m^3s^{-1}, while the outflow was 550 m^3s^{-1}. A similar flood in 1984 was also severely attenuated by the dam (Table 6.5). These records serve as useful information and will be utilised in the discussion of results.

Table 6.5: Highest extreme flood peaks on record for the Mhlathuze River (modified after van Bladeren & Burger, 1989 and van Bladeren, 1992).

Year	Catchment area (km^2)	Equivalent current research site	Discharge (m^{3}s^{-1})	Period under review	Maximum depth (m)	Return period (years)
1940	1273	-	4100	1940-1989	-	-
1963	1273	-	850	1940-1989	-	-
1984	1273	-	2620	1940-1989	-	-
1985	1273	-	540	1940-1989	-	-
1987	1273	-	3780	1940-1989	-	-
1988	1273	-	450	1940-1989	-	-
1940	1348	-	4100	1940-1989	11.98	50-100
1913	2409	1	2170	1913-1990	-	-
1917	2409	1	3290	1913-1990	7.68	20-50
1940	2409	1	3630	1913-1990	-	-
1984	2409	1	2420	1913-1990	-	-
1987	2409	1	3590	1913-1990	8.31	20-50
1984	2409 *	1	4790	1980-1990	-	-
1987	2409 *	1	6000	1980-1990	-	-
1913	2771	3	2330	1913-1987	6.01	36818
1917	2771	3	3530	1913-1987	9.54	20-50
1918	2771	3	3500	1913-1918	10.04	20-50
1940	2771	3	3890	1913-1987	10.42	20-50
1971	2771	3	725	1913-1987	-	-
1977	2771	3	3540	1913-1987	8.70	20-50
1987	2771	3	4130	1913-1987	8.45	20-50

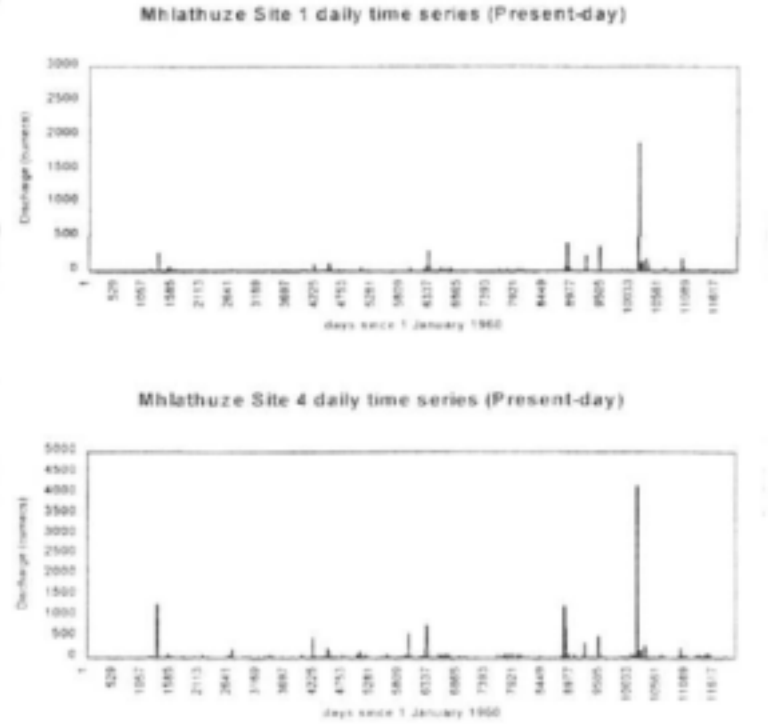
*** Calculated as if the flood peak had not been attenuated by Goedertrouw Dam.**



Mhlathuze Site 1 daily time series (Virgin)

Mhlathuze Site 4 daily time series (Virgin)

Figure 6.8: *Virgin daily time series for two sites for the Mhlathuze River.*



Mhlathuze Site 1 daily time series (Present-day)

Mhlathuze Site 4 daily time series (Present-day)

Figure 6.9: *Present-day daily times series for two sites for the Mhlathuze River.*

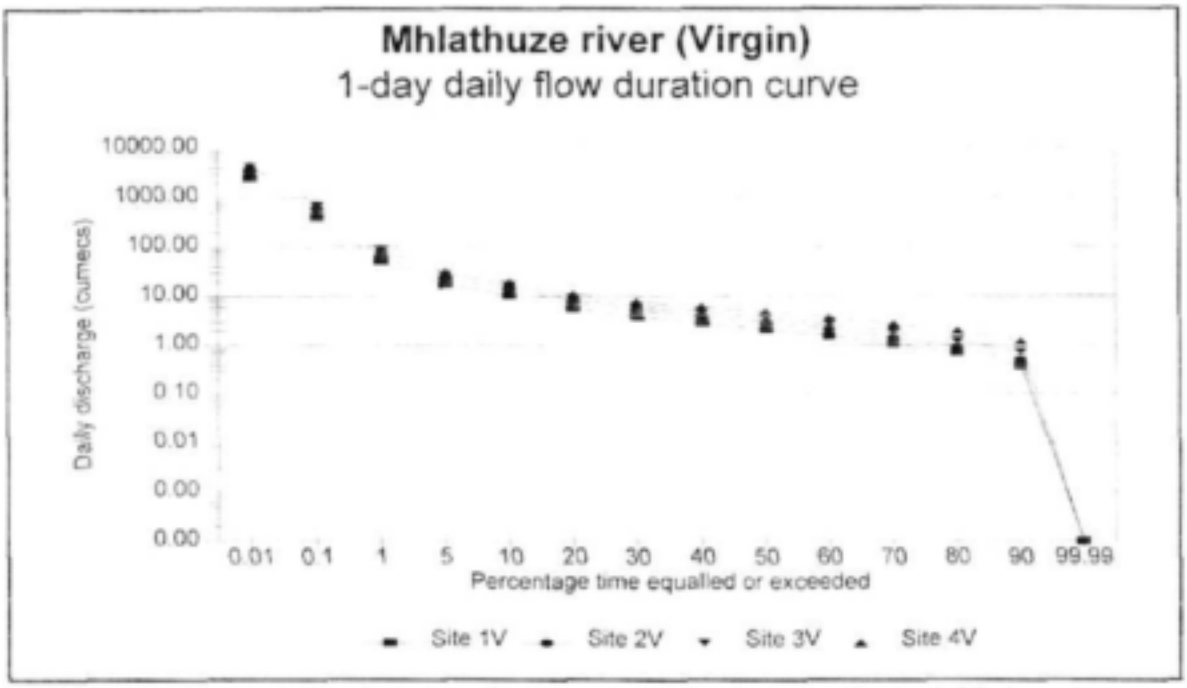


Figure 6.10: Virgin 1-day daily flow duration curves for four sites for the Mhlathuze River.

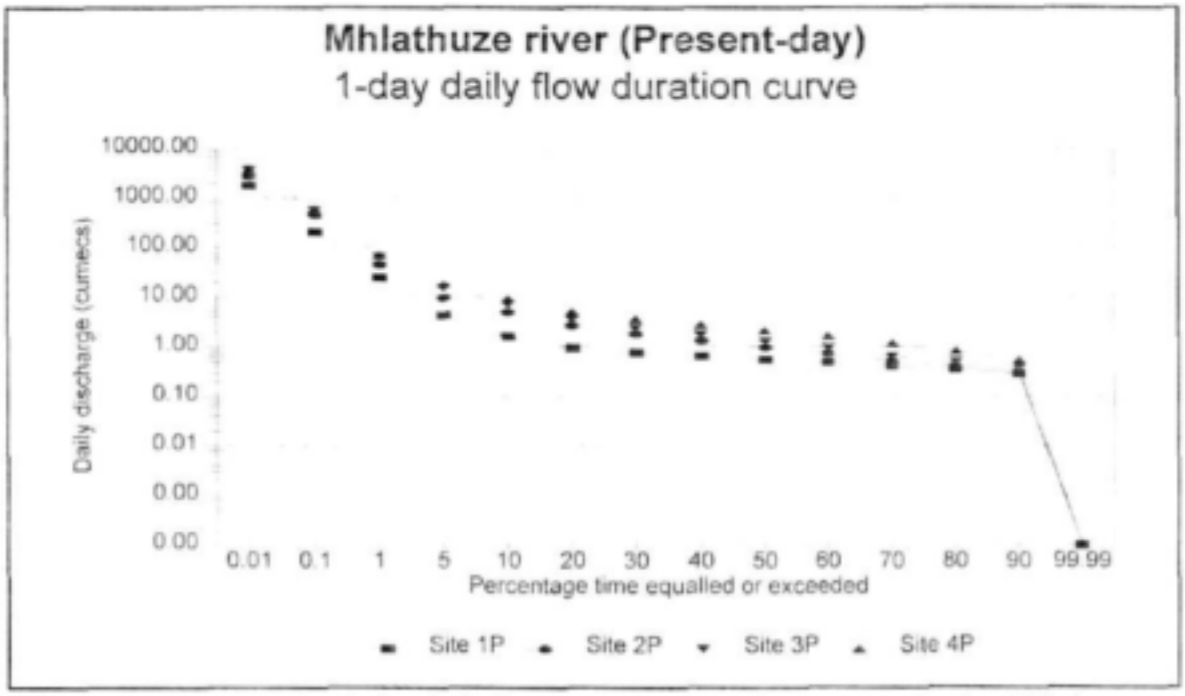


Figure 6.11: Present-day 1-day daily flow duration curves for four sites for the Mhlathuze River.

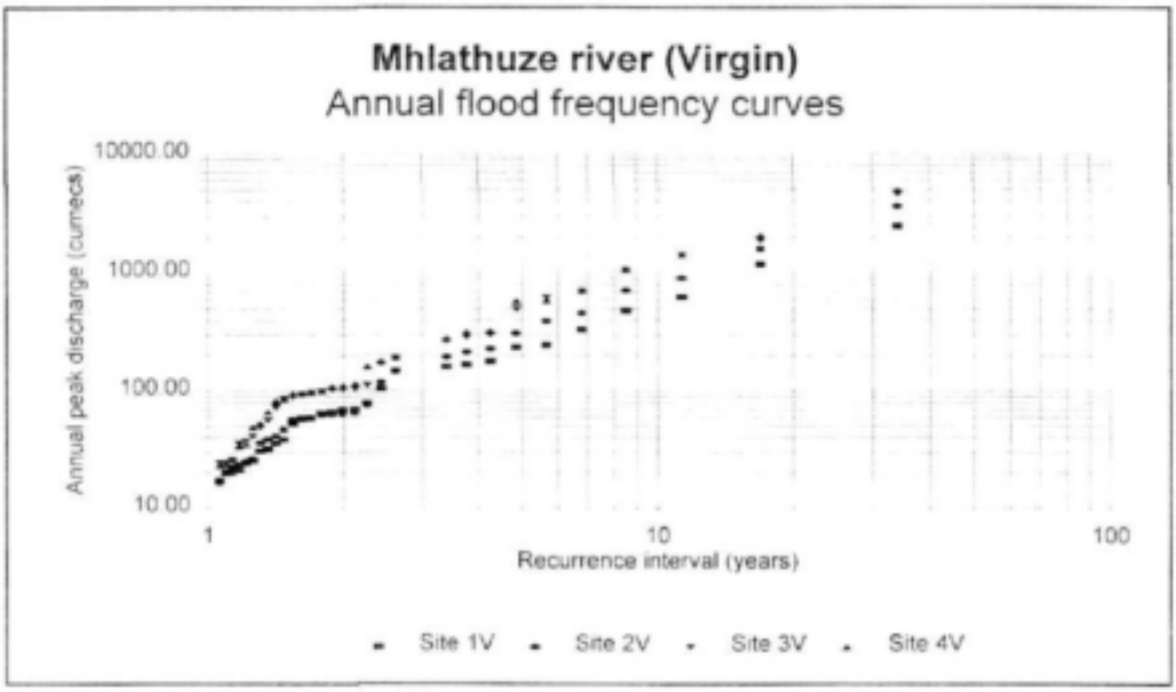


Figure 6.12: Virgin annual flood frequency curves for four sites for the Mhlathuze river.

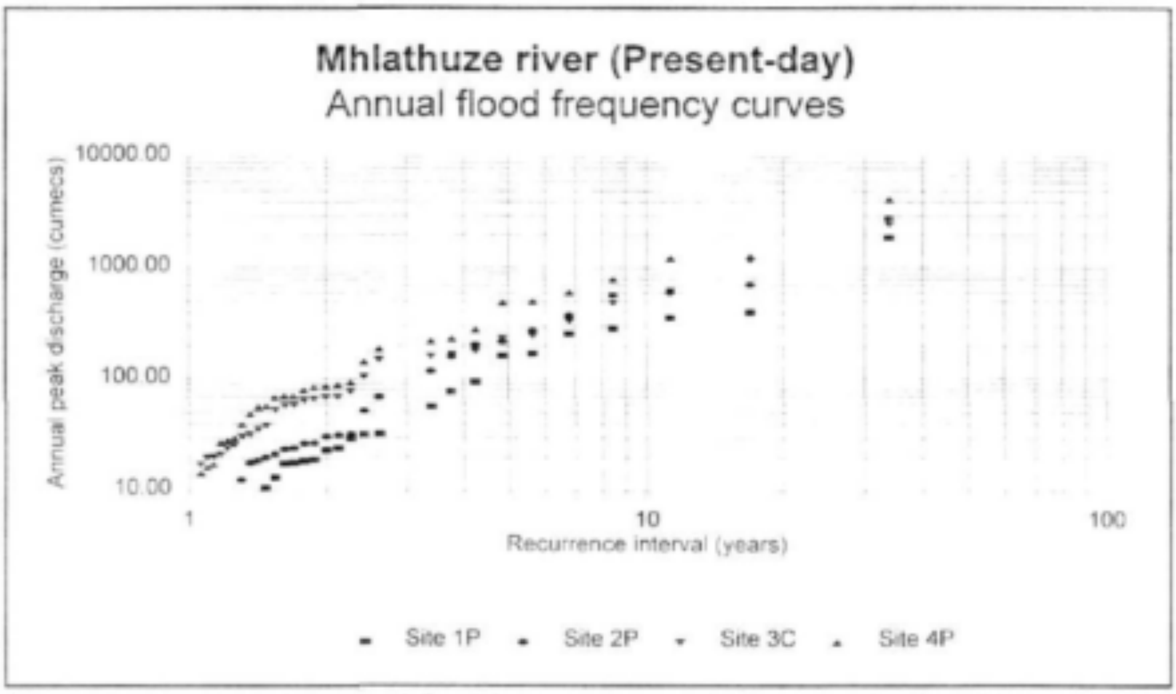


Figure 6.13: Present-day annual flood frequency curves for four sites for the Mhlathuze river.

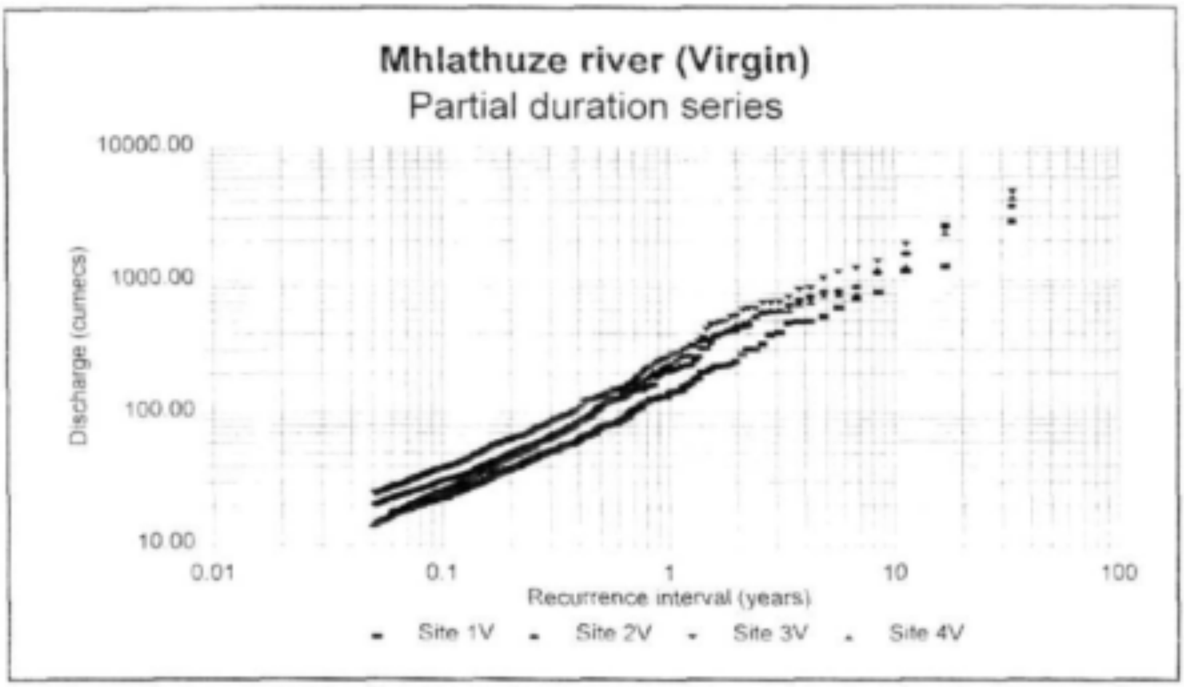


Figure 6.14: *Virgin partial duration series flood frequency curves for four sites for the Mhlathuze River.*

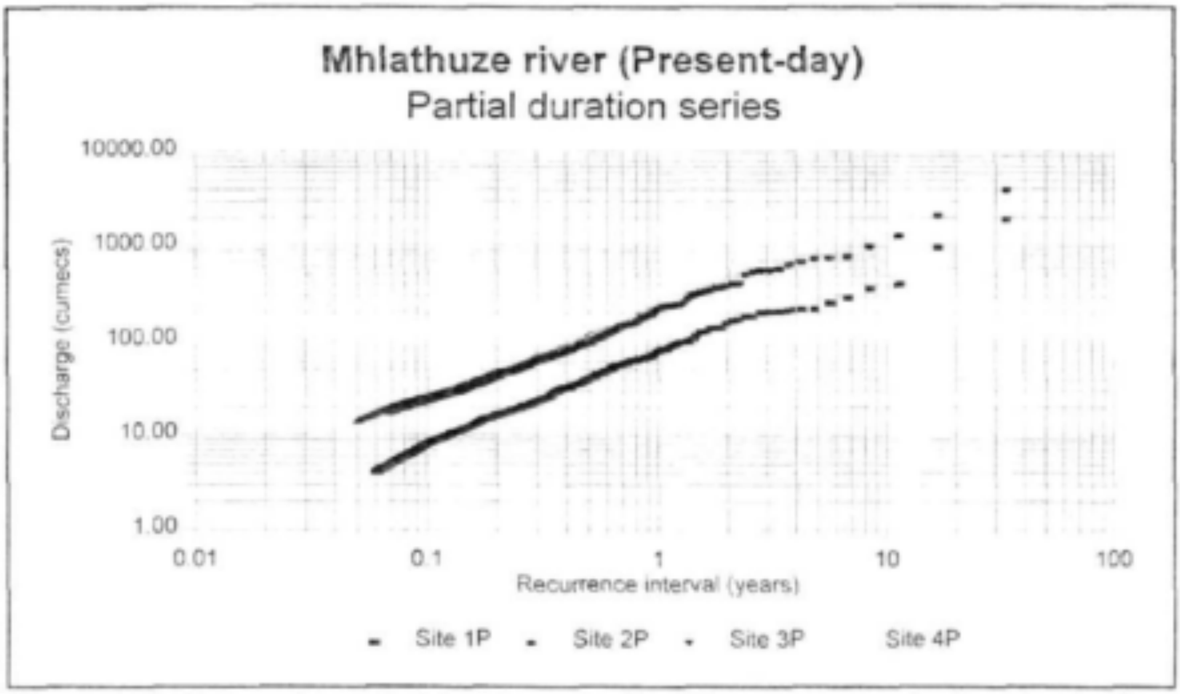


Figure 6.15: *Present-day partial duration series flood frequency curves for four sites for the Mhlathuze River.*

6.4 The Olifants River

6.4.1 Data availability

Good quality hydrological data were lacking for the Olifants River, as was information on the operating procedures of the dams that control streamflow in the upper Olifants River. As a result, synthesised hydrological data generated by Hughes (2000) using the VTI model were used.for each of the four sites of the Olifants River. The VTI model contains four basic functions for the generation of streamflow (Hughes, 2000).

1. An infiltration excess function that is largely controlled by the surface soil characteristics and the intensity of rainfall.
2. A saturation excess function that is controlled by soil depth, water holding capacity and drainage characteristics as well as the total rainfall amounts that can occur.
3. A soil moisture drainage or baseflow function that is controlled by topography, water holding capacity and the rate of drainage characteristics of the soil.
4. A groundwater drainage function that can generate groundwater outflows as spring flows or through intersection of the regional groundwater table with the river channel system.

Hughes (2000) argues that the data from the DWAF gauging stations (B1H015 and B2H003) suggests that under virgin conditions the upper Olifants is dominated by the runoff generation processes represented by the first function (infiltration excess), but with a significant, slowly responding groundwater baseflow contribution. The VTI model was run using this scenario and calibrated against an earlier yield assessment generated by consulting engineers BKS. Hughes (2000) suggests that the model output simulates larger events than appear in the DWAF observed records (flow gauging stations B1H015 and B2H003). The daily time series that were generated for the four sites for the Olifants river can be assumed to be for virgin conditions.

6.4.2 Hydrological regime of the Olifants sites

Four daily time series were generated for the Olifants sites, representing virgin flow conditions. This information is available in Appendix B if Dollar (2001). Examples of the virgin daily time series data are given in Figure 6.16. The virgin 1-day daily flow duration curves are presented in Figure 6.17.

6.4.3 Flood frequency analysis

The annual duration series flood frequency curves are presented in Figure 6.18 and the partial duration series in Figure 6.19.

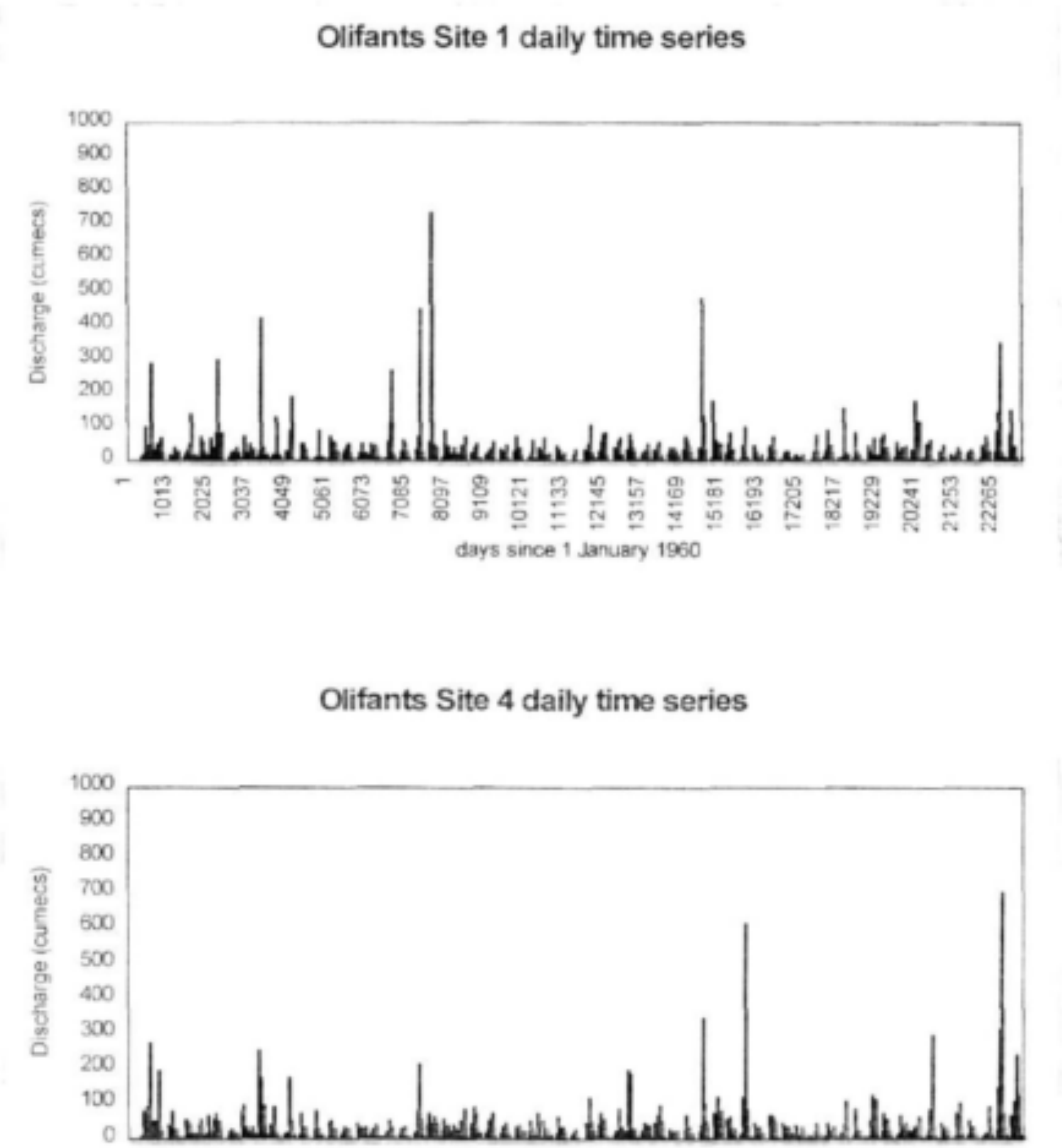


Figure 6.16: *Virgin daily time series for two sites for the Olifants River.*

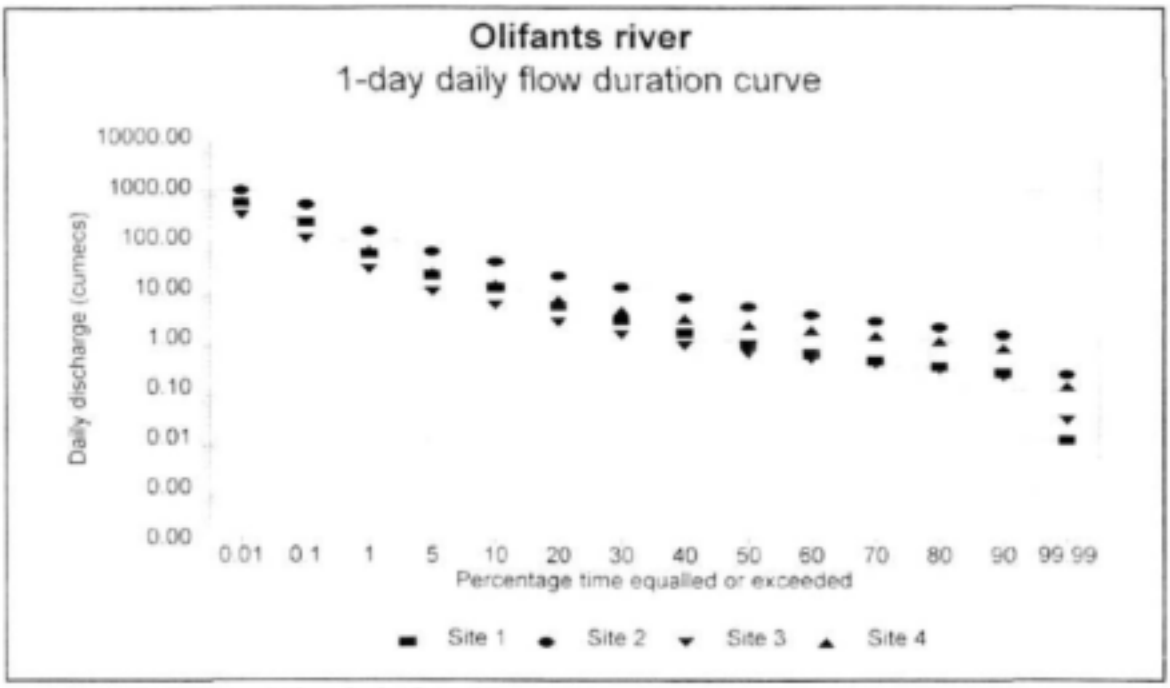


Figure 6.17: *Virgin 1-day daily flow duration curves for four sites for the Olifants River.*

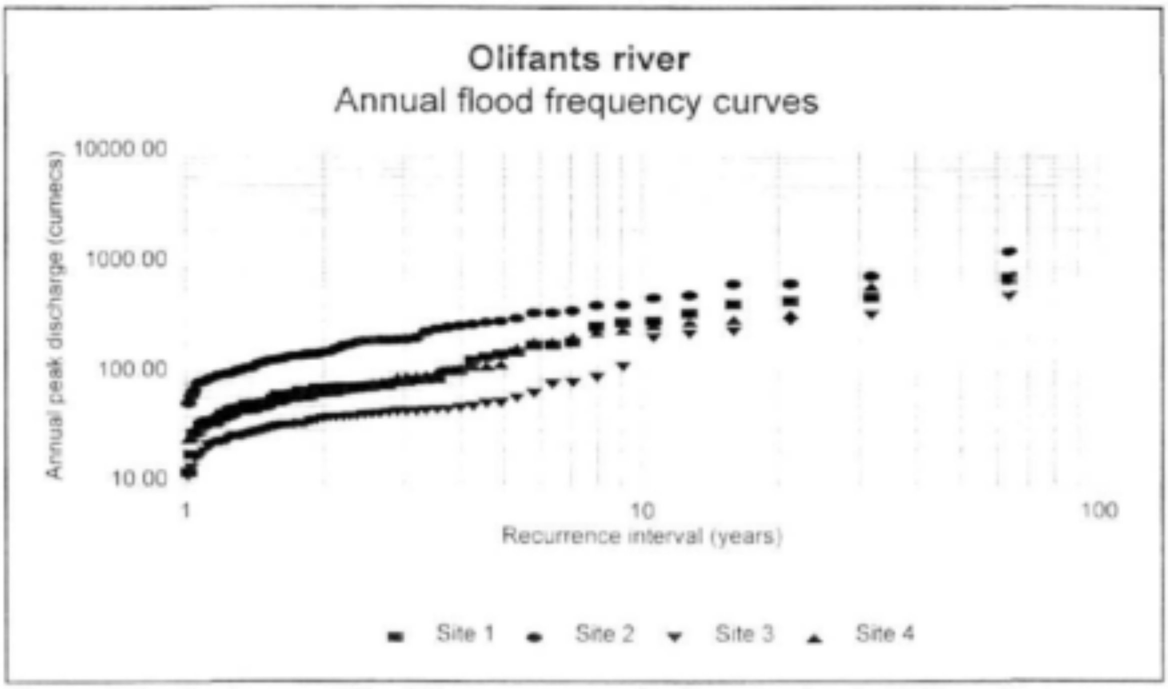


Figure 6.18: *Virgin annual flood frequency curves for four sites for the Olifants River.*

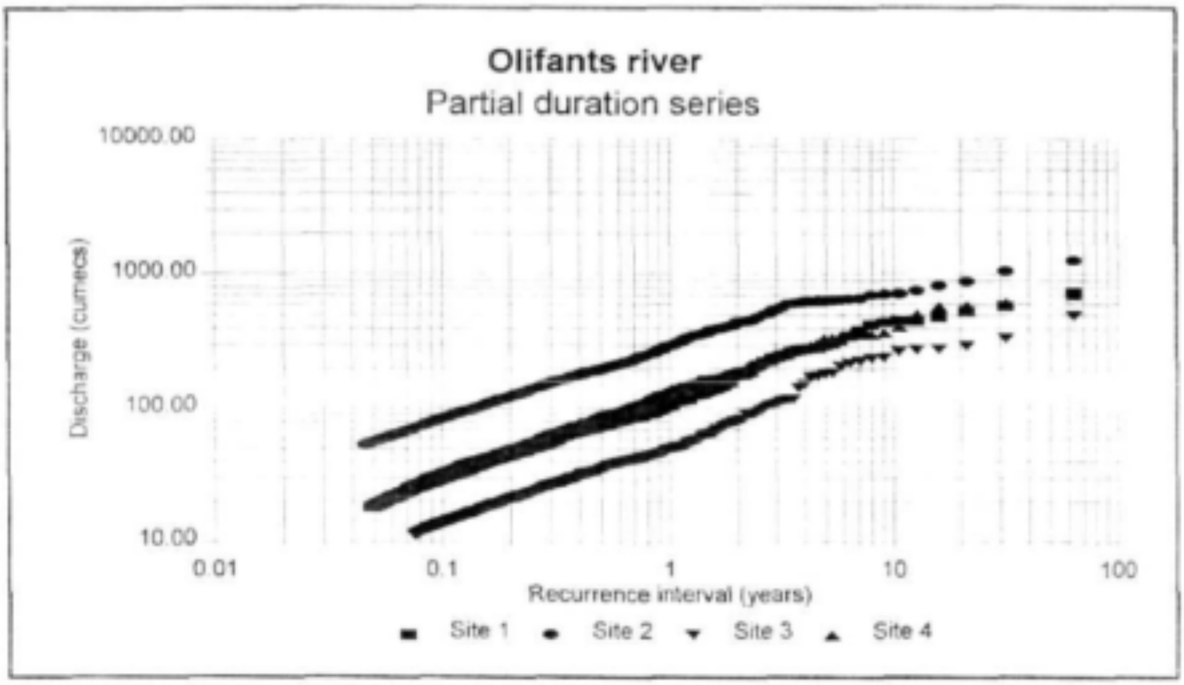


Figure 6.19: *Virgin partial duration series flood frequency curves for four sites for the Olifants River.*

6.5 Summary and conclusions

This chapter has presented the techniques used and hydrological data generated for use in the magnitude-frequency analysis. Table 6.6 presents the summarised hydrological data for the three systems.

The Mkomazi generates the largest MAR of all the rivers considered for this research. It also has the lowest CV. The data for the Mkomazi River was based on target flow duration curves generated on the basis of the source data and regionalised flow duration curves. For all intents and purposes, the synthesised data can be regarded as the natural flow regime as there is as yet no impoundment on the Mkomazi. It is difficult to assess the accuracy of the data in that, apart from the flow gauging stations in the catchments around the Mkomazi, there is nothing to calibrate the data against. It is clear from the historical flood record is that the method used does not accurately reflect the flood peaks (Table 6.6). Table 6.4 has shown that since 1856 there have been a number of floods in the middle and lower catchments that well exceed the Discharge Table Limits (DTL) of the gauging stations. In the upper catchment, there have been at least four major floods exceeding 1230 m^3s^{-1} since 1959. This would suggest that a flood of this magnitude or greater is fairly common (perhaps a 1 in 20 year flood). Van Bladeren (1992) has calculated the 1987 flood (2770 m^3s^{-1}) as being somewhere between the 50 and 100 year flood, while the flood in 1959 of 1490 m^3s^{-1} was calculated as a 20 to 50 year flood. In the lower catchment at least seven major floods exceeding 2880 m^3s^{-1} have occurred in the last 150 years. Again, this would suggest that once in 20 years a major flood is likely to occur. Van Bladeren (1992) has calculated that floods in the range of 3500 m^3s^{-1} to 5000 m^3s^{-1} are likely to have a return period in the range of 20 to 50 years. The point is that large floods occur fairly frequently in the Mkomazi River. Their significance on channel form, maintenance and bed material transport will be discussed in Chapter 9.

The Mhlathuze has a lower MAR than the Mkomazi (virgin and present-day), but has the highest CV of all the rivers under consideration (Table 6.6). This is due to the cut-off lows that generate extreme floods in relation to the 'normal flow'. For the Mhlathuze River, synthesised records were generated for two scenarios - the pre-dam flow record and the post-dam flow record. Again, it is difficult to determine the accuracy of the flow record. In the case of the Mhlathuze, however, the synthesised data sets are in good agreement with the historical flood data (Table 6.6). For the upper part of the Mhlathuze, six major flood events have been recorded since 1940 (Table 6.5). Again, this would suggest a return period of around 20 years. The flood discharge in the lower channel has been severely attenuated by the construction of the Goedertrouw Dam in 1979. Since 1913 there have been at least seven major floods at the lower end of the Mhlathuze. These are reflected in the synthesised virgin flow record. As mentioned earlier this has been shown in the September 1987 flood where the inflow to the Goedertrouw Dam was 3760 m^3s^{-1} and the outflow was 550 m^3s^{-1}. The implications of these reduced flood peaks are considerable.

Table 6.6: *Summary hydrological data for the Mkomazi, Mhlathuze and Olifants Rivers.*

Parameter	**Mkomazi virgin**	**Mhlathuze virgin**	**Mhlathuze present-day**	**Olifants virgin**
Area (km^2)	4 387	4 209	4 209	10 891
MAR (million cubic metres)	1089	362	217	449
Wet season	Summer	Summer	Summer	Summer
CV	0.41	0.93	-	0.70
Highest modelled flow (m^3s^{-1})	1021	4896	4163	735
Highest flood record flow (m^3s^{-1})	7250	6000	4790	-

The data for the Olifants system indicates that the Olifants proper has an MAR between that of the Mkomazi and Mhlathuze (Table 6.6). It has a higher CV than the Mkomazi, but lower than the Mhlathuze (Table 6.6). The hydrological data generated for the Olifants River is based on the VTI model (Hughes, 2000). The data were calibrated against flow gauging stations B1H015 and B2H003. The data indicate that the synthesised data set probably over-predicts the present-day flow environment. Records from B1H015 and B2H003 indicate that now there are significant periods when there is no flow in the Olifants River (between 10% and 30% of the time). Unfortunately there are no historical flood records for the Olifants River against which to compare the synthesised record. It is thus difficult to assess the accuracy of the synthesised record.

The daily time series must be seen within the context of the historical flood records that were available for the Mkomazi and Mhlathuze Rivers. Furthermore, Zawada *et al.* (1996) and Smith (1991) have both suggested that the present flow environment in southern African fluvial systems probably came into being around 1850. It is possible that prior to this many southern African fluvial systems experienced higher mean annual runoff and larger flood peaks (see Chapter 2 for a discussion on this subject).

Chapter 7: Field measurements of cross-section data and bed material and hydraulic calculations

7.1 Introduction

This chapter presents the methods and results for the cross-sectional data analysis, bed material sampling and hydraulic computations for the Mkomazi, Mhlathuze and Olifants Rivers. A total of 65 cross-sections were surveyed at 21 sites,13 on the Mkomazi, four on the Mhlatuze and four on the Olifants. Because of the large amount of data collected, examples of each type of analysis are presented. Full details of analyses of all sites can be found in Dollar (2001).

7.2 Cross-sectional data

7.2.1 Mkomazi River

Figure 5.1 displays the location of the thirteen sites that were selected for analysis. The sites were selected to represent the macro-reaches, taking into account also the degree of disturbance and accessibility. Sites were avoided if on a river bend, had a high degree of human impact (stock grazing or trampling for example), were close to an engineering construction (e.g. bridge or drift), or were immediately upstream or downstream of a major tributary input. Table 7.1 displays a summary of the characteristics for each of the sites for the Mkomazi River. They were classified either as pool-riffle, pool-rapid or boulder-rapid sites. Many of the sites were controlled or semi-controlled by bed rock in the channel perimeter.

7.2.1.1 Cross-sections

Where practical at each of the sites, a minimum of three cross-sections was surveyed using a Topcon Total Station. The cross-sections were spaced at an interval of one channel width apart. Cross-sections were chosen to represent the reach, but were also located so that the local hydraulic conditions were such that the stage-discharge curves could be computed without too many complicating factors. Cross-sections were also chosen so that, where possible, pools and riffles or rapids were represented at each site.

The cross-sections were marked using a fixed point in the form of a concrete bench mark with metal stake. Along each cross-section, relevant morphological data were marked so that, for example, the top of a point bar or the estimated bankfull discharge could be related to stage. The estimated bankfull stage was based on a sharp change in topography (Table 7.2). This occurred where there was a clear break of slope between the active channel and the macro-channel (see Chapter 2, Section 2.4). Figure 2.3 shows a diagrammatic representation of these features for the Mkomazi. At some sites this topographic break was accompanied by sand deposition (transect 9b), by the start of grassy vegetation (transects 10a, 10b, 12 and 13), or was coincident with the top of a lateral bar (transect 8a).

Table 7.1: *Channel characteristics for thirteen sites for the Mkomazi River.*

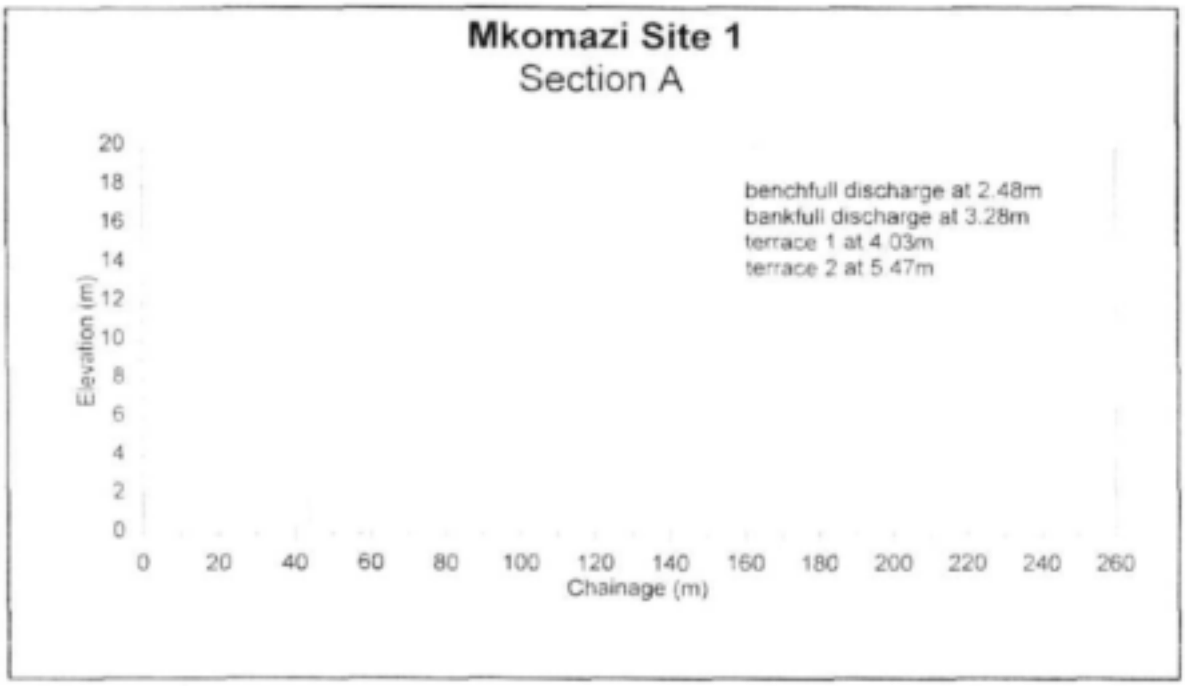
Site	Latitude and Longitude	Catchment area (km²)	Macro-reach	Regional Slope	Number of cross-sections	Reach type	Bed rock present
1 (1320m)	29° 34' 08 S 29° 31' 11 E	171	1	0.0135	3	Pool-riffle	No
2 (1260m)	29° 35' 52 S 29° 34' 15 E	304	1	0.0039	3	Pool-riffle	Yes
3 (1160m)	29° 35' 05 S 29° 41' 38 E	872	1	0.00285	3	Pool-riffle	Yes
4 (1120m)	29° 37' 25 S 29° 44' 26 E	901	1	0.0028	2	Pool-riffle	Yes
5 (940m)	29° 44' 56 S 29° 44' 26 E	1665	2	0.0028	2	Pool-riffle	Yes
6 (920m)	29° 44' 56 S 29° 54' 47 E	1741	2	0.0040	3	Pool-rapid	Yes
7 (860m)	29° 46' 20 S 30° 56' 43 E	1949	2	0.0028	2	Pool-riffle	Yes
8 (840m)	29° 47' 12 S 30° 57' 28 E	1965	3	0.0036	2	Boulder-rapid	Yes
9 (520m)	29° 55' 55 S 30° 05' 23 E	2931	3	0.0062	2	Boulder-rapid	Yes
10 (380m)	30° 00' 03 S 30° 10' 51 E	3436	4	0.00434	2	Pool-riffle	Yes
11 (360m)	30° 00' 43 S 30° 14' 05 E	3462	4	0.0036	1	Pool-riffle	Yes
12 (220m)	30° 05' 30 S 30° 24' 20 E	4177	4	0.00266	1	Pool-riffle	Yes
13 (40m)	30° 07' 50 S 30° 40' 00 E	4334	4	0.00266	1	Pool-rapid	Yes

Table 7.2: *Bankfull stage and bench-full stage characteristics for the Mkomazi River.*

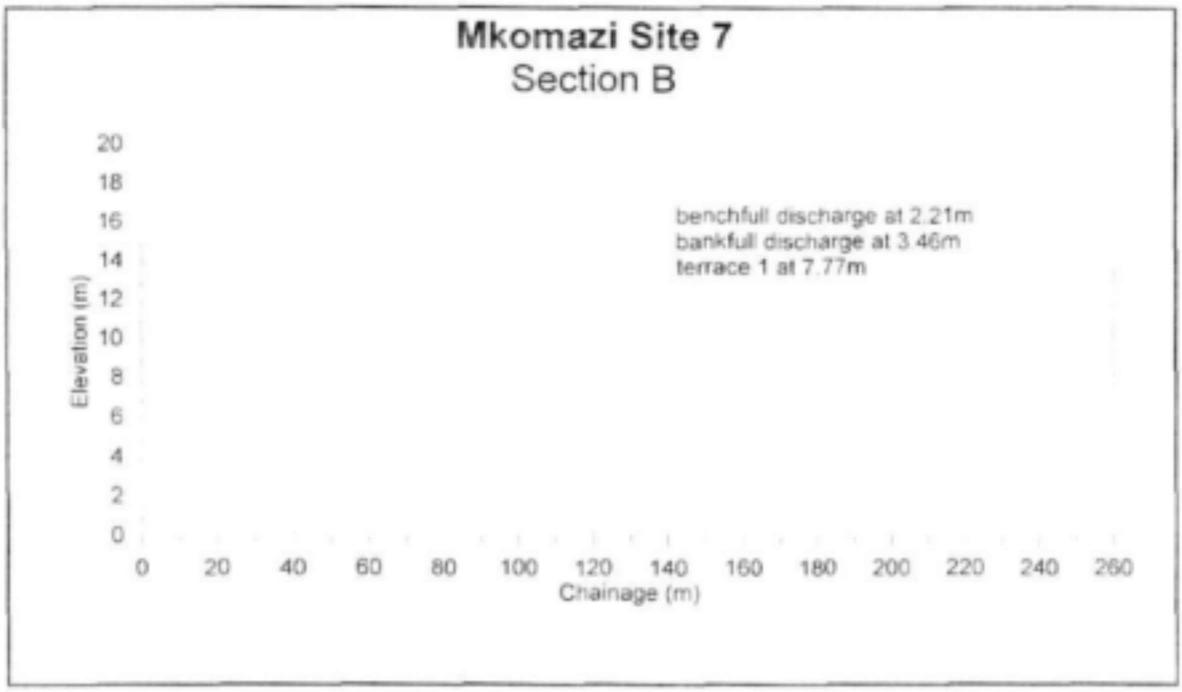
Site	Bench stage (m)	Estimated bankfull stage(m)	Site	Bench stage (m)	Estimated bankfull stage(m)
1a	2.48	3.28	6a	2.53	3.53
1b		3.05	6b	2.92	4.27
1c		3.15	6c		4.66
2a	2.76	4.43	7a		3.74
2b	2.81	4.26	7b	2.21	3.46
2c	2.05	3.73	8a		2.55
3a	1.74	5.91	8b		2.88
3b	2.15	4.96	9a	2.13	2.63
3c		5.00	9b		3.11
4a	2.68	4.06	10a		2.48
4b	2.75	4.78	10b		2.21
5a	4.39	4.79	11	2.20	3.38
5b		4.31	12		2.80
			13		2.32

Benches and terraces were identified on the basis of their relationship to the bankfull stage as estimated in the field. The bench-full stage estimate was based on two criteria. The first was an obvious break in slope below the bankfull stage. This slope was characteristically concave. The break in slope had to be related to a clear bench-like feature, with a distinct flat surface parallel and adjacent to the active channel-bed, but raised above it. The second factor was a change in vegetation. In many cases, the flatter bench was covered by grass. In this manner, a consistent definition of the estimated bench-full stage was achieved (Table 7.2). Major breaks in the cross-sectional profile above the estimated bankfull stage were designated *terraces*. The terraces were numbered in sequential order from the lowest to the highest.

Figure 7.1 displays two examples of the types of cross-sections surveyed for the Mkomazi River. Table 7.3 displays the elevation of the benches and terraces above the lowest point in the bed together with their associated vegetation and sediment characteristics. It can be seen that the features above the low bench are all associated with sediment in the sand-sized range and finer. The vegetation is mainly grass and trees.



benchfull discharge at 2.48m
bankfull discharge at 3.28m
terrace 1 at 4.03m
terrace 2 at 5.47m



benchfull discharge at 2.21m
bankfull discharge at 3.46m
terrace 1 at 7.77m

Figure 7.1: *Cross-sections for sites 1a and 7b for the Mkomazi River.*

***Table** 7.3: Morphological features for the Mkomazi River.*

Site	Vegetation	Sediment	Terrace 1 (m)	Vegetation	Sediment	Terrace 2 (m)	Vegetation	Sediment
1a			4.03	grass and trees	sand and finer	5.47	grass	sand and finer
1b			3.49	grass and trees	sand and finer	5.42	grass	sand and finer
1c			3.78	grass and trees	sand and finer	4.37	grass	sand and finer
2a	grass	sand and finer	5.37	grass and trees	sand and finer	6.36	grass	sand and finer
2b			5.93	grass and trees	sand and finer			
2c			4.06	grass and trees	sand and finer	6.53	grass	sand and finer
3a	grass and trees	sand and finer	8.20	grass and trees	sand and finer			
3b			5.72	grass and trees	sand and finer	7.03	grass	sand and finer
3c								
4a	grass and trees	sand and finer	5.25	grass and trees	sand and finer	6.90	grass	sand and finer
4b			5.59	grass and trees	sand and finer	6.68	grass	sand and finer
5a			5.93	grass and reeds	sand and finer	8.08	grass and trees	sand and finer
5b			5.74	grass and reeds	sand and finer	7.13	grass and trees	sand and finer
6a			4.89	grass and trees	sand and finer	7.11	grass and trees	sand and finer
6b			5.10	grass and trees	sand and finer			
6c			6.54	grass	sand and finer	8.50	grass	sand and finer
7a			8.46	grass and trees	sand and finer			
7b			7.77	grass and trees	sand and finer			

Table 7.3 continued: *Morphological features for the Mkomazi River.*

Site	Vegetation	Sediment	Terrace 1 (m)	Vegetation	Sediment	Terrace 2 (m)	Vegetation	Sediment	Terrace 3 (m)	Vegetation	Sediment
8a			4.84	grass and trees	sand and finer	5.58	grass and trees	sand and finer	7.75	grass and trees	sand and finer
8b			5.00	grass and trees	sand and finer	6.84	grass and tress	sand and finer			
9a	grass	sand and finer	4.78	grass and trees	sand and finer						
9b			4.74	grass and trees	sand and finer						
10a			4.71	grass	sand and finer	7.49	grass and trees				
10b			4.44	grass	sand and finer	7.95	grass and trees				
11	grass	sand and finer	3.34	grass and trees	sand and finer	5.22	grass and trees				
12			4.15	grass and trees	sand and finer	6.75	grass and trees				
13			7.08	grass and trees	sand and finer	8.82	grass and tress	sand and finer	12.07	grass and trees	sand and finer

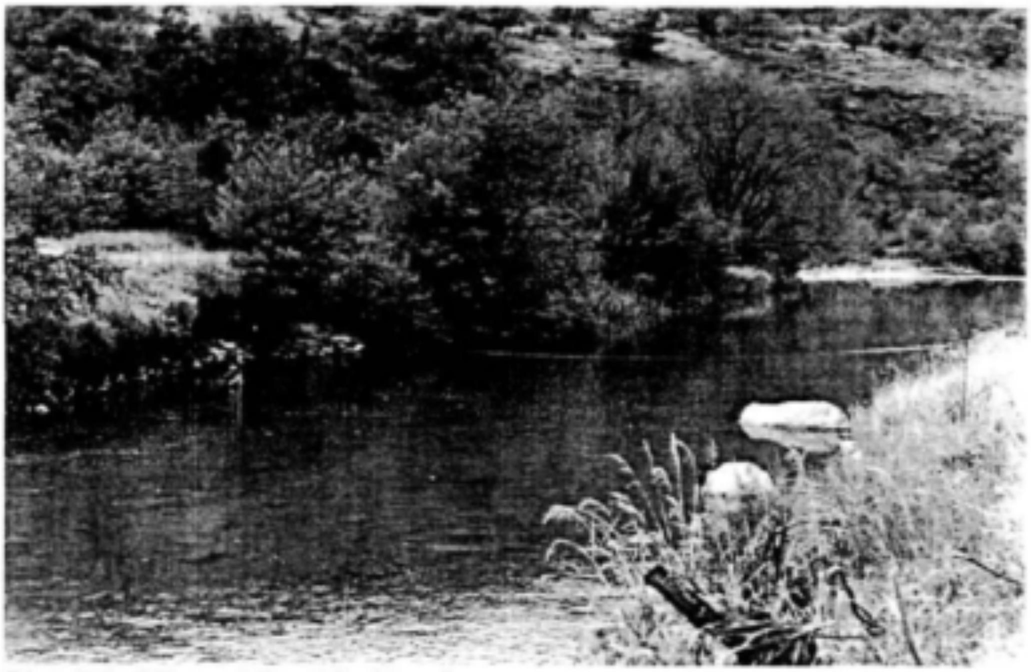


Plate 7.1: *Mkomazi Site 1 looking downstream.*

Plate 7.2: *Mkomazi Site 7 looking upstream.*

7.2.2 Mhlathuze River

Four sites were chosen for the Mhlathuze River. Figure 5.3 displays the location of the sites that were selected for analysis. Table 7.4 displays a summary of the characteristics for each of the sites. Site 1 is just below the Goedertrouw Dam and as such has been affected by the regulated flow regime. This has resulted in the channel narrowing and deepening. Site 1 is semi-controlled by bed rock, as the right bank of the site contains a dyke that has intruded into the country rock. Site 1 consists of three distributary channels, each with a different flow level. The complexity of Site 1 was such that seven cross-sections were surveyed to ensure that the hydraulic calculations were accurate. Sites 2, 3 and 4 are wide, regime sand-bed channels.

Table 7.4: *Channel characteristics for four sites for the Mhlathuze River.*

Site	**Latitude and Longitude**	**Catchment area (km²)**	**Macro-reach**	**Regional Slope**	**Number of cross-sections**	**Reach type**	**Bed rock present**
1 (100 m)	28° 44' 31 S 31° 36' 20 E	1941	4	0.0015	7	Pool-riffle	Yes
2 (40 m)	28° 44' 50 S 31° 44' 50 E	2666	4	0.00282	2	Regime[1]	No
3 (20 m)	28° 50' 45 S 31° 52' 00 E	2860	4	0.00087	1	Regime	No
4 (10 m)	28° 37' 25 S 31° 44' 26 E	3608	4	0.00070	2	Regime	No

[1] A regime channel is defined by Rowntree & Wadeson (1999) as a channel with a mobile bed that adjusts rapidly to changes in imposed flow.

7.2.2.1 Cross-sections

Figure 7.2 displays two examples of two surveyed cross-sections at sites 1 and 3 in the Mhlathuze River. Plates 7.3 and 7.4 show the general characteristics of these sites. As in the Mkomazi River, a common feature in the Mhlathuze River is the occurrence of distinct benches and terraces. Table 7.5 displays the criteria used to define the bench-full and bankfull stage for the Mhlatuze sites, while Table 7.6 displays the heights above the lowest point in the bed as well as the sediment and vegetation characteristics for each of these features for the Mhlathuze River.

Table 7.5: *Bankfull discharge and bench-full discharge characteristics for the Mhlathuze River.*

Site Number	Bench 1 (m)	Bench-full estimate criteria	Estimated bankfull (m)	Bankfull estimate criteria
1a	1.45	Break in slope and start of the reed vegetation	3.00	Change in topography
1b			2.16	Change in topography
2	1.19	Break in slope, top of grassed island and start of the reed vegetation	2.67	Change in topography
3			2.69	Change in topography
4			2.29	Change in topography

Table 7.6 *Morphological features for the Mhlathuze River.*

Site	Vegetation	Sediment	Terrace 1 (m)	Vegetation	Sediment	Terrace 2 (m)	Vegetation	Sediment	Terrace 3 (m)	Vegetation	Sediment
1a	Reeds	sand and finer									
1b			3.86	reeds and trees	sand and finer	4.45	reeds and tress	sand and finer	6.61	trees	sand and finer
2	Reeds	sand and finer	4.47	reeds and trees	sand and finer	5.87					
3			4.54	reeds and trees	sand and finer	7.25					
4			3.41	reeds	sand and finer	5.78	reeds and trees	sand and finer			

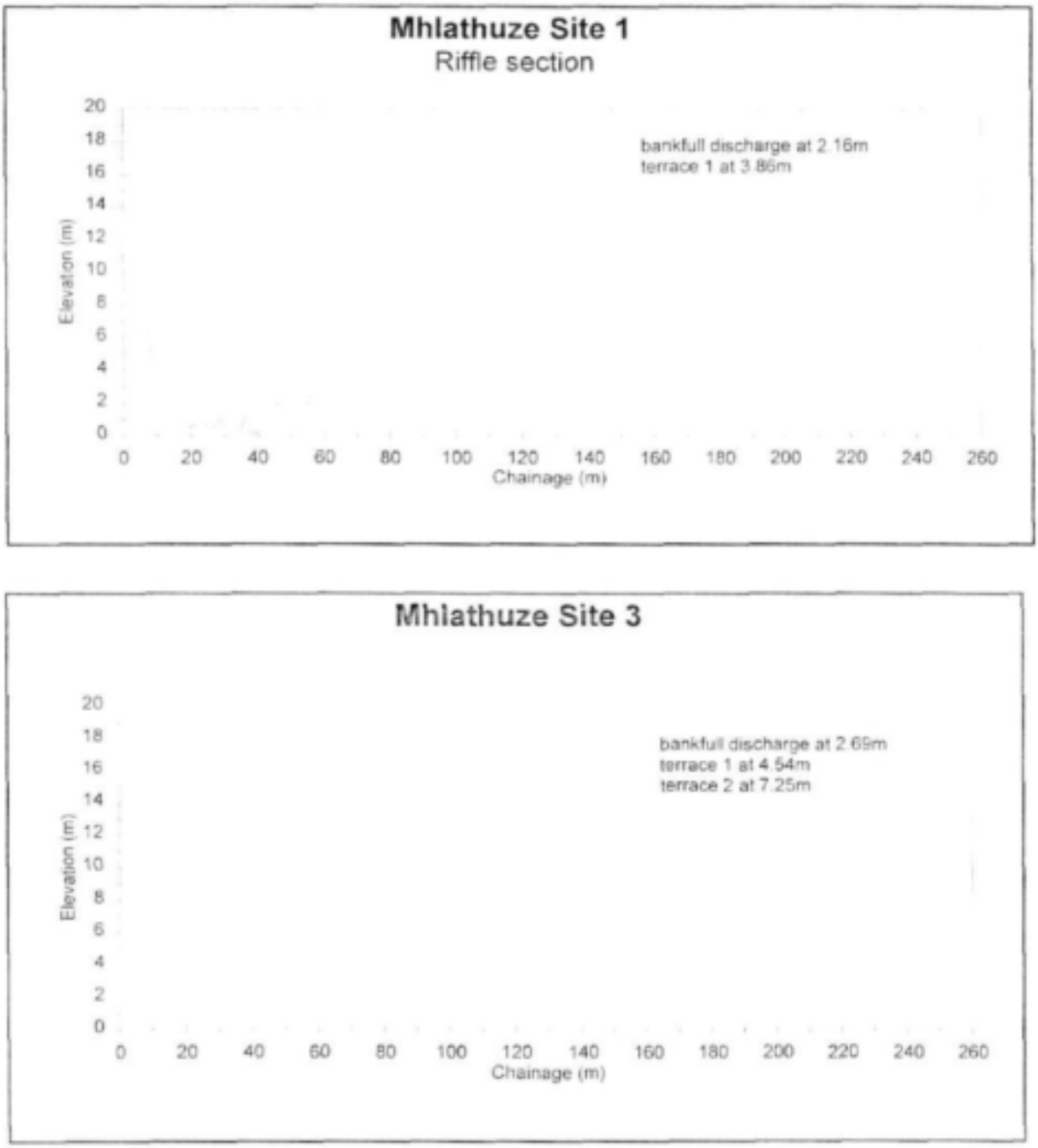


Figure 7.2: *Cross-sections for sites 1 and 3 for the Mhlathuze River.*

Plate 7.3: *Mhlathuze Site 1 looking upstream.*

Plate 7.4: *Mhlathuze Site 3 looking downstream.*

7.2.3 Olifants River

Four sites were chosen for the Olifants River. Figure 5.5 displays the location of the sites that were selected for analysis. Table 7.7 displays a summary of the characteristics for each of the sites. The Olifants River is a predominantly bed rock controlled system, and as such has little capacity for changing its overall channel morphology except by sediment deposition.

Table 7.7: *Channel characteristics for four sites for the Olifants River.*

Site	**Latitude and Longitude**	**Catchment area (km²)**	**Macro-reach**	**Regional Slope**	**Number of cross-sections**	**Reach type**	**Bed rock present**
1 (1380m)	25° 45' 31 S 29° 18' 46 E	2520	3	0.00366	7	Regime	No
2 (1030m)	25° 29' 44 S 29° 15' 18 E	10 820	4	0.00403	7	Pool-rapid	Yes
3 (1265m)	25° 40' 24 S 29° 18' 58 E	2350	4	0.00616	6	Pool-rapid	Yes
4 (1200m)	25° 37' 10 S 28° 59' 59 E	4300	3	0.00015	6	pool-riffle anabranching	Yes

7.2.3.1 Cross-sections

Figure 7.3 displays two examples of cross-sections surveyed for the Olifants River. At each of the sites for the Olifants River at least six cross-sections were surveyed. This was because the channels were complex with multiple distributaries. The water surface in the distributary channels was at different elevations due to strong upstream hydraulic control. Morphological features were noted and fixed onto the survey. Table 7.8 displays the criteria used to determine the bankfull discharges. Table 7.9 displays the height of each of these features above the lowest point in the bed as well as the sediment and vegetation characteristics of each site.

Table 7.8: *Bench-full discharge and bankfull discharge characteristics for the Olifants River.*

Site Number	Bench (m)	Bench-full estimate criteria	Estimated bankfull (m)	Bankfull estimate criteria
1	-	-	1.57	Change in topography, start of reed growth
2	-	-	3.21	Change in topography, start of reed growth
3	-	-	2.58	Change in topography
4	-	-	2.77	Change in topography

Table 7.9: *Morphological features for the Olifants River.*

Site	Terrace 1 (m)	Vegetation	Sediment	Terrace 2 (m)	Vegetation	Sediment	Terrace 3 (m)	Vegetation	Sediment
1	4.47	grass, reeds and trees	gravel and finer	6.57	grass and trees	gravel and finer			
2	3.81	reeds and trees	boulders, cobble, gravel and sand	5.38	grass and trees	gravel and finer	7.61	grass and trees	sand and finer
3	5.08	reeds and trees	Gravel and finer	6.23	grass and trees	gravel and finer	7.62	grass and trees	sand and finer
4	6.17	reeds	Gravel and finer	7.89	grass and trees	gravel and finer	9.26	grass and trees	sand and finer

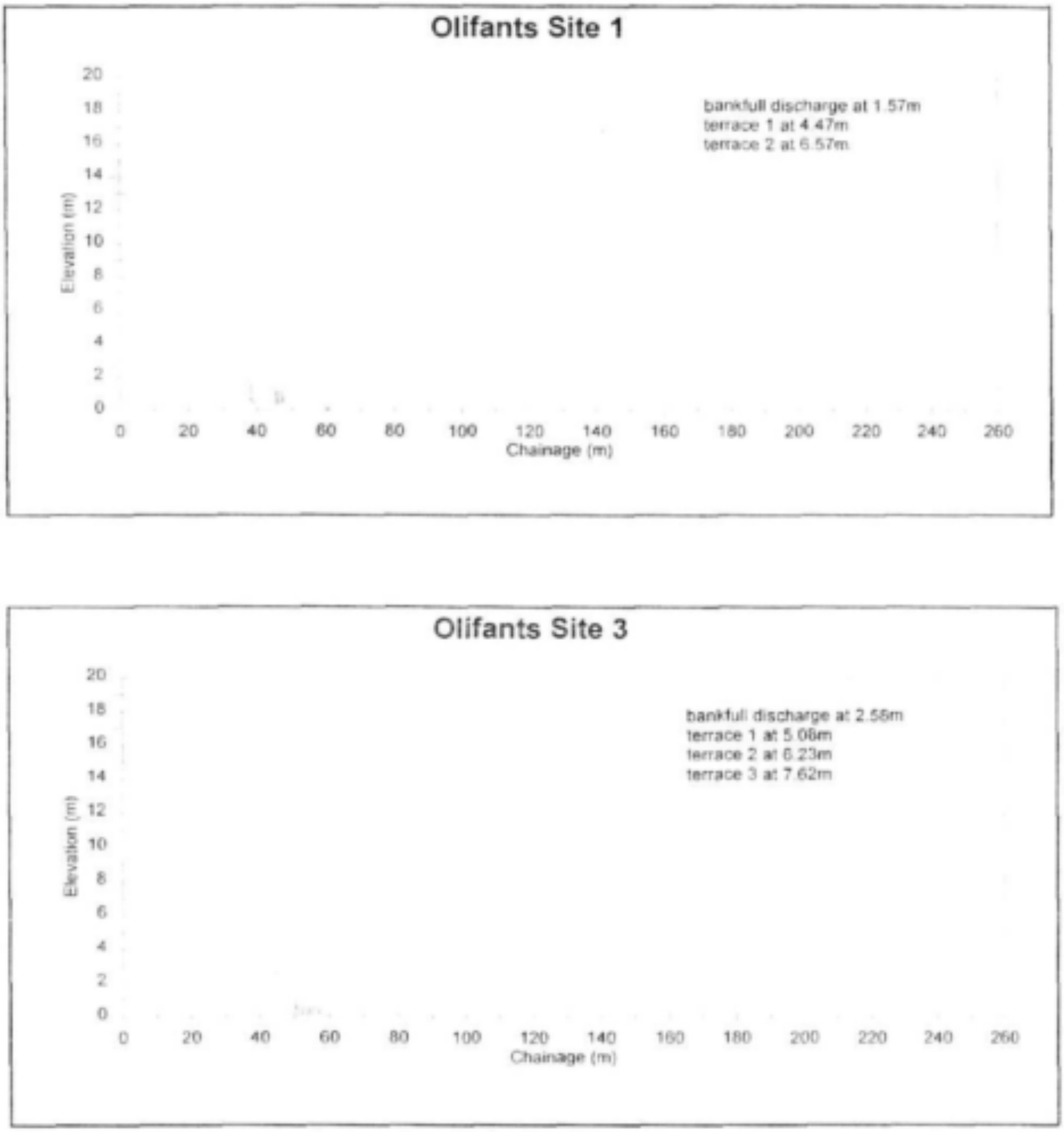


Figure 7.3: *Cross-sections for sites 1 and 3 for the Olifants River.*

Plate 7.5: *Olifants Site 1 looking upstream.*

Plate 7.6: *Olifants Site 3 looking downstream.*

7.2.4 Quality audit and summary

There are a number of issues that must be mentioned with respect to the cross-sectional surveys. First, 27 cross-sections were surveyed for the Mkomazi, 12 for the Mhlathuze and 26 for the Olifants River, a total of 65 cross-sections. Thirty-seven of these have been rated to produce stage discharge curves. This required repeated site visits. A minimum of four calibration visits were made, in some cases as many as seven calibration visits were achieved. Given time and financial constraints, it was not possible to survey any further cross-sections. The number of cross-sections may, therefore, be a limiting factor in terms of the representivity of the data.

Second, the number of cross-sections at each site varied. One of the reasons for this was the variable complexity of the sites. Where multiple channels occurred with different water levels, a greater number of cross-sections were necessary to adequately perform the hydraulic computations. For example, Site 1 on the Olifants River had four distributary channels, this required seven cross-sections to reflect the water levels at different discharges. Site 3 on the Mhlathuze on the other hand, was a simple sand-bed regime channel and therefore only one cross-section was used to represent the site. The number of cross-sections also depended on the reach type. For example where a pool-riffle reach type occurred, the cross-sections were situated to reflect both the pool and the riffle. It is argued that the cross-sections adequately represent the macro-reaches of the three rivers under investigation.

Third, the accuracy of the bed material transport computations is in part dependent on accurate surveying of the cross-sections. Any error in the cross-sectional surveys will be compounded in the hydraulic computations and in the bed material transport values. For this reason, the cross-sections were surveyed using a Electronic Total Station which results in a very accurate survey.

7.3 Bed material data

Bed material was sampled to determine the calibre of bed material at each site so that it could be used in the bed material transport equations. The problem of obtaining an accurate, reliable and representative sample of bed material is well known (cf. Wolman, 1954; Church *et al.*, 1987). Authors have suggested different methods for bed material sampling. These include surface clast counts, surface and subsurface bulking and sieving (Ferguson & Ashworth, 1991), surface counts using a grid system (Wolman, 1954), pacing (Mosley & Tindale, 1985) and transect sampling (Kellerhals & Bray, 1971; Ibbeken, 1974). Bed material sampling techniques differ and are adapted to the objectives of the survey as well as to financial and technological constraints.

Based on the literature, as well as resource constraints, it was decided to use a combination of surface clast counts and bulk subsurface sampling and sieving, the details of which will be discussed with reference to each river. A sample of the bed material was taken on one occasion only at low flow for each site, enabling the sampling of deeper pools, faster flowing riffles and rapids. While it is acknowledged that bed material characteristics can change over time, the logistics of bed material sampling, and the laboratory time necessary to process the samples, placed logistical constraints on sampling. Indeed, based on visual and photographic evidence, there appeared to be little evidence to suggest any significant change in the composition of the bed material during the period of study.

7.3.1 Mkomazi River

A combination of surface clast counts and bulk subsurface sampling and sieving was used for the Mkomazi River. At least 500 samples were taken at each site. Mosley & Tindale (1985) suggest that 70 samples per site are necessary to obtain a representative sample of the whole bed, while Wolman (1954) and Brusch (1961) suggest a sample of 60 is adequate. The Mkomazi samples should therefore have been more than adequate to represent the local conditions. Where the samples were in the sand (>2 mm) to fine gravel (<10 mm) range, a bulk sample was taken and sieved. Where the size range was medium gravel (>10 mm) or larger, the size of the median axis was measured with either a pair of calipers or a measuring tape. The data were used to construct a curve to show the percentage finer bed material for each site. Figure 7.4 displays examples of the curves constructed for sites 1, 6, 9 and 13. From these curves, the D_{16}, D_{50} and D_{84} and so on were determined. Table 7.10 displays the results in tabular form.

Table 7.10: *Bed material characteristics for the Mkomazi River.*

Site	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	SD	Mean	CV	Silt + Clay %	Sand %	Gravel + Cobble + Boulder %
1	1.8	5.6	16	7.1	8.9	0.80	0	15.4	84.6
2	2.8	10.0	45	21.1	23.9	0.88	0	6.7	93.3
3	1.1	4.2	14	6.3	7.4	0.85	0	19.6	80.4
4	0.4	12.0	90	44.8	45.2	0.99	0	30.6	69.4
5	0.2	1.7	15	7.4	7.6	0.98	2.3	27.9	69.8
6	3.8	26.0	100	48.1	51.9	0.93	0	14.6	85.4
7	8.6	48.0	220	105.7	114.3	0.92	0	4.0	96.0
8	13.0	30.0	150	68.5	81.5	0.84	0	3.3	96.7
9	4.2	60.0	410	202.9	207.1	0.98	0	9.8	90.2
10	15.0	50.0	400	192.5	207.5	0.93	0	3.1	96.9
11	22.0	65.0	160	69.0	91.0	0.76	0	1.3	98.7
12	0.7	3.9	230	114.6	115.3	0.99	0	44.1	55.9
13	3.2	26.0	96	46.4	49.6	0.94	0.7	10.9	88.4

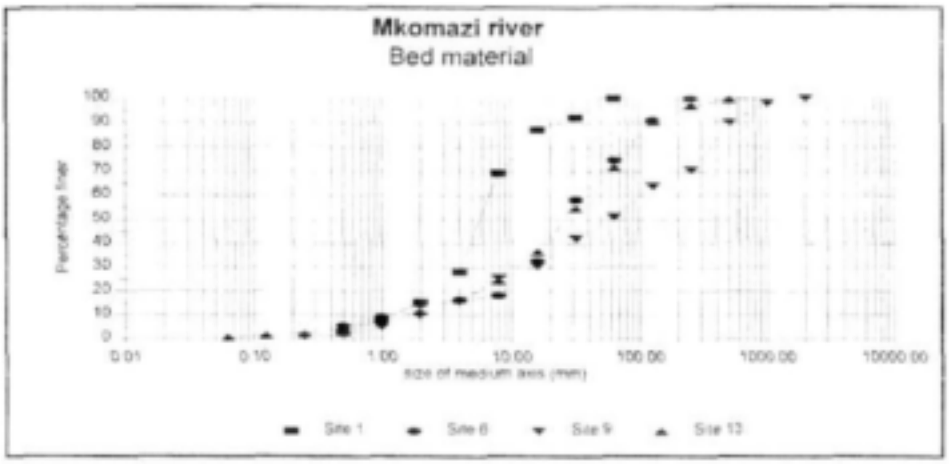


Figure 7.4 *Bed material for sites 1, 6, 9 and 13 for the Mkomazi River.*

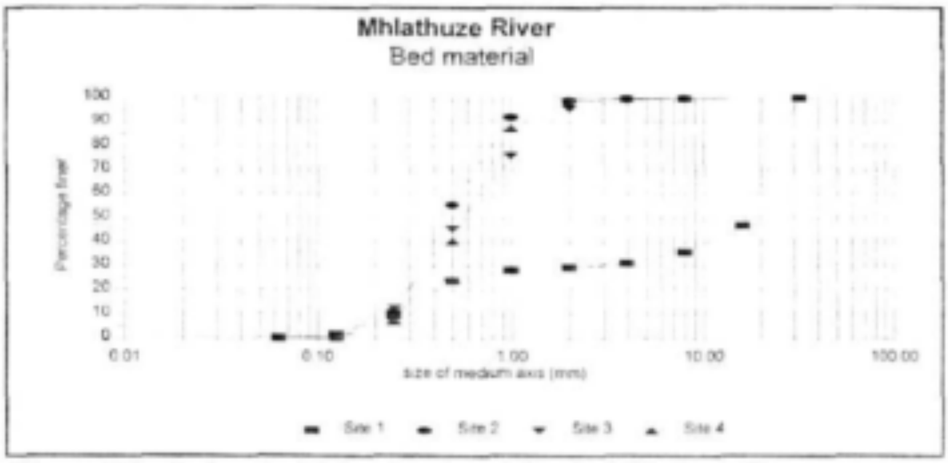


Figure 7.5: *Bed material for sites 1 to 4 for the Mhlathuze River.*

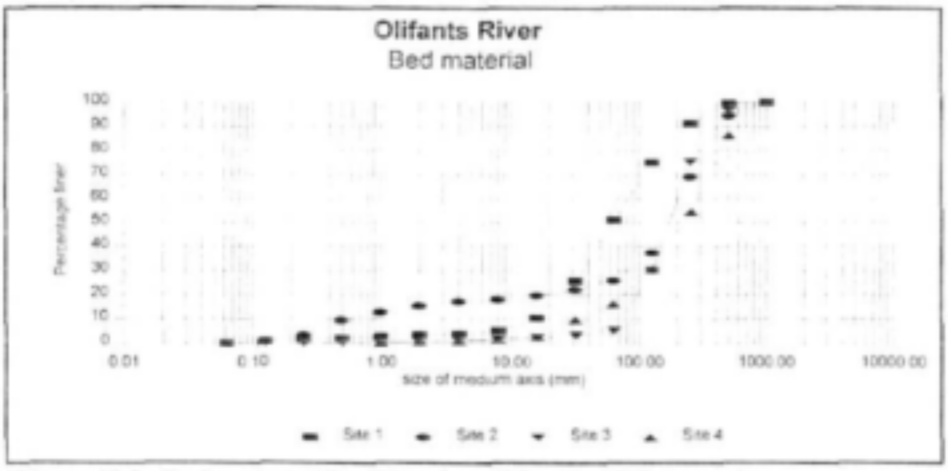


Figure 7.6: *Bed material for Sites 1 to 4 for the Mhlatuze river.*

The data indicate that the Mkomazi River is mainly a cobble-bed river. Most of the sites, with the exception of sites 4, 5 and 12, consist of over 70% gravel and cobble, with only small percentages of sand and virtually no silt or clay. The low values of silt and clay may reflect a sampling problem, in that the silt and clays could have been washed out of the sample before they could be placed in the sample bag. The data also show that the expected downstream fining of bed material in the Mkomazi River does not hold true. In fact, the general trend is an increase in the size of the bed material between sites 1 and 10. This holds true for the D_{16}, D_{50} and the D_{84}. Sites 11, 12 and 13 display variability in the downstream direction. Site 12 is predominantly a sand-bed channel, but has a large D_{84}. Sites 8, 9 and 10, which are in the gorge section of the Mkomazi, reflect a very coarse bed with a large D_{84} and a high standard deviation and coefficient of variation. The characteristics of the bed material of the Mkomazi therefore reflect the channel type; flatter, wider sections are associated with relatively finer material, while the steeper gorge sections reflect coarser bed material with a high standard deviation and coefficient of variation. The notion of downstream fining does not appear to fit the bed material characteristics of the Mkomazi River, rather the bed material characteristics tend to reflect local hydraulic conditions.

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7.3.2 Mhlathuze River

For the Mhlathuze River, a combination of surface clast counts and bulk subsurface sampling and sieving was used for Site 1. However, for sites 2, 3 and 4 the bed material is in the sand-sized range (<2 mm). Here, thirty bulk samples were taken using a grid system at each site. These were analysed in the laboratory for grain-size analysis. Figure 7.5 displays the particles size curves for sites 1 to 4. From these curves, the D_{16}, D_{50} and D_{84} and so on were determined. Table 7.11 displays the results in tabular form.

With the exception of site 1, The Mhlathuze River in the area under consideration was a sand-bed channel. Site 1 was a pool-riffle channel type and, therefore, the predominant bed material was gravel and cobble. Sites 2, 3 and 4 were sand-bed channels, with sand constituting over 75% of the bed in all cases (Table 7.11). The depth of the sand was considerable. During the sampling of the bed, a 5 metre iron rod was inserted into the bed at sites 2, 3 and 4 and in all cases, the depth of the sand in the bed exceeded five metres. Although there was some gravel present at these sites, this did not exceed 32 mm in diameter. The mean grain size in the lower three sites was around 1 mm. Very little silt and clay was measured. The low standard deviation and coefficient of variation in the lower three sites confirmed the homogeneity and well-sorted nature of the bed.

Table 7.11: *Bed material characteristics for the Mhlathuze River.*

Site	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	SD	Mean	CV	Silt + Clay %	Sand %	Gravel %
1	0.4	22.0	35.0	17.3	17.7	0.9	0.20	19.5	80.3
2	0.4	0.7	1.4	0.5	0.9	0.6	0.02	91.9	8.1
3	0.4	0.8	2.0	0.8	1.2	0.7	0.05	75.7	24.3
4	0.4	0.9	1.3	0.5	0.8	0.5	0.06	87.4	12.5

7.3.3 Olifants River system

A combination of surface clast counts and bulk subsurface sampling and sieving was used for the Olifants River system. A minimum of 500 samples were taken at each site. Curves were constructed to show the percentage finer bed material at each site. Figure 7.6 displays the curves constructed for sites 1 to 4. Table 7.12 displays the results in tabular form. The data indicate that all the sites are dominated by coarse bed material. The material is often imbricated and armoured. There is very little silt, clay or sand on the bed. Site 1 consists mainly of gravel-sized material, while sites 2, 3 and 4 are dominated by boulder-sized bed material. There is very little sand sized material in the bed at any of the sites.

It should be noted that sites 1 and 2 are on the Olifants proper, Site 3 is on the Klein Olifants and site 4 is on the Wilge River. The highest discharge occurs at Site 2, followed by sites 4, 1 and then 3.

Table 7.12: *Bed material characteristics for the Olifants River and tributaries.*

Site	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	SD	Mean	CV	Silt + Clay %	Sand %	Gravel + Cobble + Boulder %
1	22	96	277	128	149	0.85	0.6	2.6	96.8
2	5	220	520	258	263	0.98	0.0	12.6	87.4
3	140	250	480	170	310	0.55	0.0	0.4	99.6
4	90	320	500	205	295	0.69	0.0	0.2	99.8

7.3.4 Quality audit and summary

The accurate determination of the bed material for a site is difficult. This is especially so as bed material can change in the horizontal plane, with depth and over time. Due to logistical constraints, it was not possible to sample the bed material more than once through the course of the project. However, it is argued that the sampling programme resulted in a representative sample of the bed material, especially at sites containing a homogenous bed. The Mkomazi, Mhlathuze and Olifants Rivers display different bed material characteristics. The Mkomazi is mainly a cobble-bed river, the Mhlathuze is predominantly a flat, sand-bed channel, while the Olifants is a steep, cobble-bed river, with a very coarse armour layer in the boulder-size range.

7.4 Hydraulic computations

The aim of the hydraulic computations was to generate rated sections for each site. This was required for two reasons. First, the relationship between stage, discharge, wetted perimeter and water surface slope is necessary to determine bed material transport. Second, the rating was required to relate stage to channel features. A stage discharge curve was created for each cross section based on field measurements of stage and discharge and on theoretical calculations of discharge from hydraulic variables.

Each cross-section was re-surveyed between four and seven times to determine the water surface stage, water surface slope and discharge. Discharge measurements were made using the velocity area method. Velocity was measured using an electro-magnetic Marsh-McBirney Flow Mate current metre. Readings were made at every metre or half metre at 0.6 depth from the surface. Using this technique, stage-discharge rating curves were constructed for each of the cross-sections for each site for the Mkomazi River.

These curves were extended beyond the range of measured discharges using estimates based on hydraulic theory. There are a number of means of calculating flow discharge from stage. Three common methods are the Chezy, Mannings and Darcy-Weisbach equations (Chang, 1988). It has been common practice in South Africa to use Manning's resistance equation (Broadhurst *et al.*, 1997). For the purpose of this study and for consistency, the most common flow resistance equation (Manning's) was used. A full description of this technique is available in most hydrological or hydraulic text books. Here, a short review will suffice. The derivation of the basic equations that govern open channel flow begins with the assumption that a fluid can be considered as a continuum (Lane, 1998). Manning's resistance equation is given by:

$$Q = \left(\frac{A^{1.667}}{P^{0.667}}\right)\left(\frac{\sqrt{S_f}}{n}\right) \qquad \text{(\textit{Equation 7.1})}$$

where Q is discharge (m^3s^{-1}). A iscross-sectional flow area (m^2). P is wetted perimeter (m). S_f is friction slope (m/m) and n is theManning resistance coefficient ($s\ m^{-1/3}$)

The 'resistance-friction slope' term in Equation 7.1 can be combined into a single term, given by

$$k = Q\left(\frac{P^{0.667}}{A^{1.667}}\right) \qquad \textit{(Equation 7.2)}$$

Using Manning's, a table of observed and modelled discharge is generated. The modelled discharge is extrapolated beyond the range of field measurements by estimating the 'friction slope-resistance' (n). Estimating 'n' is problematic, but the use of photographs (Barnes, 1967) and previously modelled data (Chow, 1959) can help provide an adequate estimate. Indications are that the resistance coefficient reaches an asymptotic value with increasing discharge, but increases exponentially with reducing discharge as the flow depth becomes comparable to the height of the resistance elements (Broadhurst *et al.*, 1997). Applying Manning's to extreme low flows is difficult, when the flow depth is about the same depth as the resistance elements and, as a result, large coefficients are derived. In this case, the highest *n* value is applied.

Estimating the slope also proved problematic. The estimated slope was calculated as a function of the relationship between the regional slope (1:50 000 topographical map) and the lowest water surface slope measured in the field (Birkhead & James, 1998). The slope was estimated by:

$$\textit{Estimated slope} = \frac{(S_r + (S_l - S_r))}{(1 + (0.01 * Q))^{0.5}} \qquad \textit{(Equation 7.3)}$$

where S_r is the regional slope (m/m), S_l is the lowest water surface slope measured in the field (m/m)

The slope generally increases with increasing discharge, reaching an asymptotic level at approximately the regional slope (calculated off 1:50 000 topographical maps). However, this is not always the case. At some sites, the slope calculated in the field was greater than the regional slope. This situation occurs where the site is located on a steep section, often associated with strong bed rock control, or where the section traverses a riffle. In these instances, the slope decreases with increasing discharge as the riffle or rapid is drowned out. This has significant implications for sediment transport and will be discussed in greater detail in the following three chapters.

Once the observed and modelling stage discharge relations had been determined, a regression was fitted to the data. The general form of the regression is given in Equation 7.4:

$$y = a\,Q^{b} + c \qquad \textit{(Equation 7.4)}$$

where y is the maximum flow depth (m), a, b, c are the coefficient, exponent and constant respectively.

7.4.1 Computations for the three rivers

Examples of stage discharge curves generated for the three rivers are shown in Figure 7.7, 7.8 and 7.9. Table 7.13, 7.14 and 7.15 display the coefficients from the regression analyses for different cross sections at the thirteen sites for the Mkomazi River and the four sites on both the Mhlatuze and Olifants rivers. These regression coefficients were used to develop rating curves for the cross-sections.

Where there were multiple channels at a site, the individual channels were modelled separately. When a critical discharge was reached such that the individual channels flowed as a discrete unit, a different rating was applied. In this manner it was possible to rate each of the distributary channels.
Rating curves for the Mhlatuze and Olifants rivers have been published (Jordanova, 1998 in Louw, 1998b).

7.4.2 Quality audit and summary

The accuracy of the hydraulic computations depends on a number of factors: an adequate estimate of the boundary roughness 'n', the water surface slope, and the range of flows utilised to calibrate the rating curve. The modelled boundary roughness is subject to error. In an attempt to minimise possible error, values from photographs (Barnes, 1967), previously modelled data (Chow, 1959) and available roughness calculations from South Africa (Broadhurst *et al.*, 1997) were used. This increased the confidence in the boundary roughness estimates. The slope was calculated as a function of the relationship between the water surface slope measured in the field, and the regional slope as measured off a 1:50 000 topographical map. The resistance coefficient and energy gradient calculated for high flows probably achieves a higher degree of confidence, as local hydraulic controls become inundated and drowned-out, resulting in a tendency towards uniform water surface gradients and asymptotic resistance coefficient values.

The range of flows used to calibrate the rating curve for all three rivers were deemed acceptable. A minimum of four calibration site visits were undertaken for each of the sites. The range of flows varied, but were sufficient to provide a reasonable level of confidence in the rating procedure. During the period of study, the Mkomazi and Olifants Rivers experienced high flows, and thus the confidence in the hydraulic calculations for these two rivers is good. The Mhlathuze River proved to be problematic, as the flow was highly regulated and, therefore, only low flows were used to calibrate the stage discharge curve. This means that the confidence in high flow hydraulic calculations is moderate to low.

7.5 Summary and conclusions

The preceding discussion has presented the methods and results obtained from the cross-sectional data, the bed material analysis and the hydraulic computations. Of the three rivers selected for study, two, the Mkomazi and Olifants, contain a coarse heterogenous bed. The third river, the Mhlathuze, contains a homogenous, well-sorted sand-bed. All of the rivers are characterised by complex channels, with distinct in-channel benches and terraces.

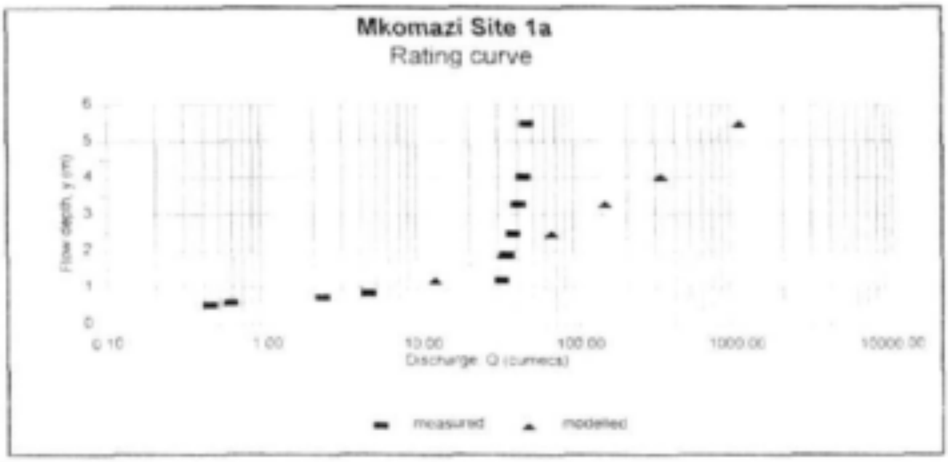

Figure 7.7: *Hydraulic rating curve for Mkomazi Site 1, cross-section A.*

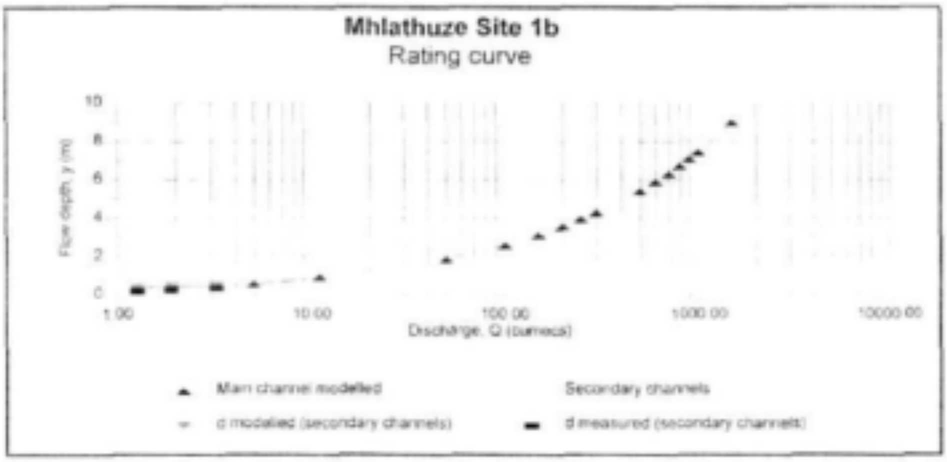

Figure 7.8: *Hydraulic rating curve for Mhlathuze Site 1, cross-section B.*

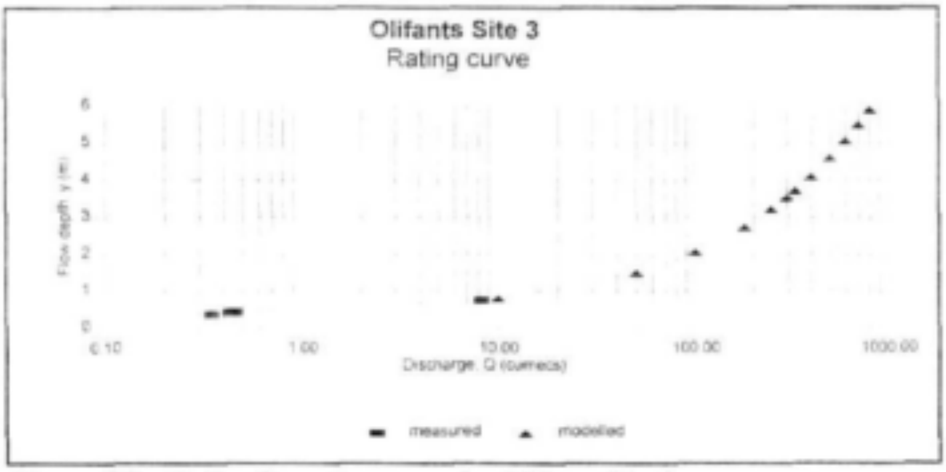

Figure 7.9: *Hydraulic rating curve for Olifants Site 3.*

Table 7.13: *Parameters in Equation 7.4 for thirteen sites for the Mkomazi River.*

Site	Paraneter		
	a	b	c
1a	0.645	0.311	0
1b	0.665	0.302	0.326
1c (>10 m^3s^{-1})	0.297	0.402	0.512
1c (<10 m^3s^{-1})	0.732	0.264	0.617
2a	0.417	0.385	0.340
2b	0.388	0.383	0.297
2c	0.912	0.289	0
3a	0.600	0.356	0.229
3b	0.313	0.419	0.449
3c	0.847	0.293	0
4a	0.471	0.381	0.757
4b	0.485	0.373	0.500
5a	0.335	0.378	2.305
5b	0.563	0.331	1.357
6a	0.349	0.363	0.834
6b	0.255	0.390	0.599
6c	0.219	0.434	2.180
7a	0.232	0.443	0.546
7b	0.349	0.401	0.023
8a	0.122	0.486	0.630
8b	0.165	0.453	0.371
9a	0.234	0.394	0.656
9b	0.341	0.355	0.194
10a	0.158	0.450	0.725
10b	0.372	0.357	0
11	0.302	0.354	0
12	0.417	0.337	0.449
13	0.182	0.442	0.646

Table 7.14: *Parameters in Equation 7.4 for four sites for the Mhlathuze River.*

Site	**Parameter**		
	a	**b**	**c**
1a	0.370	0.443	0.60
1b (<11 m^3s^{-1})	0.377	0.248	0
1b (>11 m^3s^{-1})	0.165	0.722	0
2a	0.221	0.471	0
3a	0.337	0.415	0
4a	0.245	0.467	0.310

Table 7.15: *Parameters in Equation 7.4 for four sites for the Olifants River.*

Site	**Parameter**		
	a	b	c
1 (<3.06 m^3s^{-1})	0.354	0.315	0
1 (<3.06 m^3s^{-1}<50 m^3s^{-1})	0.328	0.376	0
1 (>50 m^3s^{-1})	0.282	0.417	0
2 (<100 m^3s^{-1})	0.377	0.321	0
2 (>100 m^3s^{-1})	0.186	0.472	0
3	0.128	0.564	0.336
4 (<16.8 m^3s^{-1})	0.673	0.261	0
4 (>16.8 m^3s^{-1})	0.447	0.416	0

Chapter 8: Modeling bed material transport and sediment maintenance flushing flows

8.1 Introduction

This chapter is divided into two parts. The first part deals with the methods used for the bed material transport calculations, and the techniques employed in determining effective and dominant discharge. The second part of the chapter discusses the methods used in determining sediment-maintenance flushing flows.

8.2 Generating the effective discharge

The effective discharge was generated using the three bed material transport equations (see Section 8.2.1), together with the hydrology (Chapter 6), cross-sections, bed material data and hydraulic computations (Chapter 7). Section 8.2.5 presents the procedure that was used.

8.2.1 Bed material transport equations

Due to the large number of bed material transport formulae in existence, the selection of reliable equations suitable to the physical conditions of a particular river are of significance. For the purposes of this thesis, three bed material transport equations were selected. These are the Yang (1972), Ackers & White (1973), and Engelund & Hansen (1967) equations. The three equations chosen are all based on stream power, a factor considered to be more appropriate than shear stress (Chang, 1988).

In a number of comparative tests, the Ackers & White (1973) formula has been shown to perform well (cf. Chang, 1988; Gomez & Church, 1989); it has also been widely used in South Africa (cf. Birkhead *et al.*, 2000). The formula accounts for bed load and suspended load and has been developed from best-fit curves from almost 1000 sets of laboratory data. The Ackers & White equation has been formulated for heterogenous gravel-bed rivers. As mentioned earlier the Mkomazi and Olifants Rivers consist of coarse cobble-beds, and it is argued that the Ackers & White formula is suitable to the physical conditions of these two rivers.

The Yang equation has also been shown to perform well in comparative tests (cf. Chang, 1988; Gomez & Church, 1989), and is a useful equation for a variety of bed-types. It has separate components for sand and for gravel and larger sized material. The Yang equations for sand and gravel are identical in general form, but have different numerical values for the coefficients relating to the variation in particle size. The equations can therefore be used with a reasonable amount of confidence for all three rivers under consideration. The final equation chosen was that of Engelund & Hansen (1967). This equation was developed specifically for regime-type sand-bed alluvial channels. The Mhlathuze is such a channel.

Given the nature of the channels under consideration, it is argued that these formulae are suitable for predicting bed material transport.

In order to account (to some extent) for the heterogenous nature of the beds, the transport equations were applied to each grain size class separately, and later summed so that the relative proportions of each grain size class's contribution to the total transport rate could be accounted for. This does not imply that the equations account for the 'hiding factor' or the 'obstacle clasts' (cf. Figure 4.1). Rather, the data sets from which the Yang and Ackers & White equations were developed take into account the different types of bed material transport that occur in sand- and gravel-bed rivers through different coefficients

A number of assumptions were made in using these bed load equations. The first assumption was that the bed material sampling programme for each site was representative of the supply of material to the channel. This assumption was made due to the lack of any viable alternative. Solving this problem would require an extensive modelling exercise linking sediment delivery from the catchment to the channel, which in itself would be based on a number of further assumptions. This solution fell outside the boundary of this research. A second assumption was that the bed material size distribution could be averaged for the entire site and used to represent each cross-section. It is argued that although this may misrepresent certain cross-sections, the averaged effect will compensate for this and will provide a more representative result.

The third assumption was that the supply of material to each site is constant, and that the relative proportion of sediment sizes (and volume) supplied to each site was the same as the relative proportions of the sizes (and volume) of the sampled bed material. This assumption was necessary, as the alternative would have necessitated a complete shift of research focus towards routing the sediment through the system, which would involve a further series of assumptions. [Birkhead *et al.* (2000), for example, in modelling sediment transport through the Sabie River, used one grain size (1.0 mm) to represent the entire bed load]. For this reason, an approach was adopted that uses channel cross-sections within a short reach, from which the various hydraulic variables were measured (see Chapter 7). The sediment transport values that were generated were thus linked to individual cross-sections and represent bed material transport *potential* within the limits of accuracy of the equations.

The fourth assumption was that, where there is armouring, the armour needs to be mobilised before the sub-armour layer can be transported. This may mean that the transport values that were computed once the coarse armour layer is mobilised under-represents the actual transport rate.

The fifth assumption was that average hydraulic conditions could be used. Where depth or velocity was required, it was averaged over the cross-section. Although this may under-represent transport at certain points along the cross-section (for example, where local conditions create high velocities), it is argued that it will also over-represent transport at other points along the cross-section. In this way the averaged effect will provide the most consistent results.

Given the preceding assumptions, the following section provides an overview of the use of the three transport equations. All notation for bedload equations is explained in Table 8.1. Table 8.2 gives the data requirements for the three approaches.

8.2.1.1 Yang's equation

Yang (1972; 1973; 1984) related the bed material load to the rate of energy dissipation of the flow. His bed load transport equation is given in Equations 8.1 for sand (<2 mm) and 8.2 for gravel and larger (>2 mm). Equations 8.1 and 8.2 have the same form, but have different numerical values for the coefficients, constants and exponents. C_s, the sediment concentration, is measured in parts per million by weight. The various components of this equation are explained below.

$$\log C_s = 5.435 - 0.286\log\left(\frac{W_s d}{\nu}\right) - 0.457\log\left(\frac{U_*}{W_s}\right)$$
$$+\left[\left[1.799 - 0.409\log\left(\frac{W_s d}{\nu}\right) - 0.314\log\left(\frac{U_*}{W_s}\right)\right]\log\left(\left(\frac{US}{W_s}\right) - \left(\frac{U_c S}{W_s}\right)\right)\right]$$

(*Equation 8.1*)

$$\log C_s = 6.681 - 0.633\log\left(\frac{W_s d}{\nu}\right) - 4.816\log\left(\frac{U_*}{W_s}\right)$$
$$+\left[\left[2.784 - 0.305\log\left(\frac{W_s d}{\nu}\right) - 0.282\log\left(\frac{U_*}{W_s}\right)\right]\log\left(\left(\frac{US}{W_s}\right) - \left(\frac{U_c S}{W_s}\right)\right)\right]$$

(*Equation 8.2*)

To solve Yang's (1972) formula, the settling velocity must first be determined. The settling velocity partly determines the rate, mode and distance of transport by shearing forces in a fluid (Chang, 1988). The general method for calculating settling velocity is by the general drag equation. Stokes' law is applicable to particles of less than 60 microns which is clearly unsuitable for a general transport equation. The rate at which a particle settles in a stationary fluid depends on the viscosity and density of the fluid, and on the size, shape, density, roundness and surface texture of the particle. The difficulty is that no theory based on the physics of flow exists to predict the settling velocity of natural sediments. For this reason, workers in the field have produced empirical curves based on laboratory work. Due to limitations in the laboratory, most researchers have focussed on a limited range of particle and fluid properties, and several do not identify all the factors responsible for settling velocities. The result is that these curves are of limited use as this method is primarily applicable to spheres (James, 1998).

For natural sediments, the approach by Dietrich (1982) is deemed appropriate. Dietrich's (1982) method accounts for size, density, shape and roundness. First, the dimensionless particle size is determined:

Table 8.1 Notation used in bedload equations

symbol	**property**	**commonly used values**	**units**
C_s	sediment concentration		ppm by weight
W_s	settling velocity of a particle		m sec^{-1}
d	the geometric mean diameter of the sediment size class		m
a, b, c	longest, intermediate and shortest axes of a sediment particle		m
D_*	dimensionless particle size		dimensionless
D_n	nominal diameter, equivalent to the diameter of a sphere of the same volume as the paricle		m
s	specific gravity of sediment	2.65	dimensionless
ρ_s	density of sediment	2750	kg m^{-3}
ρ	density of the water	998.2 (@ 20° C)	kg m^{-3}
ν	kinematic viscosity of water	1.007 x 10^{-6} (@ 20° C)	m^2 s^{-1}
g	gravitational acceleration	9.807	m s^{-2}
R	hydraulic radius		m
U	mean velocity of the fluid		m sec^{-1}
U_c	critical velocity		m sec^{-1}
U_*	shear velocity		m sec^{-1}
Re*	shear Reynolds number		
F_{gr}	sediment mobility number (Ackers and White)		
n m	exponents in Equations 8.14 and 8.18 (Ackers and White)		
c A	coefficients in Equation 8.14 (Ackers and White)		

$$D_* = \left(\frac{(\rho_s - \rho) g D n^3}{\rho v^2} \right)$$ (*Equation 8.3*)

Second, the equation for predicting the settling velocity of spheres is calculated:

$$R_1 = -3.776715 + 1.92944(\log D_*) - 0.09815(\log D_*)^2 - 0.0575(\log D_*)^3 + 0.00056(\log D_*)^4$$ (*Equation 8.4*)

To account for the impact of shape on settling velocities, the Corey Shape Factor (CSF) is included (Corey, 1949). The shape factor which ranges from 0 to 1.0 is a ratio of the cross-sectional area of a sphere to the maximum cross-sectional area of an ellipsoid. The smaller the value, the flatter the particle.

$$CSF = \left(\frac{c}{\sqrt{ab}} \right)$$ (*Equation 8.5*)

where a is the longest axis, b the intermediate axis and c the shortest axis.

The CSF is used in the following form to account for natural particle shape, where the ratio of the settling velocity of a non-spherical, well rounded particle to the settling velocity of a sphere with the same D. is calculated:

$$R_2 = \left[\log\left(1 - \left(\frac{1 - CSF}{0.85} \right) \right) \right] - (1 - CSF)^{2.3} \tanh(\log D_* - 4.6) + 0.3(0.5 - CSF)(1 - CSF)^2 (\log D_* - 4.6)$$ (*Equation 8.6*)

To account for the roundness of the particle, Dietrich (1982) developed the following equation which predicts the ratio of the settling velocity of an angular particle to that of a well rounded particle:

$$R_3 = \left[0.65 - \left(\frac{CSF}{2.83} \right) \tanh(\log D_* - 4.6) \right]^{\left(1 + \left(\frac{3.5 - P}{2.5}\right)\right)}$$ (*Equation 8.7*)

where P is Powers value of roundness (Powers, 1953) on a scale of 0 is perfectly angular to 6 is perfectly round. The estimation of p is highly subjective, and is usually estimated with the standard method to assign roundness based on diagrams, photographs, or verbal descriptions. The scale ranges from 0.0 for perfectly angular to 6.0 for perfectly round (Dietrich, 1982).

Once R_1, R_2 and R_3 have been calculated, the dimensionless settling velocity W_* is calculated as:

$$W_* = R_3 10^{R_1 + R_2}$$ (*Equation 8.8*)

This can be converted into a value for settling velocity (W_s) by:

$$W_s = [\frac{W_* (\rho_s - \rho) g v}{\rho}]^{1/3} \qquad (\textit{Equation 8.9})$$

The second component of Yang''s equation that must be considered is shear velocity (U_*, calculated as:

$$U_* = (gRS)^{0.5} \qquad (\textit{Equation 8.10})$$

The last component is the ratio of critical velocity to settling velocity. The expression for this ratio depends on the Shear Reynolds number (Re*), determined as:

$$\mathrm{Re}^* = \left[\frac{U_* d}{v}\right] \qquad (\textit{Equation 8.11})$$

In smooth and transitional regions where the Shear Reynold's number is between 1.2 and 70, the ratio of critical velocity to settling velocity ratio is represented by Equation 8.12. In the rough region, where the Shear Reynolds number is greater than 70, the ratio is a constant - independent of the Shear Reynolds number (Equation 8.13).

$$\mathit{If}\ 1.2 \le \mathrm{Re}^* \le 70, \mathit{then}$$

$$\left(\frac{U_c}{W_s}\right) = \left[\frac{2.5}{\log(U_* d / v) - 0.06}\right] + 0.66 \qquad (\textit{Equation 8.12})$$

$$\mathit{If}\ 70 \le \mathrm{Re}^*, \mathit{then}$$

$$\left(\frac{U_c}{W_s}\right) = 2.05 \qquad (\textit{Equation 8.13})$$

8.2.1.2 Ackers & White equation

The Ackers & White formula (1973) is also based on the stream power concept (Ackers, 1993). They related the concentration of bed material load as a function of sediment mobility. The sediment mobility function is composed of two parts: the transport of coarse sediment is transported mainly as a bed process and is related to the stream power that generates the grain shear stress; finer sediments which travel in suspension are assumed to be a function of the total bed shear. Ackers & White (1973) thus account for both modes of transport.

The sediment concentration is calculated according to Equation 8.14:

$$C_s = cs\left(\frac{d}{R}\right)\left(\frac{U}{U_*}\right)^n\left(\left(\frac{F_g}{A}\right)-1\right)^m \qquad \textit{(Equation 8.14)}$$

Values of the parameters c, n, A and m are calculated according to the value of the dimensionless grain diameter (d_g). The first step in applying Equation 8.14, therefore, is to estimate d_g for the given particle size class. This is given as

$$d_g = d\left[\frac{g(s-1)}{\nu^2}\right]^{1/3} \qquad \textit{(Equation 8.15)}$$

The values of the parameters c, n, A and m can now be calculated depending on the value of d_g:

$$If.60 \geq d_g \geq 1$$

$$\log c = 2.86\log d_g - \left(\log d_g\right)^2 - 3.53$$

$$n = 1 - 0.56\log d_g$$

$$A = \left(\frac{0.23}{\sqrt{d_g}}\right) + 0.14 \qquad \textit{(Equation 8.16)}$$

$$m = \left(\frac{9.66}{d_g}\right) + 1.34$$

$$If.d_g \geq 60$$

$$\begin{aligned} c &= 0.025 \\ n &= 0 \\ A &= 0.17 \\ m &= 1.50 \end{aligned} \qquad \textit{(Equation 8.17)}$$

The sediment mobility number (F_g) in Equation 8.14 is determined from:

$$F_g = \left[\frac{U_*^{\,n}}{(gd(s-1))^{0.5}}\right]\left[\frac{U}{\left(32\right)^{1/2}\log\left(10R/d\right)}\right]^{1-n} \qquad \textit{(Equation 8.18)}$$

8.2.1.3 Engelund & Hansen equation

Engelund & Hansen (1967) used an adaptation of Bagnold's stream power concept to develop their model. The equation was developed specifically for regime-type alluvial sand-bed rivers. The equation relates the sediment concentration (ppm) to the rate of energy expenditure per unit weight of water (the U-S product) and the shear stress (the R-S product). Chang (1988) maintains that it can be applied to the upper flow regime to particle sizes greater than 0.15 mm without serious error. The Engelund & Hansen equation is thus written:

$$C_s = 0.05\left(\frac{s}{s-1}\right)\left[\frac{US}{\left((s-1)gd\right)^{0.5}}\right]\left[\frac{RS}{(s-1)d}\right] \qquad \textit{(Equation 8.19)}$$

8.2.2 Hydrological data

In Chapter 6, the method of generating the daily times series was presented. The daily flow data was used to generate 1-day daily flow duration curves and flood frequency curves (annual and partial duration series). Using the 1-day daily flow duration curves, flow classes were calculated for each site. The breakdown of the individual flow classes was based on the assumption that flows equalled or exceeded 10% of the time or less would probably be those flows that would be the most significant in terms of bed material transport. In the light of this assumption, the flows from the 99.99% equalled or exceeded to the 10% equalled or exceeded are divided into 10% duration flow classes. The flow exceedences less than this are divided into smaller flow class durations, 5%, 4%, 0.9% and 0.09% respectively. The geometric mean of each flow class was then calculated.

8.2.3 Hydraulic data

Chapter 7 has presented the methods used to determine the stage-discharge relations for each of the cross-sections. These were applied to the flow classes calculated from the flow duration curves, and then related to the cross-sections at each site so that parameters such as width, mean depth, hydraulic radius, slope, perimeter and average velocity could be calculated for the geometric mean of each flow class.

Table 8.2 *Data requirements for bedload formulae*

Data input	Data source	Yang	Ackers and White	Engelund and Hansen
geometric mean of the sediment class	particle size analysis of bed material	✓	✓	✓
nominal diameter		✓		
particle shape	field measurement of a, b and c axes	✓		
particle roundness	roundness charts	✓		
specific gravity or density of sediment	tables for main rock type	✓	✓	✓
density of water	tables of water properties	✓		
kinematic viscosity of water	tables of water properties	✓	✓	
mean flow velocity	hydraulic calibration	✓	✓	✓
hydraulic radius	hydraulic calibration	✓	✓	✓
energy gradient	hydraulic calibration	✓		✓

8.2.4 Bed material data

Chapter 7 has presented the methods used and the data obtained for the bed material data. These data were used in determining the bed material transport for each of the rivers.

8.2.5 Bed material transport equations

Having obtained the above mentioned information, it was possible to apply the three bed material transport equations to each flow class for each site. It is important to note that the equations were utilised such that each grain-size class was calculated separately. This enabled the calculation of initiation of motion and settling velocity for each grain-size class, as well as the proportion that each size class contributed to the overall transport rate. The actual transport values for each flow class for each size class are presented in Appendix F of Dollar (2001). The procedure for applying the above methods to generate the bed material transport for each site is as follows:

a) Compute the flow classes at each site from the hydrological information (Tables 9.1 to 9.4)

b) Compute the width, mean depth, hydraulic radius, slope, wetted perimeter and average velocity for each flow class from the cross-sectional data and hydraulic rating curves

c) Determine relative size classes for the bed material

d) For each bed material size class and for each flow class compute the sediment concentration according to the specified bedload formula

For the Yang equation:

compute the settling velocity using the Dietrich approach (Equations 8.3 to 8.9)
compute the shear velocity (Equation 8.10)
compute the Shear Reynolds number (Equation 8.11)
compute the velocity to settling velocity ratio for the sand class and the gravel and greater class (Equations 8.12 and 8.13)
compute the sediment concentration for the sand class and the gravel and greater class (Equations 8.1 and 8.2)

For the Ackers & White equation:

compute the dimensionless grain diameter (Equation 8.15)
compute the constants, coefficients and exponents (Equations 8.16 and 8.17)
compute the shear velocity (Equation 8.10)
compute the sediment mobility for fine and coarse sediments (Equation 8.18)
compute the sediment concentration (Equation 8.14)

For the Engelund & Hansen equation:

compute the sediment concentration using the Engelund & Hansen model (Equation 8.19)

For each flow class/sediment size class:

e) Compute the sediment load in kg m^{-3} s (concentration x discharge)

f) Compute the total annual load in tonnes (load x flow duration)

Combining sediment size classes:

g) Compute the total annual load in tonnes for all sediment size classes combined (sum of (f))

Combining flow classes:

h) Compute the percentage bed material moved by each flow class as a proportion of the whole for each flow class

i) Compute the maximum competence for each flow class

These computations were carried out using Quattro Pro.

8.2.6 Stream power and shear stress

Stream power was calculated for each flow class. Stream power (ω) has been shown to be an effective substitute for bed load transport potential. Williams (1983) has shown that a minimum power per unit area of 1000 Wm^{-2} or more will move boulders with an intermediate diameter of 1.5 m. The value is given in Watts per metre squared. Unit stream power is written:

$$\varpi = \frac{\gamma Q S}{w}$$ *(Equation 8.21)*

γ specific weight of the fluid (9800 Nm^{-3})

Q discharge (m^3s^{-1})

w channel width (m)

Shear stress (τ) was also calculated. The conventional means of calculating boundary shear stress was utilised. The value is given in Newtons per metre squared. Average depth was used in calculating the boundary shear stress.

$$\tau = \rho g D S$$ *(Equation 8.22)*

D average depth (area/width) (m)

8.2.7 Dominant discharge

Dominant discharge was calculated using the Marlette & Walker (1968) equation (see Equation 3.1). Dominant discharge was calculated separately from the data that were generated for the three transport equations.

8.3 Sediment-maintenance flushing flows

One of the consequences of impounded rivers is that reduced magnitude and frequency of flooding may lead to the accumulation of finer sediment on the channel bed. The channel may then narrow, resulting in increased flood risk and reducing the variety and areal extent of aquatic habitat. Furthermore, it was shown in Chapter 4 that unless the coarse bed is moved on a 'regular' basis, fine material may fill the interstices resulting in higher incipient motion values, which in turn may lead to further sedimentation. To avoid this situation, it is necessary to ensure that the sand- and fine gravel-sized material are moved through the river system. The determination of the magnitude and frequency of flows necessary to maintain the aquatic habitat in a natural condition is known as sediment-maintenance flushing flows (Reiser *et al.*, 1989). Two options for setting sediment-maintenance flushing flows were considered: the Milhous approach and the Relative Bed Stability (RBS) approach. These will be discussed in turn.

8.3.1 Milhous's approach

The Milhous approach uses a number of equations developed using the Oak Creek data to determine the maximum size of the wash load, suspended load and bed load for each flow class (Milhous, 1973). The hydraulic component of the model determines the conditions required to remove and transport sediment through the stream channel and to maintain the channel morphology (Milhous, 1998b). The maximum size of the sediment to be moved is the maximum size of the wash, suspended or bed load depending on the specified objective. The following equations were used to calculate the maximum size of the wash load ($d_{max\ w}$), suspended load ($d_{max\ s}$) and bed load ($d_{max\ bl}$).

$$d_{max\ w} = \frac{RS_e}{0.56(G_s - 1)} \qquad \text{(Equation 8.23)}$$

$$d_{max\ s} = \frac{RS_e}{0.28(G_s - 1)} \qquad \text{(Equation 8.24)}$$

$$d_{max\ bl} = d_{50_a}\left[\frac{RS_e}{0.018(G_s - 1)d_{50_a}}\right]^{2.85} \qquad \text{(Equation 8.25)}$$

R is the hydraulic radius (m)
S_e is the energy slope (m/m)
G_s is the specific gravity of the particles
d_{50a} is the median grain size of the stream bed armour and should only be used when the median size of the bed load is less than the median size of the armour (Milhous, 2000). The objective is to keep the bed material moving through the stream when the armour is relatively stable.

The equation used in the calculation of the median size of the bed load (d_{50bl}) is:

$$d_{50\ bl} = d_{50a}\left[\frac{RS_e}{0.046(G_s - 1)d_{50\ a}}\right]^{2.85} \qquad \text{(Equation 8.26)}$$

When the median size of the bed material is less than the median size of the armour, the bed load equations are for the calculation of the sizes of the bed load during flushing of the bed material, and not for general movement at higher stream flows. Earlier, Milhous & Bradley (1986) developed a stream substrate movement parameter, β, to determine the flushing flows needed in a stream. β is the critical dimensionless shear stress, calculated using the median size of the bed surface material. The equation for the substrate movement parameter beta (β) is:

$$\beta = \frac{RS_e}{d_{50a}(G_s - 1)} \qquad \text{(Equation 8.27)}$$

The selection of the values of the substrate movement parameters needed to define a flushing flow were developed from data obtained from bed load transport research in Oak Creek, Oregon (Milhous, 1973). The data indicated that the value of the β required for the removal of fines and sand from the surface of a gravel-bed river for surface flushing is 0.021, and for the removal of material within the substrate (depth flushing) is 0.035. An important inherent assumption is that the Oak Creek results can be extrapolated to other rivers.

The mode of sediment removal is important. Milhous (1998c) argues that the sediment should be moved as washload when the objective is to move sediment rapidly through the stream and where the presence of the target size is detrimental to the ecosystem. Sediment should be moved as suspended load when the objective is to move sediment at reasonable rates, but where some deposition is acceptable. Sediment should be moved as bed load when the larger sizes are to be scoured, for example the removal of gravel from a pool. The load size equations were developed using gravel-bed rivers, and hence it is probably unwise to use equations where the median size is less than 2.0 mm.

8.3.2 Relative Bed Stability (RBS)

The central assumption in the RBS approach is that a channel can become unstable when particle sizes equal to or greater than a critical percentile are moved at bankfull (or some other pre-determined stage) (Olsen *et al.*, 1997). For the purposes of this thesis, the critical particle size is taken as the D_{84} (i.e. the particle diameter for which 84% of the bed particles are finer). This is consistent with several studies (cf. Carling, 1988; Sidle, 1988; Leopold, 1997; Olsen *et al.*, 1997). The assumption in using the D_{84} is that a coarse grain size must be entrained before the bed becomes fully mobilised and unstable.

The first step in calculating RBS is to determine the threshold of motion. Mean shear stress over the bed was calculated using the DuBoys equation:

$$\tau_{bankfull} = \rho g R S \qquad \text{(Equation 8.28)}$$

The second step is to calculate the critical dimensionless shear stress (τ_{ci}*). The value of τ_{ci}* varies as a function of absolute particle size (D_i) and the relative size of D_i/D_{50}. This dependence is explained in terms of particle hiding and exposure. Particles larger than the mean size are exposed to the flow due to their greater protrusion into the flow, and are thus more easily entrained than would be the case with more uniform sediment. The converse is true for particles smaller than the median grain size, which remain hidden in the armoured layer. Thus the Andrews (1983) equation is used:

$$\tau^{*}_{ci} = \theta\left(\frac{D_i}{D_r}\right)^{-x} \qquad \text{(Equation 8.29)}$$

θ	dimensionless coefficient (usually 0.045) (after Komar, 1989; Petit, 1994; Olsen *et al.*, 1997)
x	power slope relationship (usually 0.7) (after Komar, 1989; Petit, 1994; Olsen *et al.*, 1997)
D_i	particle diameter (m)
D_r	reference diameter (usually D_{84}) (m)

The Shields criterion is then used to predict the threshold of bed load initiation, where τ_{ci} is the critical dimensional stream bed shear stress:

$$\tau_{critical} = \tau_{ci} = \tau^{*}_{ci}(\rho_s - \rho) g D_i \qquad \text{(Equation 8.30)}$$

To calculate RBS:

$$RBS_{\tau} = \frac{\tau_{critical}}{\tau_{bankfull}} \qquad (\textit{Equation 8.31})$$

If $\tau_{critical}$ is greater than $\tau_{bankfull}$, then the stream channel can be considered to be stable. The higher the value of $\tau_{critical}$ over $\tau_{bankfull}$, the greater the stability of the channel. If $\tau_{critical}$ is less than $\tau_{bankfull}$, then the stream channel can be considered to be unstable. For example, if $\tau_{bankfull}$ is estimated to be 50 N/m^2 and $\tau_{critical}$ is 90 N/m^2, the RBS value would be 90/50 = 1.8, and thus the channel can be considered to be stable.

The RBS value was calculated for a number of scenarios for each flow class, including the RBS for the D_{84}, D_{16}, D_{50}, D_{90}, gravel and sand classes. These are presented in Appendix H of Dollar (2001).

8.4 Conclusion

The approach that has been outlined in this chapter was applied to all three rivers under consideration. The following two chapters present the results and discussion of the implementation of this approach to the Mkomazi (Chapter 9) and Mhlathuze and Olifants Rivers (Chapter 10).

Chapter 9: Results and Discussion - the Mkomazi River

9.1 Introduction

This chapter presents the results obtained for the bed material transport analysis and the sediment-maintenance flushing flow computations for the unregulated Mkomazi River. The chapter is divided into two sections. The first deals with the bed material transport analysis and the second with the sediment-maintenance flushing flow computations. In the first section, the results are discussed in the context of a number of research questions:

1. *What is the relationship between the channel morphology and discharge?*
2. *What is the dominant discharge?*
3. *What is the effective discharge?*
4. *Is there any relationship between estimated bankfull discharge, dominant discharge and effective discharge?*

It is important to note that the values that were obtained from the modelling exercise were compared as percentages, rather than assigning them absolute values. The full data set relating to sediment transport computations can be found in Appendices F to H in Dollar (2001).

9.2 Flow classes of the Mkomazi River

Tables 9.1a-c display the flow classes calculated from the 1-day daily flow duration curves for each of the 13 sites on the Mkomazi River. The geometric mean of each flow class was used to represent each flow class in the bed material transport calculations. For example, at Site 1 (Table 9.1a) the range of flows experienced between 0.1% time equalled or exceeded and the 0.01% time equalled or exceeded is from 47 m^3s^{-1} to 103 m^3s^{-1}. The geometric mean of this class is 69.6 m^3s^{-1}. This was used in conjunction with the duration that each flow class represented as a proportion of one year (365.25 days). For example, a flow class that represents 0.09% of the time occurs for 0.3 days in one year.

9.3 Research questions

9.3.1 Research question 1: What is the relationship between the channel morphology and discharge?

Bankfull stage

The estimated bankfull discharge ranges from 117 m^3s^{-1} (Site 9) to 482 m^3s^{-1} (Site 3) (Table 9.2) with no consistent downstream trend (Figure 9.1). The R-squared value between estimated bankfull discharge and MAR is 0.04 (insignificant at the 95% level). The estimated return periods for the bankfull discharge range from 1.1 years to >39 years on the annual series with an average return period of 8.6 years, while

Table 9.1a: *Flow classes calculated for the Mkomazi River sites 1 to5. Values are in m^3s^{-1}. Qm is the geometric mean for the given flow class.*

% time equalled or exceeded	**duration %**	**Q**	**Qm**	**Q**	**Qm**	**Q**	**Qm**	**Q**	**Qm**	**Q**	**Qm**
		Site 1		**Site 2**		**Site 3**		**Site 4**		**Site 5**	
99.99		0.00		0.00		0.00		0.00		0.01	
	10		0.01		0.02		0.04		0.07		0.13
90		0.19		0.34		1.01		1.06		1.78	
	10		0.24		0.42		1.25		1.32		2.21
80		0.30		0.52		1.55		1.63		2.74	
	10		0.35		0.61		1.81		1.90		3.19
70		0.41		0.71		2.11		2.22		3.72	
	10		0.48		0.83		2.45		2.58		4.32
60		0.55		0.96		2.84		2.99		5.01	
	10		0.65		1.13		3.34		3.52		5.89
50		0.77		1.33		3.92		4.13		6.93	
	10		0.93		1.60		4.71		4.97		8.33
40		1.11		1.92		5.67		5.97		10.0	
	10		1.39		2.40		7.08		7.46		12.5
30		1.74		3.00		8.84		9.32		15.6	
	10		2.23		3.85		11.4		12.0		20.0
20		2.86		4.95		14.6		15.4		25.7	
	10		3.99		6.89		20.3		21.4		35.9
10		5.56		9.60		28.3		29.8		50.0	
	5		7.18		12.4		36.6		38.5		64.6
5		9.27		16.0		47.2		49.7		83.4	
	4		13.5		23.6		68.6		72.2		131.
1		19.6		34.9		99.6		105		208	
	0.9		30.4		54.2		147		155		291.
0.1		47.1		84.1		216		228		406	
	0.09		69.6		124		307		324		503.
0.01		103		183		437		460		622	

Table 9.1b: *Flow classes calculated for the Mkomazi River sites 6 to 9. Values are in m^3s^{-1}. Qm is the geometric mean for the given flow class.*

% time equalled or exceeded	duration %	Q		Q		Q		Q	
		Site 6		Site 7		Site 8		Site 9	
99.99		0.010		0.011		0.011		0.509	
	10		0.136		0.144		0.148		1.29
90		1.82		1.923		1.98		3.27	
	10		2.26		2.39		2.46		3.81
80		2.80		2.96		3.05		4.45	
	10		3.26		3.45		3.55		5.12
70		3.80		4.02		4.14		5.89	
	10		4.41		4.67		4.80		6.92
60		5.12		5.43		5.58		8.14	
	10		6.02		6.37		6.55		9.58
50		7.07		7.49		7.70		11.3	
	10		8.50		9.01		9.26		13.4
40		10.2		10.9		11.1		16.0	
	10		12.8		13.5		13.9		20.0
30		15.9		16.9		17.4		25.0	
	10		20.5		21.7		22.31		32.0
20		26.3		27.9		28.6		40.9	
	10		36.6		38.8		39.9		55.3
10		51.1		54.1		55.6		74.8	
	5		65.9		69.9		71.8		92.7
5		85.1		90.2		92.7		115	
	4		1351		143		147		186
1		213		225		232		302	
	0.9		297.		315		324		421
0.1		415		440		452		588	
	0.09		513		544		559		728
0.01		635		673		691		900	

Table 9.1c: *Flow classes calculated for the Mkomazi River sites 10 to 13. Values are in* m^3s^{-1}.

% time equalled or exceeded	duration %	Q	Qm	Q	Qm	Q	Qm	Q	Qm
		Site 10		Site 11		Site 12		Site 13	
99.99		0.532		0.543		0.572		0.578	
	10		1.35		1.38		1.45		1.47
90		3.42		3.50		3.68		3.72	
	10		3.99		4.07		4.29		4.33
80		4.65		4.75		5.00		5.05	
	10		5.35		5.47		5.76		5.81
70		6.16		6.29		6.63		6.69	
	10		7.24		7.40		7.79		7.87
60		8.51		8.70		9.16		9.25	
	10		10.0		10.2		10.8		10.9
50		11.8		12.0		12.7		12.8	
	10		14.1		14.4		15.1		15.3
40		16.8		17.1		18.0		18.2	
	10		20.9		21.4		22.5		22.8
30		26.1		26.7		28.1		28.4	
	10		33.4		34.2		36.0		36.3
20		42.8		43.7		46.0		46.5	
	10		57.8		59.1		62.2		62.9
10		78.2		79.9		84.2		85.0	
	5		96.9		99.0		104		105
5		120		123		129		131	
	4		194		199		210		211
1		315		323		340		342	
	0.9		440		452		475		478
0.1		614		631		664		667	
	0.09		759		780		821		826
0.01		939		965		1016		1021	

the return periods for the partial series range from 0.1 years to >39 years with an average of 7.1 years (Table 9.3). Most of these values are higher than the average annual return period of 1.5 years suggested for bankfull discharge by Leopold (1997). Furthermore, the bankfull discharge as estimated in the field does not appear to be related to any particular flow return period (Table 9.4). The estimated bankfull discharge was compared to the 1.5 and 2.44 year return period for the annual series and the 0.9 and 2 year return period for the partial series - no relationship is evident (Table 9.4).

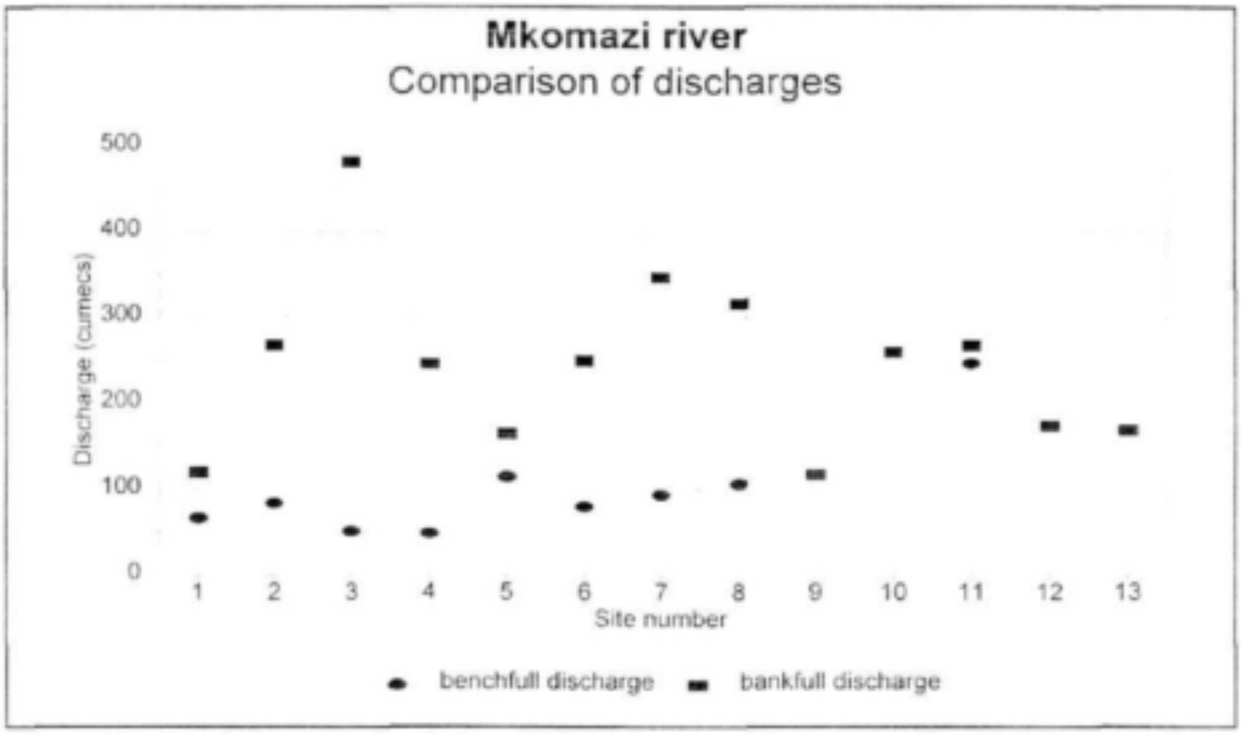

Figure 9.1: *Inundation stage for the benchfull discharge and the estimated bankfull discharge for the Mkomazi River.*

There are three possible explanations for this lack of trend. First, the field estimated bankfull discharges may be incorrect. Second, there may be no such thing as a bankfull stage/feature, the variability of the hydrological regime coupled with strong bed rock control precluding such a stage/feature - the morphology of the channel may be related more to the resistance of the channel perimeter to erosion than the shaping fluid (i.e. the flow). Third, the estimated bankfull condition may represent the active channel prior to the most recent flood and, in this sense, the equilibrium morphology has been disrupted by the flood. These issues will be discussed in Chapter 10.

Benchfull stage

There is a more consistent downstream increase in the 'benchfull' discharge (Figure 9.1), although the calculated R-squared value between MAR and 'benchfull' discharge is only 0.53 (insignificant at the 95% level). The 'benchfull' discharge ranges from 49 m^3s^{-1} at Site 4 to 247 m^3s^{-1} at Site 11 (Table 9.5). The return period of the bench ranges from 1.0 years to 10 years on the annual series with an average

Table 9.2: *Summary data for the Mkomazi River. Data presented are the average data for each site. Values are in m^3s^{-1}.*

Site	MAR	$Q_{1.5}$	$Q_{2.44}$	$Q_{p0.9}$	$Q_{p2.0}$	dominant discharge	effective discharge	bench	estimated Q_b	terrace 1	terrace 2	terrace 3
1	67	18	31	30	38	19	35	67	121	245	803	
2	122	31	55	53	68	28	74	84	268	602	1028	
3	356	89	148	146	180	69	138	52	482	1137	1527	
4	375	94	156	154	189	55	72	49	246	457	906	
5	634	182	293	286	347	136	291	115	165	537	1478	
6	640	186	299	294	354	119	225	80	249	899	2216	
7	681	197	317	310	375	242	276	94	347	1481		
8	698	203	326	320	385	62	147	107	316	1546	2722	3921
9	910	255	440	497	575	156	343		117	1457		
10	950	260	450	518	600	174	358		260	1113	4726	
11	976	268	470	532	617	208	367	247	268	855	3239	
12	1027	285	500	560	649	306	387		174	598	3183	
13	1032	290	501	563	653	154	300		169	675	4850	10164

where MAR is the Mean Annual Runoff in million cubic metres, $Q_{1.5}$ is the 1.5 year return period on the annual series, $Q_{2.44}$ is the 2.44 year return period on the annual series, $Q_{p0.9}$ is the 0.9 year return period on the partial series, $Q_{p2.0}$ is the 2.0 year return period on the partial series and estimated Q_b is estimated bankfull discharge.

Table 9.3: Estimated discharges and return periods for morphological features for the Mkomazi River (average values).

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	Mean
bench m^3s^{-1}	67	84.	52	49	115	80	94	107			247			
FFC yrs	10	5.9	1.3	1.2	1.2	1	1	1.1			1.5			2.7
PDS yrs	8	2.9	0.2	0.1	0.1	0.1	0.1	0.1			0.2			1.3
Estimated Qb m^3s^{-1}	120	268	482	245	165	249	347	316	117	260	268	174	168	
FFC yrs	>39	>39	10	7.2	1.4	2.1	3.4	2.7	1.1	1.5	1.5	1.3	1.2	8.6
PDS yrs	>39	>39	6	4.6	0.2	0.5	1.5	0.9	0.1	0.2	0.2	0.9	0.1	7.1
terrace 1 m^3s^{-1}	245	602	1137	457	537	899	1481	1546	1457	1113	855	598	675	
FFC yrs	>39	>39	>39	9.5	21.9	>39	>39	>39	>39	>39	>39	2.9	5	>39
PDS yrs	>39	>39	>39	6.5	19.4	>39	>39	>39	>39	>39	>39	1.3	3.6	>39
terrace 2 m^3s^{-1}	803	1028	1527	906	1478	2216		2722		4726	3239	3183	4850	
FFC yrs	>39	>39	>39	>39	>39	>39		>39		>39	>39	>39	>39	>39
PDS yrs	>39	>39	>39	>39	>39	>39		>39		>39	>39	>39	>39	>39
terrace 3 m^3s^{-1}								3921					10164	
FFC yrs								>39					>39	>39
PDS yrs								>39					>39	>39

Values for bench, estimated Q_b, terrace 1, 2 and 3 are in m^3s^{-1}. FFC refers to the average annual return period on the annual series (years). PDS refers to the average return period for the partial duration series (years).

***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	9.06
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

return period of 2.7 years, and 0.1 years to 8 years on the partial series with an average return period of 1.3 years (Table 9.6). Other than for sites 1 and 2, these values are in the range of the 1.50 year return period on the annual series that Leopold (1997) predicted for the bankfull discharge (Table 9.6).

The analysis of terrace inundation is limited by the confidence in the hydrological analysis. The upper end of the flow duration curve, especially the extreme events, is poorly represented for the Mkomazi. Flow data generated by the hydrological modelling indicates that many of the terraces are not inundated by the present flow regime (Table 9.6). In Chapter 6, Table 6.4 lists the known floods for the Mkomazi River. In the middle parts of the catchment (catchment area 1744 km^2) for the period of record 1931 to 1990, four large floods have been identified. The site at which these floods were estimated is close to sites 5 and 6 (Table 9.6) where two terraces were identified. At site 5, the hydraulic analysis estimated an inundation flow of 537 m^3s^{-1} for the low terrace and an inundation flow of 1478 m^3s^{-1} for the second terrace. At Site 6, it is estimated that the low terrace is inundated at 899 m^3s^{-1}, while the second terrace is inundated at 2216 m^3s^{-1}. The largest flood on record close to this site is 2770 m^3s^{-1} in 1987. A flood of a similar magnitude (2010 m^3s^{-1}) occurred in 1975. These floods were therefore sufficient to inundate these terraces. Van Bladeren (1992) has estimated the return period of these floods as being 50 to 100 years and 20 to 50 years respectively.

The best flood record of extreme floods available for the Mkomazi is close to the mouth. This is in close proximity to Site 12 and Site 13 (Table 9.6). Site 12 has two terraces, the upper terrace has an estimated inundation flow of 3183 m^3s^{-1}, while Site 13 has two terraces, one at 4850 m^3s^{-1} and a second, higher terrace with an estimated inundation flow of 10 164 m^3s^{-1}. The historical flood record for a site just downstream of Site 13 is given in Table 6.4. The largest flood on record was estimated as 7250 m^3s^{-1} in 1856, with a similar sized flood in 1987 of 6830 m^3s^{-1}. There are a number of smaller floods on record, the smallest of which was 2880 m^3s^{-1} in 1976. During the period of record (1856 to 1990), there have been at least seven floods which have inundated the lower terraces at both sites. This inundation thus occurs approximately every 20 years.

From the hydraulic analysis based on the cross-sectional data, it is clear that these floods achieve high velocities, shear stresses and stream power, and are capable of moving the coarsest bed material (see Section 9.3.3). At Site 5, the largest flood of 2770 m^3s^{-1} produced an estimated average velocity of 8 ms^{-1}, and a unit stream power of 1019 Wm^{-2}. At Site 6 the largest flood on record produces an estimated average velocity of c. 6.5 m^3s^{-1} and a unit stream power of around 1175 Wm^{-2}. At sites 9 and 10, similar results were obtained .

It is possible that the terraces are features that have formed as a result of the bi-polar type flood frequency curve. The terraces may also be related to different climate and hydrological response in the past, a hypothesis that remains untested and is beyond the scope of this research.

9.3.2 Research question 2: *What is the dominant discharge?*

The dominant discharge was calculated from the three transport equations using the Marlette & Walker (1968) equation. The dominant discharge reflects the discharge that transports over 50% of the bed material load. The results are presented in Table 9.5. The average dominant discharge increases downstream (Figure 9.2). The R-squared value calculated for the relationship between mean dominant discharge and MAR is 0.65 (significant at the 95% level).

The three transport equations used predict consistent values for dominant discharge (Table 9.5). The Ackers & White equation generally predicts the lowest transport rates for each site and the highest dominant discharge. For example at Site 7a the coarse bed material and high entrainment thresholds meant that the Ackers & White equation predicted that only the highest flow class could entrain any material, and consequently the calculated dominant discharge is high. At Site 7b the Ackers & White equation predicts that no bed material transport will occur. At Site 12, the wide channel results in very low stream power and consequently the dominant discharge is also high.

There is good agreement between the dominant discharge and flow return period for the Yang and Engelund & Hansen equation, but not for the Ackers & White equation (Table 9.7). The R-squared value (significant at the 95% level) between the dominant discharge as estimated using the Yang equation and the 1.5 and 2.44 year return period on the annual series and the 0.9 year and 2.0 year return period on the partial series is 0.79, 0.83, 0.84 and 0.84 respectively. Likewise for the Engelund & Hansen equation the R-squared values (significant at the 95% level) are 0.82, 0.82, 0.82 and 0.83 for the 1.5 and 2.44 year return period on the annual series, and the 0.9 year and 2.0 year return period on the partial series respectively (Table 9.7). There appears to be no relationship between the dominant discharge as estimated by the Ackers & White equation and the flow return period. The relationship between the dominant discharges as estimated by the three equations is reflected by a high correlation between the Yang and Engelund & Hansen estimates (R-squared of 0.88), but no correlation between the dominant discharges estimated using the Ackers & White and either Yang or Engelund & Hansen equations (R-squared values of 0.39 and 0.42 respectively) (Table 9.7).

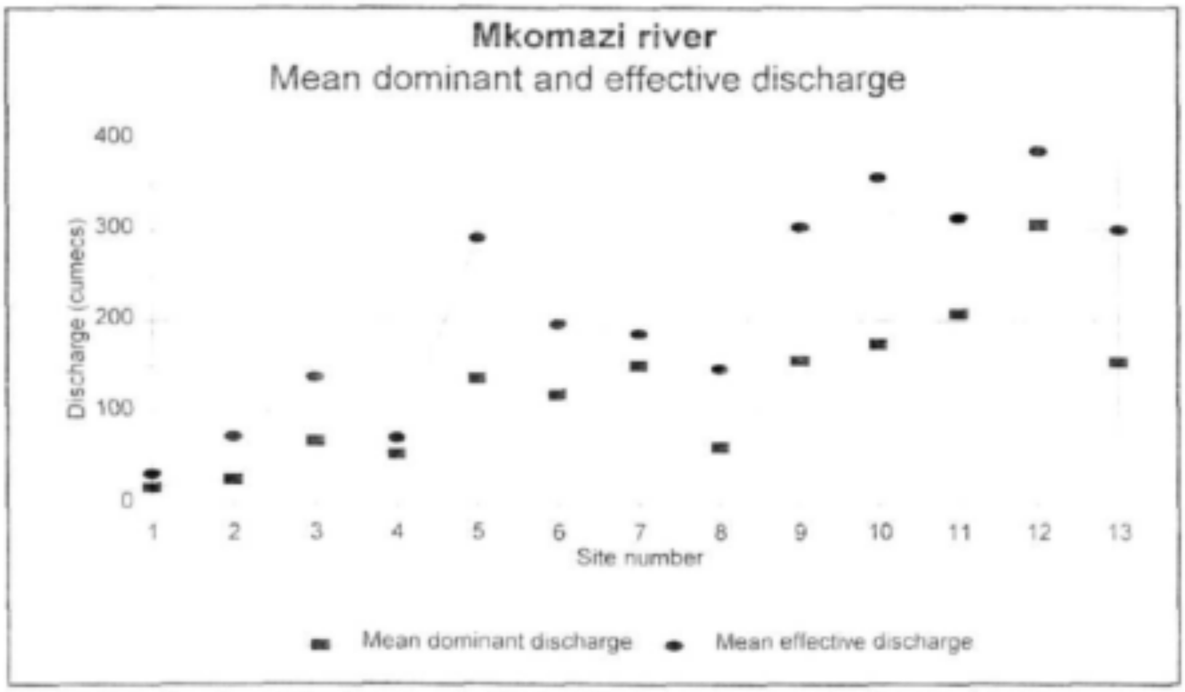

Figure 9.2: *Dominant discharge and effective discharge (mean value for sites) for the Mkomazi River.*

Table 9.5: *Dominant discharge and effective discharge for the Mkomazi River. Values are in m^3s^{-1}. Note that the values are the geometric mean for a particular flow class.*

Site	Dominant discharge (Yang)	Dominant discharge (Ackers & White)	Dominant discharge (Engelund & Hansen)	Effective discharge (Yang)	Effective discharge (Ackers & White)	Effective discharge (Engelund & Hansen)
1a	16.46	20.14	13.66	30.367	30.367	30.367
1b	19.30	21.22	13.60	30.367	30.367	30.367
1c	17.42	34.40	12.27	30.367	56.01	30.367
2a	24.19	41.04	18.96	54.193	124.21	54.193
2b	24.13	41.95	18.50	23.643	124.21	54.193
2c	31.17	31.17	18.31	54.193	124.21	54.193
3a	66.84	76.84	66.51	146.69	146.69	146.69
3b	58.00	62.90	66.13	68.557	146.69	146.69
3c	71.53	84.74	67.15	146.69	146.69	146.69
4a	53.14	57.22	51.68	72.23	72.23	72.23
4b	52.07	58.63	54.34	72.23	72.23	72.23
5a	127.19	149.96	132.50	291.28	291.28	291.28
5b	127.19	149.96	132.50	291.28	291.28	291.28
6a	119.89	136.95	119.29	134.59	297.16	39.27
6b	96.90	100.44	118.16	134.59	134.59	297.16
6c	117.48	144.86	117.10	134.59	297.16	297.16
7a	68.50	543.79	81.74	142.58	543.78	142.58
7b	125.25	-	86.12	142.58	-	142.58
8a	60.76	61.40	62.15	146.58	146.58	146.58
8b	61.51	62.30	62.69	146.58	146.58	146.58
9a	172.01	179.36	139.70	186.15	421.35	421.35
9b	130.10	176.24	139.04	186.15	186.15	421.35
10a	155.73	226.02	159.00	439.51	439.51	194.39
10b	142.48	204.96	155.34	194.39	439.51	439.51
11	217.82	280.81	124.63	451.61	451.61	199.18
12	206.73	502.47	209.41	209.71	475.33	475.33
13	146.73	150.74	165.74	211.34	211.34	477.94

9.3.3 Research question 3: *What is the effective discharge?*

For all sites, the most effective discharge was the discharge that was equalled or exceeded on average between 5% and 0.1% of the time, i.e. the upper two flow classes but one (5-1% and 1-0.1%) (Table 9.6). The value calculated for the effective discharge appears to be related to a combination of local conditions (channel geometry, slope, bed material calibre) and the manner in which the equations calculate the percentage transport. For example, in macro-reach 3, where there is high stream power and shear stress due to steep channel gradients, flows become competent to transport bed material at lower flow classes. This results in the most effective discharge being predominantly in the 5-0.1% range. It also results in the upper three flow classes (5-1%; 1-0.1%; 0.01-0.01%) being less 'effective', and the bed material tends to be transported by a wider range of flow classes. A good example of this is Site 8, which has a very steep, confined bed rock channel. Here, high shear stresses and stream power, even at lower flows, result in the upper three flow classes transporting little more than 40% of the bed material. The flow classes lower than this thus account for 60% of the bed material transport.

The effective discharge for the Mkomazi was taken to be the geometric mean of the flow class that transports the most bed material (Figure 9.3). This may be misleading as two adjacent flow classes transport often have very similar percentages of the total sediment load. For example in Site 2a, the flow class 23.643 m^3s^{-1} represents 36.82% of the bed material transported, while the flow class above it (54.193 m^3s^{-1}) represents 36.86% (Yang equation). The former class is therefore identified as the effective discharge although it transports only 0.04% more material than the flow class below it. Furthermore, what appear to be large differences in effective discharge may be simply a shift into the next flow class (Table 9.5). Another possible problem in the identification of dominant discharge is that the effective discharge is thus to some extent dependent on the division of the flow duration curve. As described in Chapter 8, the flow classes greater than the 10% equalled or exceeded range were divided into 5%, 4%, 0.9% and 0.09% flow class durations respectively.

To overcome these problems cumulative sediment transport curves were constructed so that the range of discharges transporting the bulk of the sediment can be better identified. These are presented in Figures 9.4 to 9.6. The results indicate that the bulk of the bed material transported (>80%) occurred (all three equations) between the 20% equalled or exceeded and 0.1% equalled or exceeded range, with most bed material being transported by flows with an exceedence of between 5% and 0.1%. The higher and lower flows transport proportionally less of the bed material. There are two outliers, sites 7 and 8. As noted above, the steep slope and bed rock nature of site 8 generates high unit stream power and velocities, which result in a greater proportion of the bed moving at lower flow classes than occurs at other sites, hence the different shaped curve. Site 7 has an extremely coarse bed. The Ackers & White equation predicts that no bed material transport occurs at site 7b and that transport will only occur at the highest flow class (i.e. 0.1-0.01%) at site 7a. These two outliers demonstrate the importance of local conditions in a stream bed. The results demonstrate that the sediment transport rates are probably supply limited.

Table 9.6: *Effective discharge flow classes for the Mkomazi River.*

Site	Yang (flow class)	Ackers & White (flow class)	Engelund & Hansen (flow class)
1a	1-0.1%	1-0.1%	1-0.1%
1b	1-0.1%	1-0.1%	1-0.1%
1c	1-0.1%	1-0.1%	1-0.1%
2a	1-0.1%	1-0.1%	1-0.1%
2b	5-1%	5-1%	1-0.1%
2c	1-0.1%	5-1%	1-0.1%
3a	1-0.1%	1-0.1%	1-0.1%
3b	5-1%	1-0.1%	1-0.1%
3c	1-0.1%	1-0.1%	1-0.1%
4a	5-1%	5-1%	5-1%
4b	5-1%	5-1%	5-1%
5a	1-0.1%	1-0.1%	1-0.1%
5b	1-0.1%	1-0.1%	1-0.1%
6a	5-1%	1-0.1%	1-0.1%
6b	5-1%	5-1%	1-0.1%
6c	5-1%	1-0.1%	1-0.1%
7a	5-1%	-	5-1%
7b	5-1%	-	5-1%
8a	5-1%	5-1%	5-1%
8b	5-1%	5-1%	5-1%
9a	5-1%	1-0.1%	1-0.1%
9b	5-1%	1-0.1%	1-0.1%
10a	1-0.1%	1-0.1%	5-1%
10b	5-1%	1-0.1%	1-0.1%
11	1-0.1%	1-0.1%	5-1%
12	5-1%	1-0.1%	1-0.1%
13	5-1%	5-1%	1-0.1%

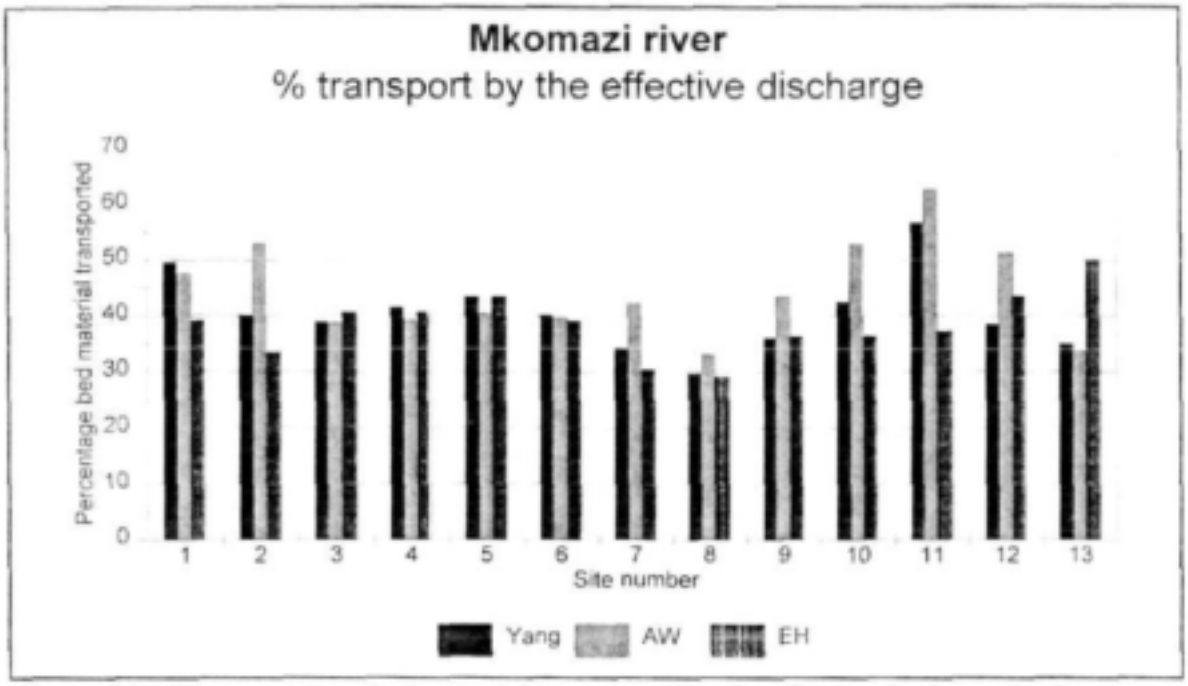

Figure 9.3: *The percentage bed material transported by the effective discharge for the Mkomazi River.*

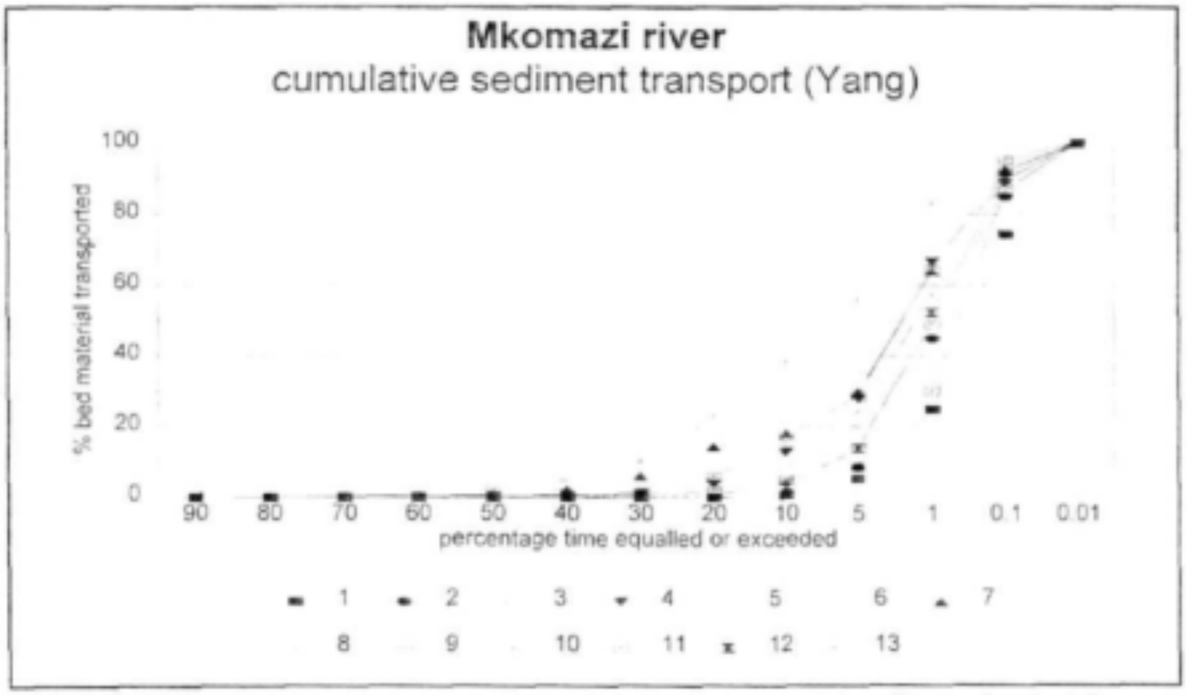

Figure 9.4: *Cumulative sediment transport for the Yang equation for all sites for the Mkomazi River.*

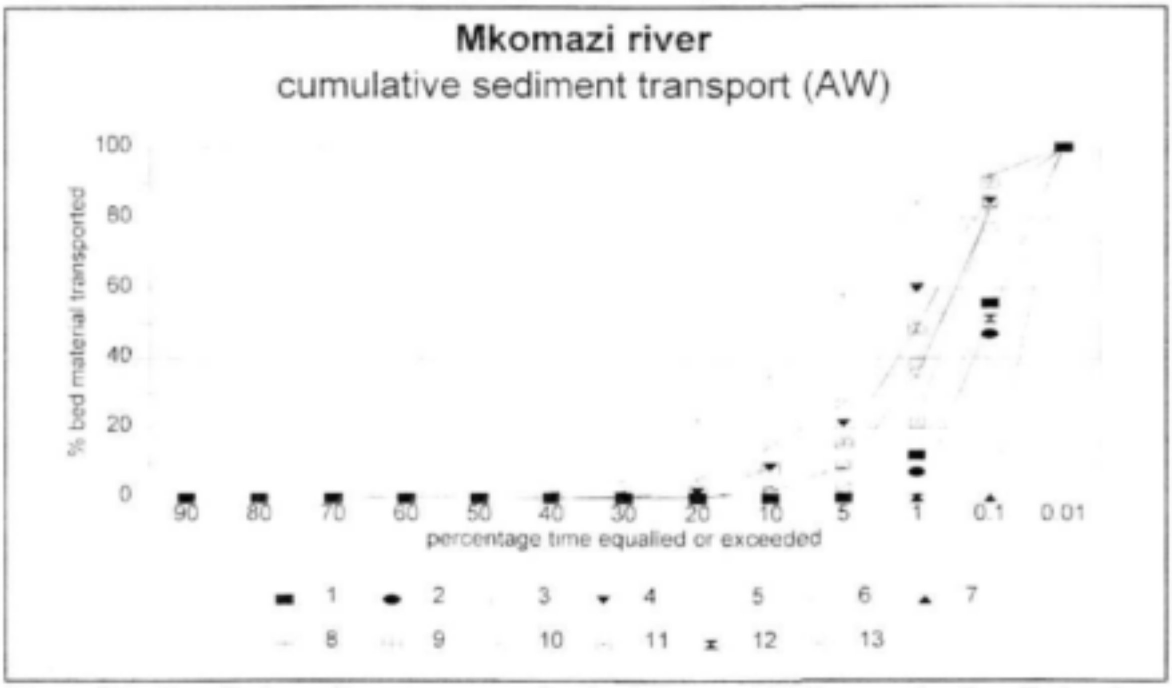

Figure 9.5: *Cumulative sediment transport for the Ackers and White equation for all sites for the Mkomazi River.*

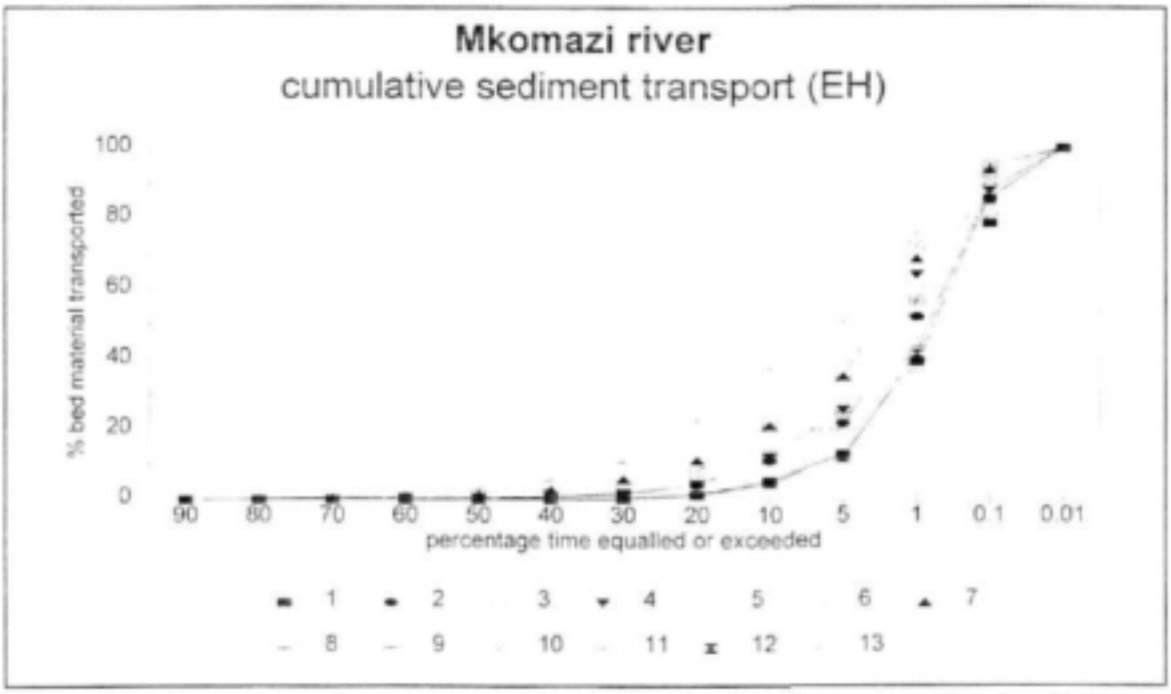

Figure 9.6: *Cumulative sediment transport for the Engelund & Hansen equation for all sites for the Mkomazi River.*

Figure 9.7 shows the maximum competence of the highest flow class (0.1-0.01%) in relation to the D_{16}, D_{50} and D_{84} of the bed material (bearing in mind the limitations of the equations). The data indicate that at 10 of the 13 sites (1, 2, 4, 6, 7, 8, 9, 10, 12 and 13) both the Yang and Ackers & White equations predict that the highest flow class does not have the competence to transport the D_{84}. Although the Engelund & Hansen method predicts that, other than at sites 9, 10, 12 and 13, these flows have the competence to transport the D_{84}, it must be remembered that this equation was developed for alluvial sand-bed channels and, consequently, may not be valid for gravel- and cobble-bed rivers. It would seem, therefore, that the coarse bed material in the Mkomazi is relatively stable at all but the highest flows.

Infrequent flow events, with an exceedence less than 0.1%, may have the competence to transport the largest material. As indicated in Section 9.3.1, the stream power generated during high magnitude flood events is sufficient to transport even the coarsest material on the bed. Unit stream powers for these flood events are in the 1000 Wm^{-2} range - the stream power which, according to Williams (1983) , will move boulders of 1.5 m in diameter. It is argued that these floods perform two main tasks: first, they maintain the macro-channel and, second, they generate sufficient stream power to mobilise the entire bed, thus 'resetting' the system. It may therefore be useful to think in terms of two sets of effective discharge. For the majority of the time there are a set of discharges contained within the active channel banks (i.e. below the bankfull stage). These effective discharges (5-0.1% on the flow duration curve which occur on average 18 to 0.4 days a year) appear to account for the bulk of the bed material transported over a long period of time. It is likely that the 'benchfull'stage and the bankfull stage are represented by morphological features that are related to flows of these durations. A second category of high magnitude low frequency effective discharges termed 'reset discharges' are also significant as they 'reset' the system. The terraces in the macro-channel are probably related to these larger flood events which appear to occur on average once every 20 years or so. It is likely that the nested channel architecture is a response to these two categories of effective discharge.

These results compare well with results from other countries. Pickup & Warner (1976) for example, working on the Cumberland basin in New South Wales, Australia, found that the effective discharge for sediment transport occurred on average between 1.15 years and 1.45 years on the annual series, while the estimated bankfull discharge stage had a return period between 4 to 7 years. Andrews (1980) has shown that for the Yampa River basin in the United States, the average effective discharge occurred between 1.5 and 11 days per year. Pitlick & Van Steeter (1998), also working in the United States on the upper Colorado River, found that the effective discharge was equalled or exceeded for 2% of the time, or approximately 7 days a year. The effective discharge transported approximately 30% of the annual load, while 80% of the total load was transported by the highest 10% of the flows. Similar results have been reported by Ashmore & Day (1988) and Nash (1994).

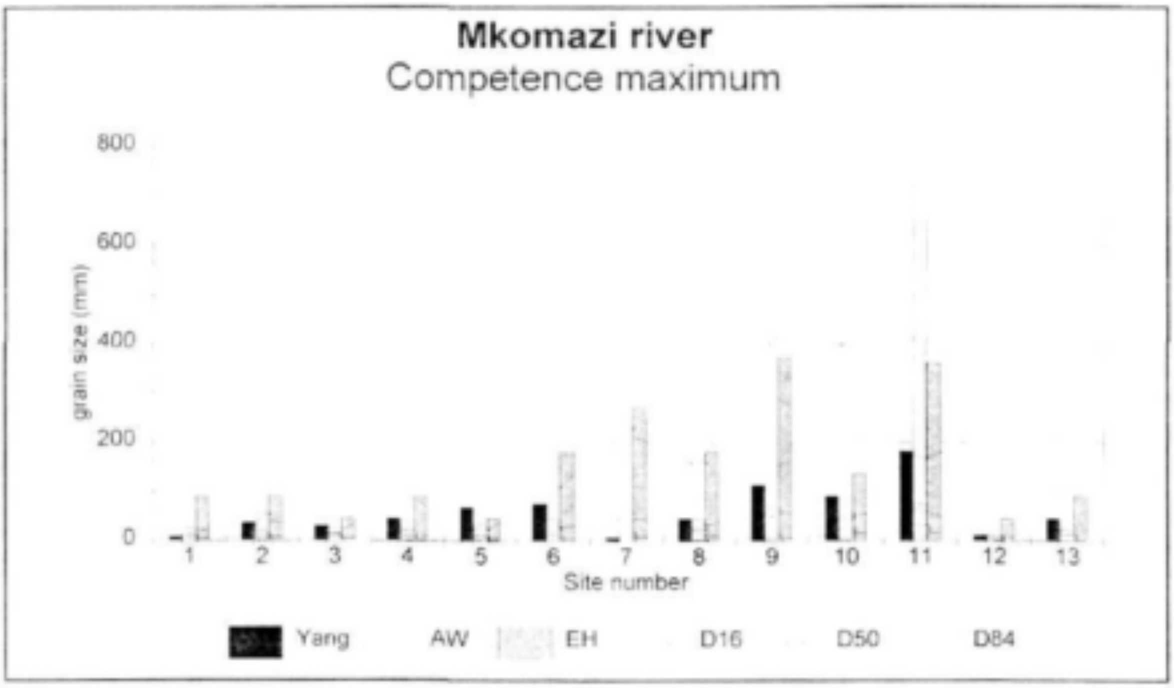

Figure 9.7: *Maximum competence of the highest flow class for the Mkomazi River in relation to the particle size distribution at each site.*

9.3.4 Research question 4: *Is there any relationship between estimated bankfull discharge, dominant discharge and effective discharge?*

There appears to be no agreement between the bankfull discharge and the dominant and effective discharge (Table 9.5). These findings were further checked by regressing the average estimated bankfull discharge and the average dominant and effective discharge (R-squared values of 0.01 and 0.10 respectively). There is coarse agreement between the average benchfull discharge and both the average dominant and effective discharges (Figure 9.8). Statistically, however, there is no relationship between the benchfull discharge and the dominant and effective discharge for the Ackers & White and Engleund & Hansen equations (Table 9.7), but there is for the Yang equation (R-squared of 0.73 and 0.82 for the dominant discharge and effective discharge respectively). If the average benchfull discharge is regressed against the average dominant discharge, an R-squared value of 0.58 is calculated. This is insignificant at the 95% level. Similarly, if the average benchfull discharge is regressed against the average effective discharge an R-squared value of 0.54 is computed, this is also insignificant at the 95% level. Despite this statistical insignificance, Figure 9.8 demonstrates that there is coarse agreement between mean 'benchfull discharge', dominant discharge and effective discharge.

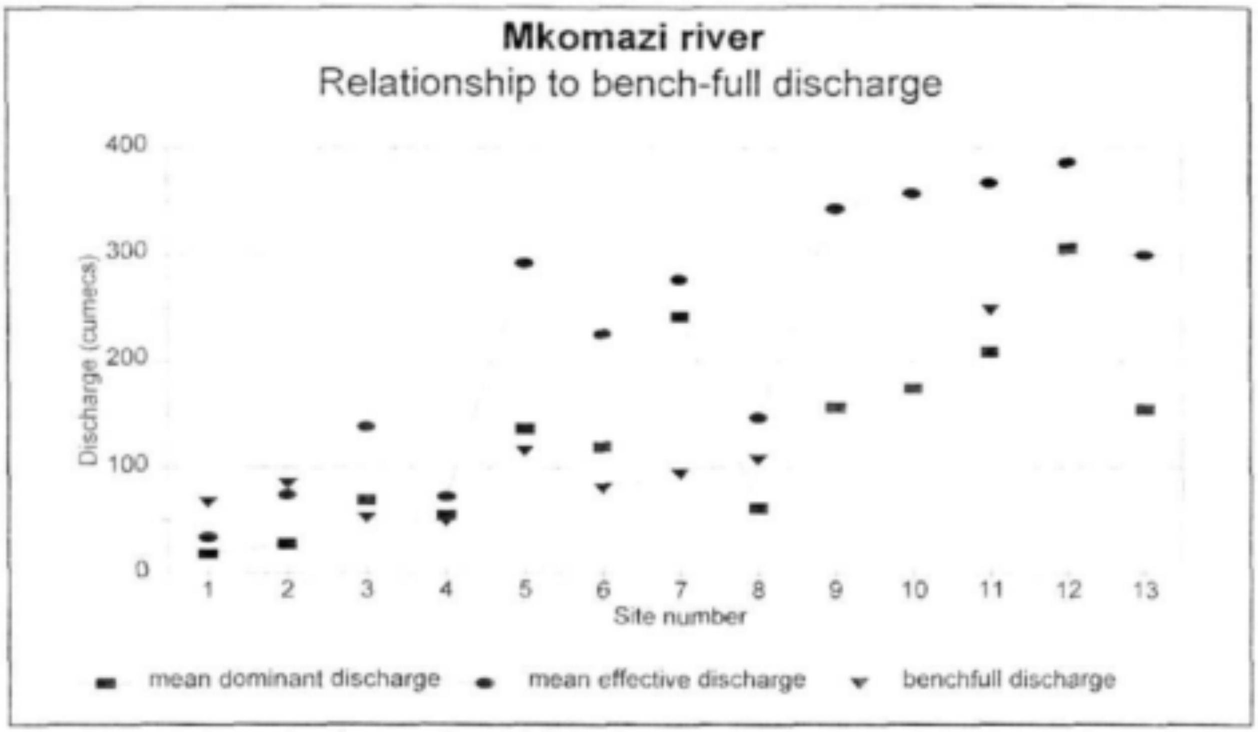

Figure 9.8: *Relationship between benchfull discharge and dominant and effective discharge for the Mkomazi River.*

9.4 Synthesis

The results have been discussed in terms of the research questions set out at the beginning of the chapter. It has been argued that there is no significant downstream trend in estimated bankfull discharge. It was pointed out earlier that there are three possible explanations for this trend (see Section 9.3.1). It is argued that the strong bed rock control and variable hydrological regime suggests that it may be inappropriate to adopt the bankfull stage (defined as the boundary between the active channel and the macro-channel) as the effective discharge. It is likely that the morphology of the channel is related more to the resistance of the channel perimeter to erosion than to the shaping fluid.

No relationship exists between the estimated bankfull discharge and the flood recurrence interval. However there does appear to be good agreement between the bench and the 0.9 and 2.0 year return period on the partial duration series.

The effective discharge as calculated by the three transport equations shows good internal consistency. The effective discharge is in the 5-0.1% exceedence range on the 1-day daily flow duration curve. It was also noted that the upper two but one flow classes account for the bulk (>80%) of the bed material transported in the Mkomazi. Although transport rates are high at the highest flow class (0.1-0.01%) this is more than offset by the limited duration, and consequently this flow class was never the effective discharge for any of the sites. It has also been demonstrated that the effective discharges do not have the energy to transport the entire bed. It is the larger floods, with average return periods of approximately 20 years, that generate sufficient stream power and shear stress to mobilise the entire bed. It is argued that, for the Mkomazi, it may be instructive to consider a range of effective discharges, first the effective discharges that transport the most bed material over a long period of time and, second, a 'reset discharge' that is able to mobilise the entire bed, thus serving as a channel forming discharge. These two sets of discharges are, in fact, the geomorphologically effective discharges for the Mkomazi River.

9.5 Sediment-maintenance flushing flows

This section of the chapter deals with the results obtained from the sediment-maintenance flushing flow computations. Milhous' approach for bed load and the β index were applied to the thirteen sites of the Mkomazi River. Table 9.7 presents a summary of the results. This table was constructed so that the β value and the d_{max84} and d_{max50} were compared to the equivalent result obtained for the three transport equations. For example, at Site 1a, the β index was calculated for the flow class 0.246 m^3s^{-1} as being 0.0513. This is more than sufficient to flush sands as a 'surface flush' and a 'depth flush'. (The β index predicts surface flushing for sands where β is equal to 0.021 and depth flushing for sand where β is equal to 0.035). This was compared to the equivalent initiation of motion for the sand-sized class predicted by the three transport equations. For Site 1a, Yang predicts sand motion at 3.991m^3s^{-1}, Ackers & White at 13.467 m^3s^{-1} and Engelund & Hansen at 0.355 m^3s^{-1}. Thus the table (Table 9.7) is constructed in such a way as to compare the initiation of motion of the sand-sized material for the three transport equations to the 'surface' and 'depth' flushing as predicted by the β index. Where β predicts surface and depth flushing at lower flow classes than the equivalent for the transport equations, the letter 'L' (lower) is shown. Where β predicts surface and depth flushing at higher flow classes than the equivalent for the transport equations, the letter 'H' (higher) is shown.

It can be seen that at all sites (Table 9.7), other than sites 10b and 11, the Milhous β value predicts 'surface flushing' and 'depth flushing' at discharges lower than the equivalent Yang equation for sand. Similarly, the β value predicts surface and depth flushing at discharges (other than at Site 10b) well below the equivalent values predicted by the Ackers & White equation. The same general conclusion applies to the β value when compared to the equivalent Engelund & Hansen equation. In this case the β value predicts surface and depth flushing at higher flows than the equivalent value for the Engelund & Hansen equation at a number of sites (6a, 6b, 7a, 7b, 9a, 9b, 10b, 11 and 13).

Table 9.7 also shows the relationship between the maximum competence predicted from the Milhous equations (d_{max84} and d_{max50}) and the maximum competence calculated for the Yang, Ackers & White and Engelund & Hansen equations. The same approach was adopted for the β index. The letter 'L' is shown where the d_{max84} and d_{max50} predict lower maximum competence than the equivalent for the transport equations. 'H' is shown where the d_{max84} and d_{max50} predict higher maximum competence than the equivalent for the transport equations. It can be seen that for sites 1 to 5, 7, 10 and 12 the d_{max84} predicts considerably higher competence than the Yang and Ackers & White equation. However, at sites 6, 8, 9, 11 and 13, the Milhous equations predict lower competence maxima than the Yang and Ackers & White equations. The Engelund & Hansen equation on the other hand predicts higher competence than the

Milhous equations at sites 2a, 2b, 2c, 4a, 4b, 6a, 6b, 6c, 7a, 7b, 8a, 8b, 9a, 9b, 11 and 12 and lower competence at sites 1a, 1b, 1c, 3a, 3b, 3c, 5a, 5b, 10a, 10b and 12.

The comparison of the competence of the d_{max50} and the maximum competence calculated from the three transport equations (Table 9.7) indicate that the d_{max50} predicts both higher and lower competence values, even at one site. At Site 1, for example (Table 9.7), d_{max50} predicts higher competence at cross-sections a and c and lower competence at cross-section b for the Yang equation. This trend is reflected at all of the sites for the d_{max50} for all the equations. There appears to be no consistency in the results obtained. This highlights one of the problems in determining sediment-maintenance flushing flows from equations that were developed for one river (Oak Creek in this case) and extrapolating them to other rivers. It is impossible to test which of the results are more accurate, as there is no actual bed material transport data for the Mkomazi against which to test these results. It is argued therefore that Milhous equations should be used with extreme caution.

Figure 9.9 shows the RBS values (Relative Bed Stability) obtained for the Mkomazi River. The y-axis of the graph is the critical percentile on the 1-day daily flow duration curve where the D_{16} and D_{84} become mobile so that the bed can be considered to be unstable for that bed material size class (RBS). Similarly, the y-axis represents the critical percentage time equalled or exceeded on the 1-day daily flow duration curve where 'surface' (0.021 Milhous) and 'depth' (0.035 Milhous) flushing occurs. As can be seen, sites 1 to 5 of the Mkomazi are computed as becoming unstable at low flow classes, ranging from the 10th to 50th percentile with an average of around the 30th percentile. However, sites 6 to 13 show a different value. The RBS estimate is that the bed will become unstable at much higher flow classes, ranging from the 20th to the 99.99th percentile with an average of around the 85th percentile. These values are in excess of the β values calculated for Milhous. It is difficult to assess the accuracy of the RBS value without data against which to compare it. Once again, this stresses the need for caution in using methods that have not been thoroughly tested on a wide range of rivers, or have not been developed using a broad, comprehensive data set.

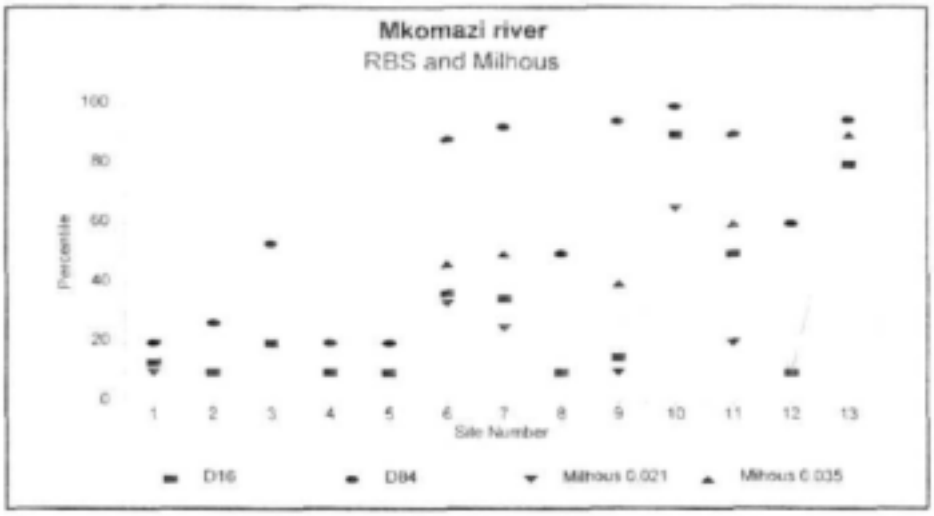

Figure 9.9: *RBS values for the Mkomazi River. The β value is calculated for the 0.021 (surface) and 0.035 (depth) flushing flows. These values represent the flow class at which the β value is 0.021 and 0.035 respectively.*

Table 9.7: *Comparison of the Milhous approach to the transport equations approach for the Mkomazi River.*

Site	β			d_{maxbl}			d_{max50}		
	^{1}Y	^{1}AW	^{1}EH	^{2}Y	^{2}AW	^{2}EH	^{2}Y	^{2}AW	^{2}EH
1a	L	L	L	H	H	H	H	H	L
1b	L	L	L	H	H	H	L	L	L
1c	L	L	L	H	H	H	H	L	H
2a	L	L	L	H	H	L	L	L	L
2b	L	L	L	H	H	L	L	L	L
2c	L	L	L	H	H	L	H	L	L
3a	L	L	L	H	H	H	H	H	L
3b	L	L	L	H	H	H	L	L	L
3c	L	L	L	H	H	H	H	H	L
4a	L	L	L	H	H	L	L	L	L
4b	L	L	L	H	H	L	L	L	L
5a	L	L	L	H	H	H	H	H	H
5b	L	L	L	H	H	H	H	H	H
6a	L	L	H	L	L	L	H	H	H
6b	L	L	H	L	L	L	L	L	L
6c	L	L	L	L	L	L	L	L	L
7a	L	L	H	H	H	L	L	H	L
7b	L	L	H	H	H	L	L	H	L
8a	L	L	L	L	L	L	L	L	L
8b	L	L	L	L	L	L	L	L	L
9a	L	L	H	L	L	L	L	L	L
9b	L	L	H	L	L	L	L	L	L
10a	L	L	L	H	H	H	L	H	L
10b	H	H	H	H	H	H	L	L	L
11	H	L	H	L	L	L	L	L	L
12	L	L	L	H	H	H	H	H	H
13	L	L	H	L	L	L	L	L	L

1 L = β predicts surface flushing and depth flushing at lower flows than the equivalent for the transport equations, where Y is Yang, AW is Ackers & White and EH is Engelund & Hansen equations.
H = β predicts surface flushing and depth flushing at higher flows than the equivalent for the transport equations.

2 L = d_{maxbl} and d_{max50} predict lower maximum competence than the equivalent for the transport equations.
H = d_{maxbl} and d_{max50} predict higher maximum competence than the equivalent for the transport equations.

9.5.1 Effective discharge for sand, gravel and cobble

Using the method in outlined in Section 9.3.3., the effective discharge for sand, gravel and cobbles was calculated utilising the Yang equation, as this equation appeared to produce the most realistic results for the Mkomazi river. Figure 9.10 presents the summary data. It can been seen from this figure that although some variation exists, the effective discharge for the sand fraction generates a lower percentage of bed material transport than for the gravel- and cobble-fraction. This suggests that, as expected, sand is being transported at a wider range of flow classes than gravel and cobble.

Table 9.8 displays the effective discharge flow classes for the sand, gravel and cobble fractions of the bed for the Yang equation. It can be seen that the effective discharge for the sand-sized fraction is mainly in the 5-1% class (18 out of 27 cross-sections), with the rest (9 out of 27 cross-sections) in the 1-0.1% flow class. The effective discharge for the gravel fraction is mainly in the 1-0.1% flow class (13 out of 27 cross-sections), followed by the 5-1% flow class (12 out of 27 cross-sections) and the 0.1-0.01% flow class (2 out of 27 cross-sections). For the cobble fraction, the effective discharge is mainly the 0.1-0.01% flow class (5 out of 8 cross-sections) followed by the 1-0.1% flow class (3 out of 8 cross-sections). As mentioned earlier, this demonstrates that a greater proportion of the sand-fraction of the bed is transported at low discharges than the gravel- and cobble-fraction of the bed. It is suggested that using this method may provide a more realistic estimate of the sediment-maintenance flushing flow requirement for the different grain-sized fractions, as the duration dimension is also incorporated.

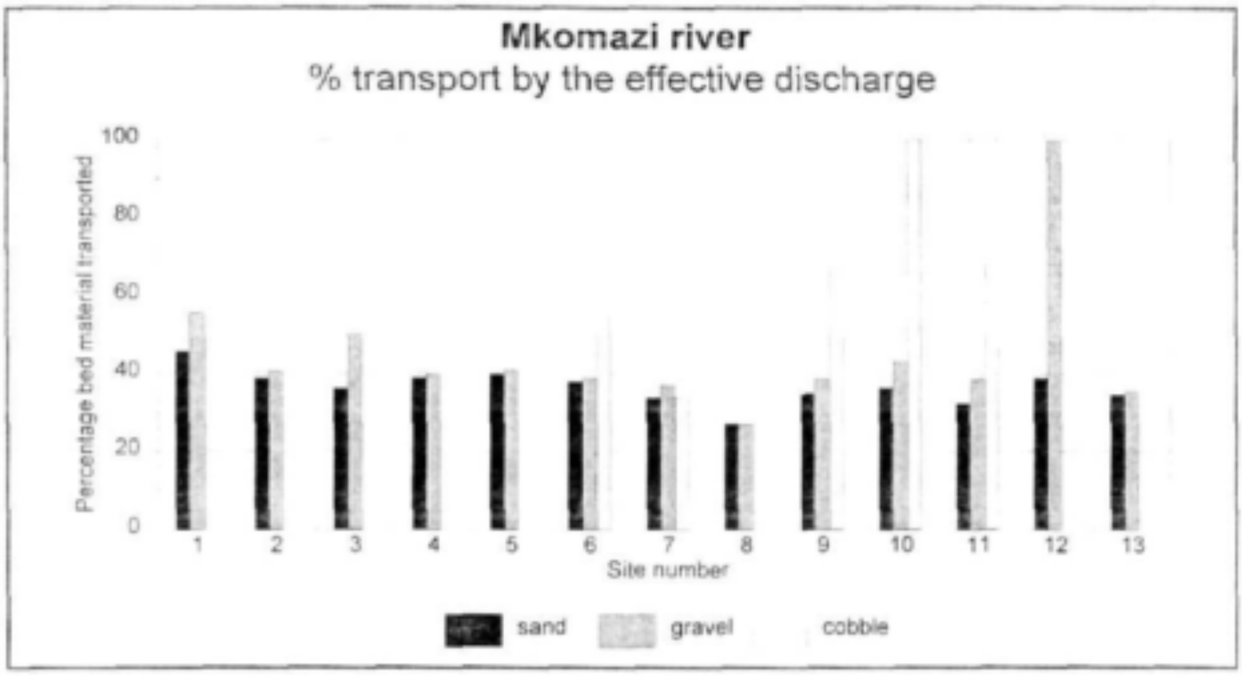

Figure 9.10: *The effective discharge for sand, gravel and cobble using the Yang equation for the Mkomazi River.*

Table 9.8: *Effective discharge flow classes for the Mkomazi River for sand, gravel and cobble for the Yang equation.*

Site	Sand (flow class)	Gravel (flow class)	Cobble (flow class)
1a	1-0.1%	1-0.1%	-
1b	1-0.1%	1-0.1%	-
1c	1-0.1%	0.1-0.01%	-
2a	5-1%	1-0.1%	-
2b	5-1%	1-0.1%	-
2c	1-0.1%	1-0.1%	-
3a	1-0.1%	1-0.1%	-
3b	5-1%	1-0.1%	-
3c	1-0.1%	1-0.1%	-
4a	5-1%	5-1%	-
4b	5-1%	5-1%	-
5a	1-0.1%	5-1%	-
5b	1-0.1%	1-0.1%	-
6a	5-1%	1-0.1%	-
6b	5-1%	5-1%	0.1-0.01%
6c	5-1%	5-1%	0.1-0.01%
7a	5-1%	5-1%	-
7b	5-1%	1-0.1%	0.1-0.01%
8a	5-1%	5-1%	-
8b	5-1%	5-1%	-
9a	5-1%	5-1%	1-0.1%
9b	5-1%	5-1%	1-0.1%
10a	5-1%	5-1%	0.1-0.01%
10b	5-1%	1-0.1%	0.1-0.01%
11	1-0.1%	1-0.1%	1-0.1%
12	5-1%	0.1-0.01%	-
13	5-1%	5-1%	-

9.6 Summary

The results from the sediment-maintenance flushing flow analysis indicate that the Milhous approach tends to predict incipient motion for sand at discharges well below the values predicted by the Yang and Ackers & White transport models. However, the values are similar to the levels predicted by the Engelund & Hansen model. This is probably because both the Engelund & Hansen model and the Milhous approach are based on a simple exponential stream power approach. The RBS method needs to be used with a degree of circumspection, as the approach is based on critical shear stress which has been shown to be inappropriate for coarse-bedded material (Yang, 1972). It is argued that both the Milhous and RBS methods should be used with caution. The methods were either developed from one data set (Oak Creek for Milhous) or are an amalgamation of existing equations (RBS approach). It is argued that using the effective discharge for different grain-sized classes may be a more appropriate way in which to define sediment-maintenance flushing flows. Although these models are imperfect, they are based on a broader data set, and can be chosen to satisfy the physical conditions of the channel.

9.7 Conclusions

The results suggest that the Mkomazi River does not conform to conventional wisdom developed for temperate alluvial rivers. It appears that the Mkomazi is strongly controlled by local conditions such as bed rock, a variable hydrological regime and a coarse heterogenous 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 'benchfull discharge'.

It has been argued that it is instructive to consider the magnitude-frequency debate in the Mkomazi River in terms of two sets of 'effective discharges'. First, 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, 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 and therefore to maintain the channel.

It is suggested that the channel architecture of the Mkomazi is a response to these 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

10.1 Introduction

This chapter will present the methods and results obtained for the bed material transport analysis and the sediment-maintenance flushing flow computations for the Mhlathuze and Olifants Rivers. These two rivers are both highly regulated and their channel forms will reflect to a varying extent adjustmetn to this disturbed flow regime. The data analaysis will focus on answering a the following questions:

1. *Do the results obtained from the two regulated systems add to the understanding gained from the Mkomazi River?*

2. *What is the impact of flow regulation on the relationships? Are the observed morphological conditions related to virgin flow conditions or to the regulated present-day conditions?*

3. *What lessons can be learnt for Instream Flow Requirement (IFR) assessments?*

4. *Given the results obtained, what flows should be recommended and why?*

In the context of these broad research questions, the chapter is divided into two sections, the first section considers the Mhlathuze River and the second section considers the Olifants River.

10.2 The Mhlathuze River

10.2.1 Overview

Four sites were chosen for analysis for the Mhlathuze, all downstream of the Goedertrouw Dam. Site 1 was approximately 25 kilometres downstream of the Dam, while Site 2 was a further 35 kilometres downstream of Site 1. Between Site 1 and Site 2 a major tributary, the Mfule, joins the Mhlathuze. Site 2 is 35 kilometres downstream of Site 3. Site 4 (an artificial channel) was a further 15 kilometres downstream of Site 3. Between Site 3 and Site 4 a major tributary, the Nseleni, joins the Mhlathuze. The lower three sites (i.e. sites 2, 3 and 4) were all single thread sand-bed regime channels, while Site 1 was a pool-riffle channel type with multiple distributaries. Because of the sand bed nature of the river, the analysis was confined to considerations of channel morphology and dominant or effective discharge. No analysis is presented for Milhous's flushing flows or estimates of Relative Bed Stability.

The Goedertrouw Dam was completed in 1979. This has had a significant impact on the downstream hydrology of the river (Table 10.1). The MAR at Site 1 has been reduced from $185x10^{6}m^{-3}$ virgin flow to the present-day scenario of $64x10^{6}m^{-3}$. This represents only 34.8% of the virgin MAR at Site 1. Flow recovers downstream as tributary inputs mitigate the impact of the dam. It can also be seen from Table 10.1 that under virgin flow conditions the ratio of increase of MAR between the sites was considerably less than it is for the present-day. The virgin MAR nearly doubled between Site 1 and Site 4 (1.96), while for the present-day, the rate of increase is by a factor of 3.39. This has significant implications for the channel morphology and bed material transport and will be discussed further later in the chapter.

Table 10.1: *MAR for four sites for the Mhlathuze River (million cubic metres).*

Site number	Virgin MAR	Downstream iIncrease ratio	Present-day MAR	Downstream iIncrease ratio	% of Virgin MAR
1	185		64		34.8
2	255	1.38	127	1.98	49.8
3	313	1.69	176	2.75	56.2
4	362	1.96	217	3.39	60.9

As noted in Chapter 5, the passage of tropical cyclones and cut-off low pressure systems is characteristic of the Mhlathuze catchment and northern KwaZulu-Natal generally. Table 6.5 displays the highest flood peaks on record for the Mhlathuze River. The values calculated for the 1984 and 1987 floods (below Goedertrouw Dam) are 2420 m^3s^{-1} and 3590 m^3s^{-1} respectively. Van Bladeren (1992) estimated that were it not for the Goedertrouw Dam these floods would have been 4790 m^3s^{-1} and 6000 m^3s^{-1} respectively. The Goedertrouw has therefore not only reduced the MAR downstream, but it has also attenuated the flood peaks.

The methods that were used to obtain the daily flow time series for the virgin and present-day data for the Mhlathuze were presented in Chapters 6 and 8. Tables 10.2 and 10.3 present the flow classes calculated for the Mhlathuze River for the virgin and present-day data.

10.2.2 Analysis of channel morphology

The field methods that were used to classify the morphological features for the Mkomazi River were applied to the Mhlathuze River. Tables 10.4 to 10.8 display the relevant data. Given the fact that there were only four sites selected for analysis for the Mhlathuze River, no statistical analyses (R-squared values) could be reliably applied to the data. The data are thus discussed in relation to the general trends displayed.

Table 10.2: *Flow classes calculated for the Mhlathuze River for the virgin data. Qm is the geometric mean of the flow class. Values are in m^3s^{-1}.*

% time equalled or exceeded	Q	Qm	Q	Qm	Q	Qm	Q	Qm
	Site 1		Site 2		Site 3		Site 4	
99.99	0		0		0		0	
		0		0		0		0
90	0.371		0.488		0.716		1.190	
		0.506		0.656		0.932		1.510
80	0.690		0.883		1.212		1.917	
		0.856		1.112		1.491		2.275
70	1.061		1.401		1.833		2.700	
		1.280		1.721		2.211		3.154
60	1.543		2.115		2.666		3.684	
		1.787		2.469		3.095		4.201
50	2.070		2.882		3.592		4.790	
		2.399		3.342		4.112		5.373
40	2.781		3.876		4.708		6.028	
		3.258		4.521		5.424		6.820
30	3.817		5.273		6.250		7.715	
		4.613		6.354		7.479		9.110
20	5.575		7.657		8.950		10.758	
		7.604		10.378		12.236		14.170
10	10.371		14.067		16.729		18.665	
		13.416		17.907		21.375		23.653
5	17.354		22.795		27.311		29.973	
		29.942		38.388		48.661		53.078
1	51.662		64.646		86.701		93.994	
		145.270		195.995		245.495		263.205
0.1	408.492		594.222		695.125		737.033	
		1020.30		1435.33		1736.42		1849.76
0.01	2472.70		3466.99		4337.55		4642.44	

Table 10.3: *Flow classes calculated for the Mhlathuze River for the present-day data. Values are in m^3s^{-1}.*

% time equalled or exceeded	Q	Qm	Q	Qm	Q	Qm	Q	Qm
	Site 1		Site 2		Site 3		Site 4	
99.99	0		0		0		0	
		0		0		0		0
90	0.279		0.306		0.369		0.537	
		0.311		0.353		0.429		0.657
80	0.346		0.407		0.498		0.803	
		0.374		0.455		0.565		0.973
70	0.405		0.508		0.640		1.178	
		0.440		0.605		0.773		1.392
60	0.477		0.720		0.934		1.644	
		0.515		0.831		1.088		1.870
50	0.556		0.960		1.268		2.126	
		0.597		1.115		1.476		2.418
40	0.641		1.294		1.718		2.750	
		0.696		1.514		2.009		3.138
30	0.756		1.772		2.350		3.580	
		0.837		2.135		2.837		4.211
20	0.927		2.573		3.424		4.954	
		1.215		3.522		4.883		6.698
10	1.593		4.821		6.963		9.055	
		2.591		6.775		10.330		12.757
5	4.214		9.521		15.325		17.973	
		10.046		20.166		30.714		35.156
1	23.950		42.711		61.555		68.765	
		69.354		136.895		184.467		202.479
0.1	200.832		438.769		552.808		596.202	
		595.123		1094.27		1410.45		1530.55
0.01	1763.52		2729.08		3598.66		3929.17	

Table 10.4: *Discharge data for the Mhlathuze River. Values are in m^3s^{-1}. A & W = Ackers and White. E & W = Engelund and Hansen.*

	Site	**1 pool**	**1 riffle**	**2**	**3**	**4**
MAR	Virgin	185	185	255	313	362
	Present-day	64	64	127	176	217
Flows by recurrence interval						
Virgin flow	$Q_{1.5}$	40	40	47	88	90
	$Q_{2.44}$	105	105	118	168	178
	$Q_{p\ 0.9}$	130	130	190	244	257
	$Q_{p\ 2.0}$	244	244	417	542	593
Present-day flow	$Q_{1.5}$	13	13	20	50	68
	$Q_{2.44}$	32	32	52	105	142
	$Q_{p\ 0.9}$	68	68	139	181	210
	$Q_{p\ 0.9}$	153	153	269	377	464
Morpholog ical flows						
	bench	27		36		77
	Estimated	116	64	196	149	234
	terrace 1		332	568	531	1380
	terrace 2		1061	1007	1768	
Dominant discharge						
Virgin flow	Yang	39	16	108	130	52
	A & W	62	18	105	153	100
	E & H	47	29	246	185	106
Present-day flow	Yang	52	8	146	154	104
	A & W	70	7	137	124	122
	E & H	45	28	305	229	131
Effective discharge						
Virgin flow	Yang	1020	145	1435	1736	1850
	A & W	1020	145	1435	245	1850
	E & H	1020	145	1435	1736	1850
Present-day flow	Yang	*595*	*10*	*1094*	*1410*	*1531*
	A & W	*595*	*10*	*1094*	*184*	*1531*
	E & H	*595*	*69*	*1094*	*1410*	*1531*

Table 10.5: *Inundation frequencies and discharges for different morphological features for the virgin annual series data for the Mhlathuze River.*

Site	Bench return period	Discharge m^3s^{-1}	Estimated Q_s return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}
1 pool	1.3	27	2.5	116				
1 riffle			1.8	64	6.8	332	16	1061
2	1.3	36	3.4	196	7.5	568	12	1006
3			2.3	149	4.9	531	16	1768
4	1.4	77	3	234			13	1380
Average	1.3		2.6		6.4		14	

Table 10.6: *Inundation frequencies for different morphological features for the present-day annual series data for the Mhlathuze River.*

Site	Bench return period	Discharge m^3s^{-1}	Estimated Q_s return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}
1 pool	2.2	27	4.3	116				
1 riffle			3.5	64	10	332	26	1061
2	2.3	36	4.2	196	9	568	21	1007
3			2.6	149	9.5	531	30	1768
4	1.8	77	3.8	234			19	1380
Average	2.1		3.7		9.5		24	

Table 10.7: *Inundation frequencies for different morphological features for the virgin partial series data for the Mhlathuze River.*

Site	Bench return period	Discharge m^3s^{-1}	Estimated Q_s return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}
1 pool	0.1	27	0.8	116				
1 riffle			0.4	64	2.6	332	11	1061
2	0.1	36	0.9	196	2.6	568	7.5	1007
3			0.6	149	1.9	531	11	1768
4	0.3	77	0.8	234			6.7	1380
Average	0.2		0.7		2.4		9.1	

Table 10.8: *Inundation frequencies for different morphological features for the present-day partial series data for the Mhlathuze River.*

Site	Bench return period	Discharge m^3s^{-1}	Estimated Q_b return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}
1 pool	0.3	27	1.5	116				
1 riffle			0.9	64	7.5	332	17	1061
2	0.3	36	1.2	196	4.9	568	15	1007
3			0.8	149	2.6	531	16	1768
4	0.4	77	1	234			15	1380
Average	0.3		1.1		5		16	

The estimated bankfull discharges for the four sites on the Mhlathuze range from 64 m^3s^{-1} (Site 1) to 234 m^3s^{-1} (Site 4) (Table 10.4). The flood frequency analysis for the virgin flows indicates that the bankfull stage ranged from a 1.8 year to a 3.4 year return period on the annual series (average of 2.6) (Table 10.5). The partial series ranged from 0.4 years to 0.9 years (average 0.7) (Table 10.7). These values are outside but close to the range estimated for alluvial channels in temperate climes (Leopold, 1997). Under present-day flow conditions the average return periods have increased (Tables 10.6 and 10.8) to between 2.6 years and 3.7 years on the annual series (average 3.7) and 0.8years and 1.5 years (average 1.1) on the partial series. Thus the frequency of inundation of the bankfull level has decreased under the regulated flows, and is further from the values given by Leopold (1997).

The estimated bench full discharge ranged from 27 m^3s^{-1} (Site 1) to 77 m^3s^{-1} (Site 4). Under virgin flow conditions, the bench had an average annual return period of 1.3 years on the annual series and 0.2 years on the partial series (Table 10.5 and Table 10.7). This has increased to 2.1 years and 0.3 years under present-day conditions. The $Q_{1.5}$ flows over-predict the bench full flow under virgin conditions and under-predict for present-day conditions. It is proposed that the bench is equivalent to the bankfull stage of the modern active channel, with a recurrence interval for inundation of around 2 years in a channel with a variable flow regime as characterises the Mhlatuze. From the partial series it can be seen that in wet years the bench must be inundated frequently.

Under virgin flow conditions, the terraces were regularly inundated. Terrace 1 had an average return period on the annual series of 6.4 years and 2.4 years on the partial series, while Terrace 2 had an average return period of 14 years on the annual series and 9.1 years on the partial series (Table 10.5 and Table 10.7). The inundation frequency under present-day conditions has been significantly reduced, but the highest terraces are still likely to be inundated approximately once in twenty to thirty years.

Figure 10.1 displays the relationship between the inundation discharge and the virgin Mean Annual Runoff (MAR), used as a surrogate for catchment size, for the different morphological features for the virgin flow. The data shows that there is a clear increase in inundation discharge for each of the morphological features in the downstream direction. This would suggest that the Mhlathuze River is functioning as an alluvial system in the sense that it has the capacity to change its boundary in response to the observed discharge of water and sediment.

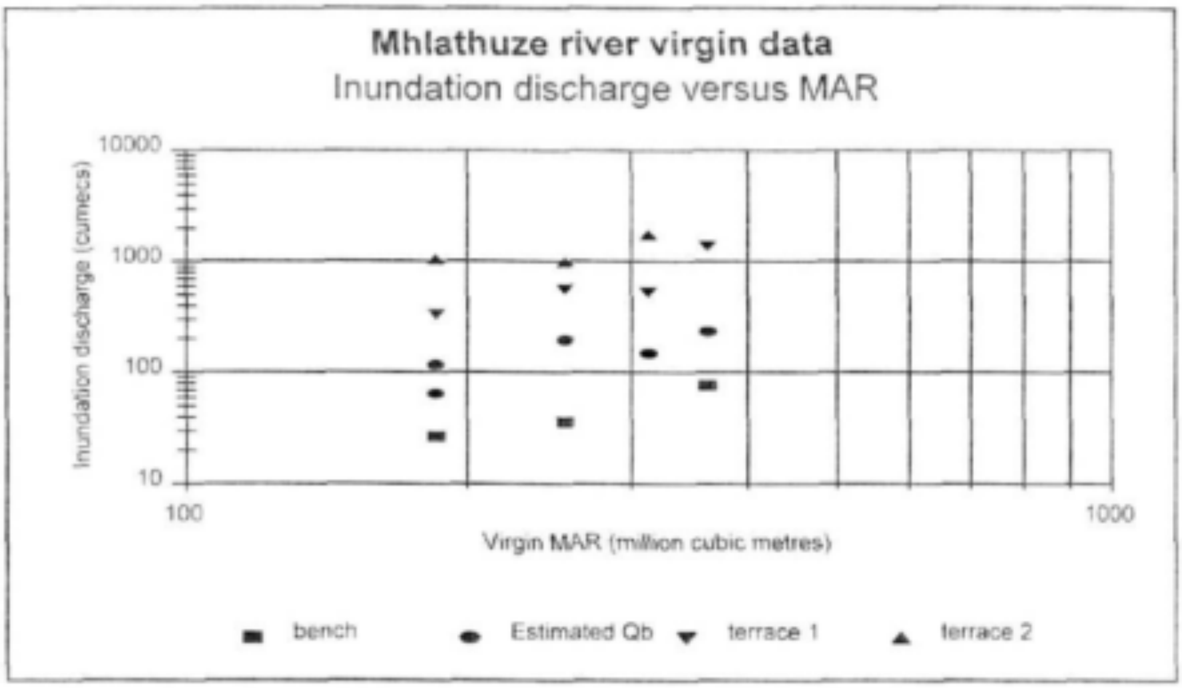

***Figure 10.1**: Inundation discharge versus MAR for different morphological features for the Virgin data for the Mhlathuze river*

Under virgin flow conditions, the MAR increased between sites 1 and 4 by a factor of 1.96 (Table 10.1). Under present-day conditions, this increase is considerably greater (3.39). This situation reflects the impact of the Dam and the flow recovery due to two major tributary inputs downstream of Goedertrouw Dam, the Mfule and Nseleni. It is likely that the dam has trapped a significant portion of the bed load. Evidence at Site 1 from aerial photography analysis confirms that this, together with the flow reduction, has resulted in significant downstream narrowing and deepening of the channel with a concomitant encroachment of riparian vegetation (Dollar, 1998b). It is only when the Mfule joins the Mhlathuze between Site 1 and Site 2 that the channel recovers, not only in terms of flow, but also in terms of sediment load. Thus, there is considerable evidence to suggest that the regulated flow regime has had a noticeable impact on the channel morphology of the Mhlathuze River, particularly at Site 1. On the basis of conventional wisdom, it is possible to argue that this adjustment is an attempt by the river to alter its morphology in sympathy with the imposed regulated flow regime. The morphological-flow relationships indicate that the Mhlathuze below the Goedertrouw Dam has, to some extent, adjusted to the present-day regulated flow regime. Downstream of the dam the river has an alluvial sand-bed channel and is free to alter its boundary. In a controlled or semi-controlled channel such as the Mkomazi, it is unlikely that such an adjustment could occur as rapidly.

10.2.3 Dominant discharge

The dominant discharge was computed using the Marlette & Walker (1968) equation. The dominant discharge as predicted by the different transport equations shows reasonable consistency (Table 10.4). Figure 10.2 shows the relationship between dominant discharge and estimated bankfull discharge. Dominant discharge is close to the bankfull discharge at Sites 2 and 3, but significantly below it for Sites 1 and 4.

The dominant discharge for the Mhlathuze increases (other than Site 1 riffle) under present-day flow conditions (Table 10.4). This does not imply that the sediment load increases under present-day flow conditions, but rather points to the fact that higher flows (classes) are necessary to transport the bulk of the sediment (i.e. the discharge that transports over 50% of the bed material load). The three transport equations predict a marked reduction in transport capacity (see Table 10.9) downstream of Site 1. This is due to flow recovery from the input of discharge from downstream tributaries.

The data in Table 10.9 show that Site 1 riffle has a greater estimated transport capacity than Site 1 pool. The reason is that the riffle has a greater energy gradient than the pool (although this equalises at higher flows), and thus the riffle generates greater unit stream power than the pool section. The three transport equations are based on stream power and, consequently, the predicted transport capacity at the riffle is greater than for the pool section. The transport equations predict that it is only at high discharge flow classes that the pools generate sufficient stream power to transport significant quantities of sediment. Figures 10.3 and 10.4 display the relationship between mean dominant discharge and MAR for the virgin and present-day flow respectively. Dominant discharge is not related to catchment size.

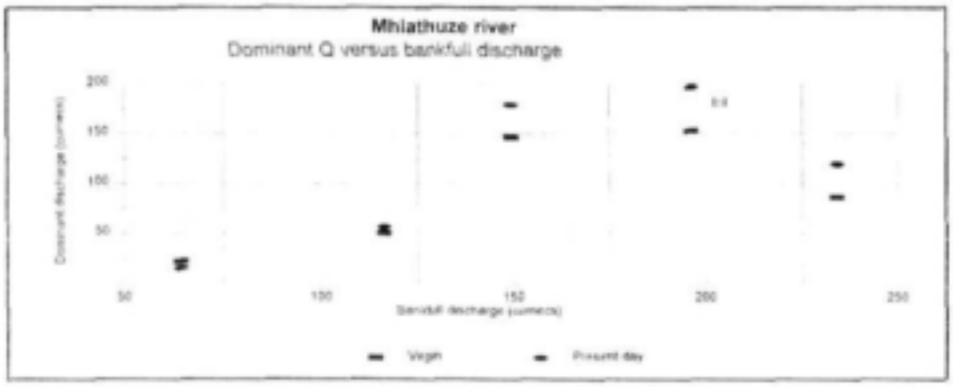

Figure 10.2: *Dominant discharge versus bankfull discharge for virgin and present-day flow for the Mhlathuze River. Dominant discharge is the average as predicted by the three bedload formulae.*

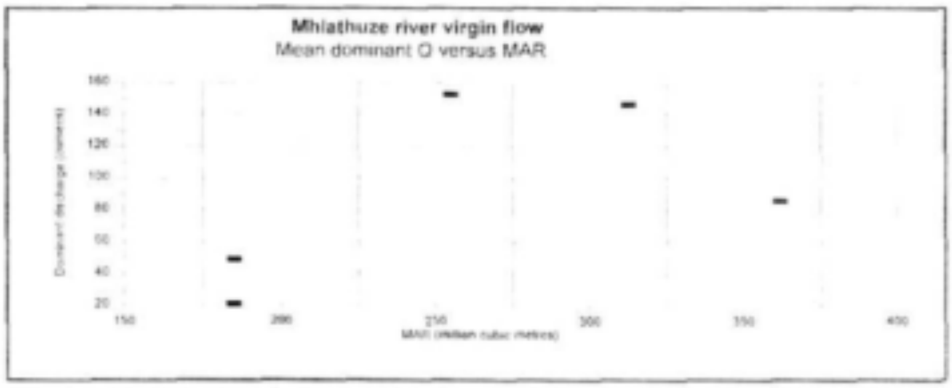

Figure 10.3: *Mean dominant discharge versus MAR for the Mhlathuze River virgin flow.*

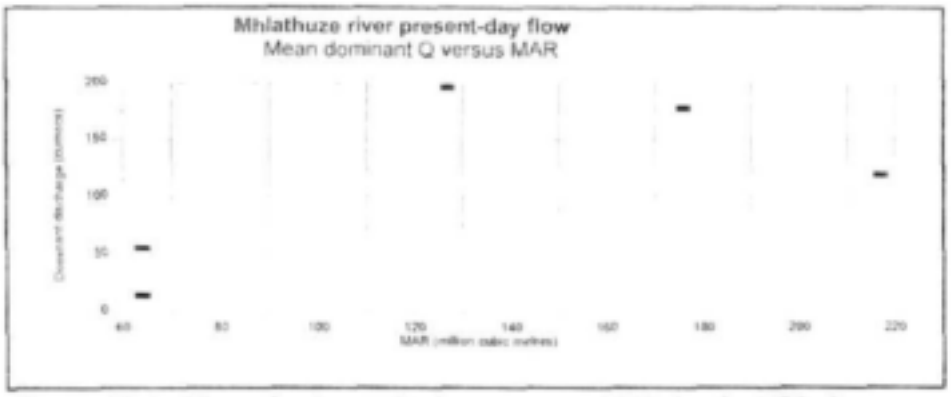

Figure 10.4: *Mean dominant discharge versus MAR for the Mhlathuze River present-day flow.*

Table 10.9: *Bed material transport capacity for the Mhlathuze River for virgin and present-day flow conditions. Values are in tonnes per annum.*

Site	Yang equation	Ackers & White equation	Engelund & Hansen equation
1 virgin pool	358 413.98	69 022.46	2 508 133.52
1 present-day pool	108 274.69	15 304.99	838 594.89
Reduction factor	*3.31*	*4.51*	*2.99*
1 virgin riffle	1 633 893.07	560 810.19	78 763 611.41
1 present-day riffle	395 246.16	102 732.94	20 145 380.49
Reduction factor	*4.13*	*5.45*	*3.91*
2 virgin	226 158.36	31 364.30	1 765 064.19
2 present-day	130 082.20	17 631.78	985 260.14
Reduction factor	*1.73*	*1.78*	*1.79*
3 virgin	131 497.28	44 935.26	242 999.47
3 present-day	85 222.71	28 725.44	158 773.38
Reduction factor	*1.54*	*1.56*	*1.53*
4 virgin	142 855.25	54 707.55	180 059.54
4 present-day	86 362.39	29 982.55	111 659.97
Reduction factor	*1.65*	*1.82*	*1.63*

10.2.4 Effective discharge

The effective discharge is defined as the geometric mean of the flow class that transports the most bed material over a long period of time. The effective discharge for the present-day, regulated flow decreases relative to the virgin flow. For example, the effective discharge calculated using the Yang equation is 1020 m^3s^{-1} at site 1 pool under virgin conditions, this declines to 595 m^3s^{-1} under present-day conditions. Similar results are obtained at all sites for the different equations (Table 10.4). For the virgin flows, all sites along the Mhlathuze were represented by an effective discharge that was equalled or exceeded between 1-0.01% of the time (Table 10.10). The only difference under the present-day flow regime was a reduction of the flow duration for effective discharge at the riffle, Site 1.

Table 10.10: *Effective discharge flow classes for the Mhlathuze River.*

Site	Yang (flow class)	Ackers & White (flow class)	Engelund & Hansen (flow class)	Yang (flow class)	Ackers & White (flow class)	Engelund & Hansen (flow class)
	Virgin flow			Present-day flow		
1 pool	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%
1 riffle	1-0.1%	1-0.1%	1-0.1%	5-1%	5-1%	1-0.1%
2	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%
3	0.1-0.01%	1-0.1%	0.1-0.01%	0.1-0.01%	1-0.1%	0.1-0.01%
4	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%

Under both flow regimes, the effective discharge for all sites other than Site 1 riffle are in excess of the dominant discharge, the estimated bankfull discharge, or the $Q_{1.5}$, $Q_{2.44}$, $Q_{p0.9}$ and $Q_{p2.0}$ (Table 10.4). It should be noted that the two cyclones that impacted on the Mhlathuze in 1984 and 1987 (see Chapter 5) have skewed the flow duration curves and flood frequency curves, such that the highest flow class (0.01% equalled or exceeded) is almost seven times larger than the second highest flow class (0.1% equalled or exceeded) (Tables 10.2 and 10.3). The bi-polar flood frequency curve has resulted in the generation of extremely high values for the effective discharge.

The upper three flow classes (5-1%; 1-0.1%; 0.1-0.01%) are the most significant in terms of effectiveness (see Figure 10.5 for the analysis for virgin flows). It is only at Site 1 riffle, that the upper three flow classes do not account for more than 80% of the bed material transported. At Site 1 pool, and sites 2, 3 and 4, the effective discharge accounts for over 40% of the bed material moved (Figure 10.6).

Figures 10.7 to 10.9 display the distribution of the cumulative sediment transport under virgin flow conditions for the three transport equations. The Yang equation indicates that other than Site 1 riffle, the four sites along the Mhlathuze show similar shaped curves. As noted above, the bulk of the bed is transported by the upper three flow classes. For example both the Yang and Engelund and Hansen formulae predict that less than 10% of the total bed material load is transported by flows of less than the 20th percentile (Figure 10.7). The curve for Site 1 riffle displays a different shape, as the steeper slope and higher unit stream power at the riffle results in higher predicted transport capacities at lower discharges. It is also evident that although the transport equations predict different transport volumes (Table 10.9), they all predict similar trends.

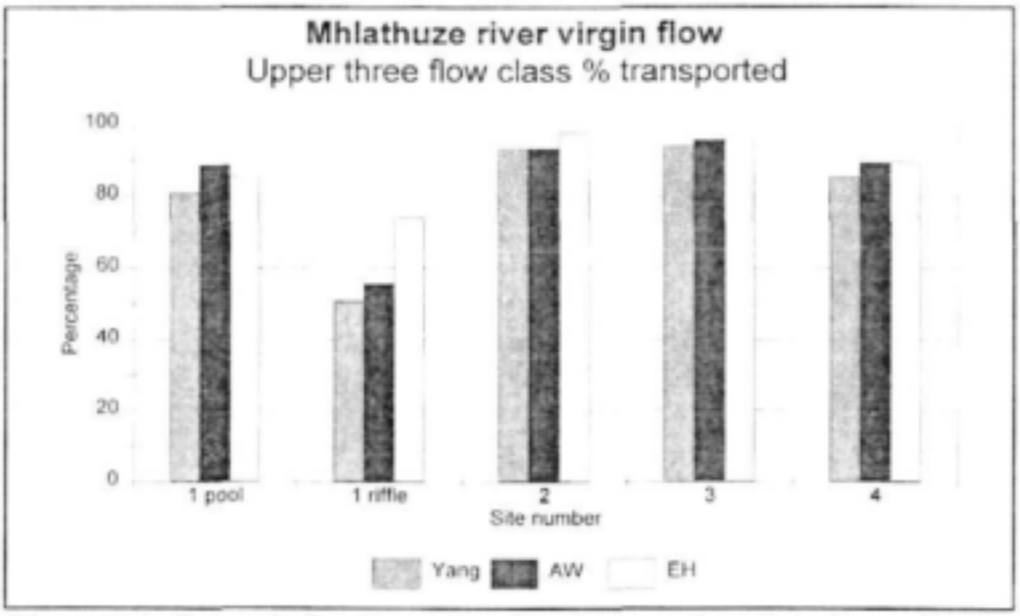

Figure 10.5: *Percent bedload transported by the upper three flow classes (5-1%; 1-0.1% and 0.1-0.01%) for virgin flow for the Mhlathuze River.*

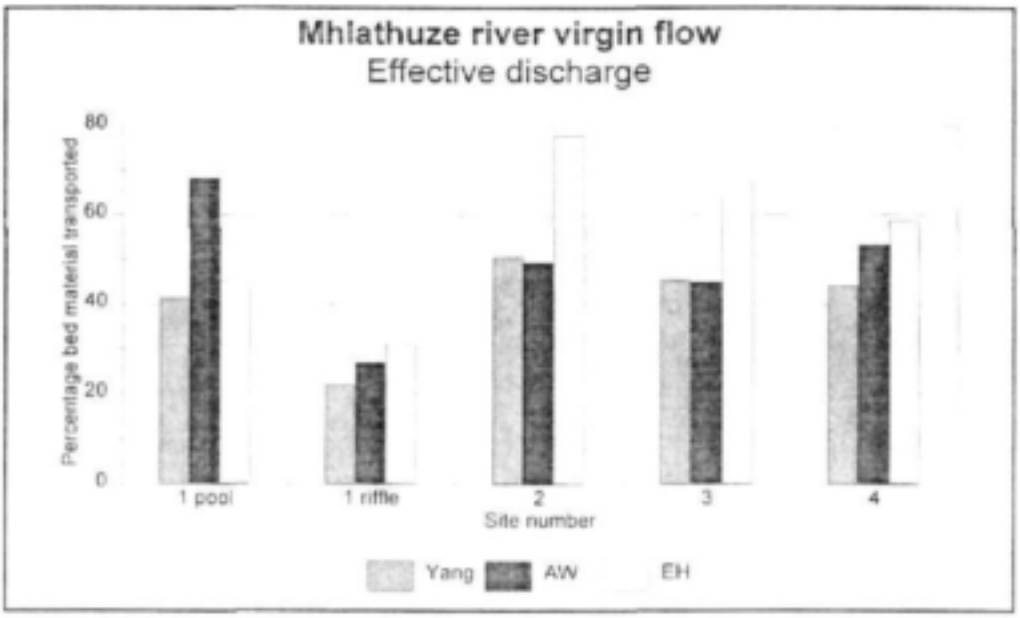

Figure 10.6: *Percent bedload transported by the effective discharge for virgin flow for the Mhlathuze River.*

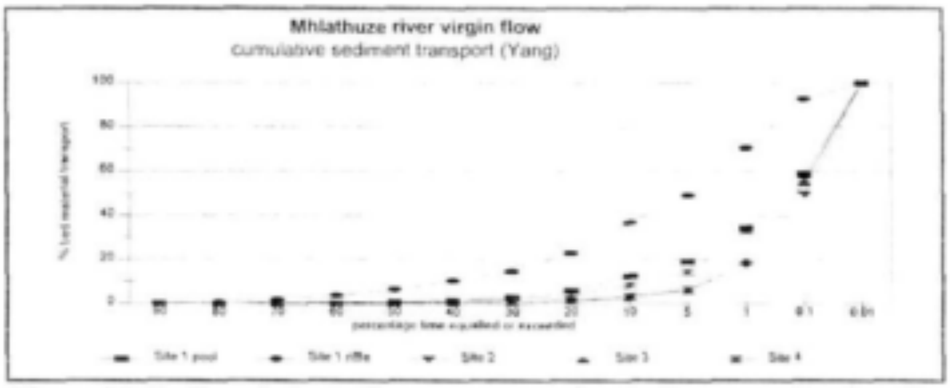

Figure 10.7: *Cumulative sediment transport for the Yang equation for all sites for the virgin flow for the Mhlathuze River.*

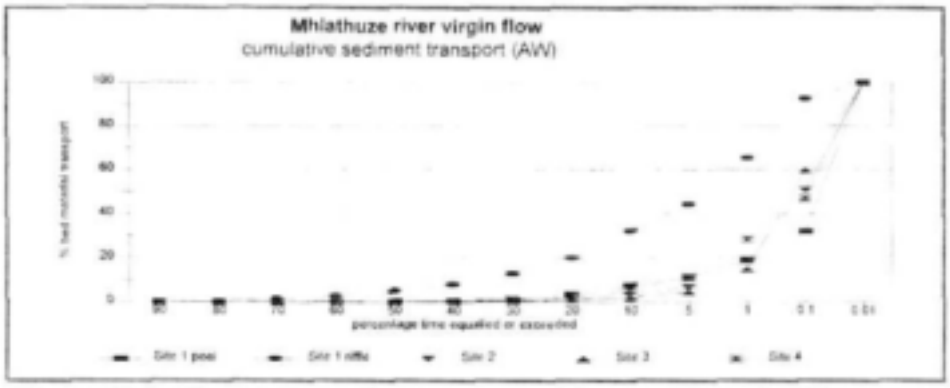

Figure 10.8: *Cumulative sediment transport for the Ackers & White equation for all sites for the virgin flow for the Mhlathuze River.*

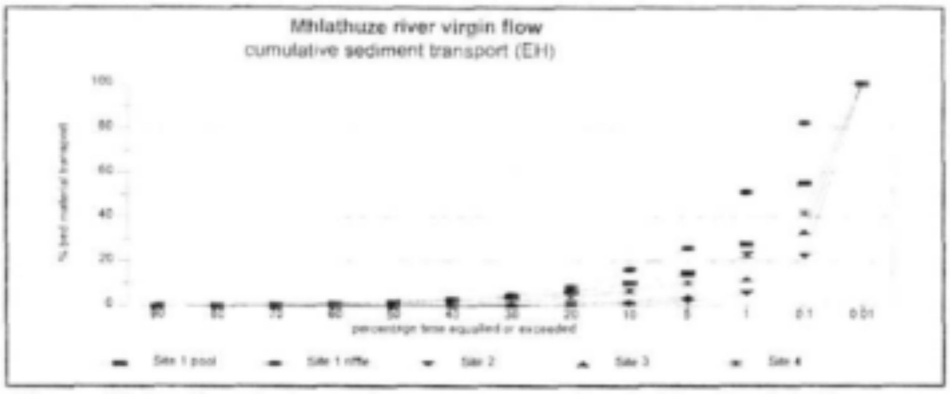

Figure 10.9: *Cumulative sediment transport for the Engelund & Hansen equation for all sites for the virgin flow for the Mhlathuze River.*

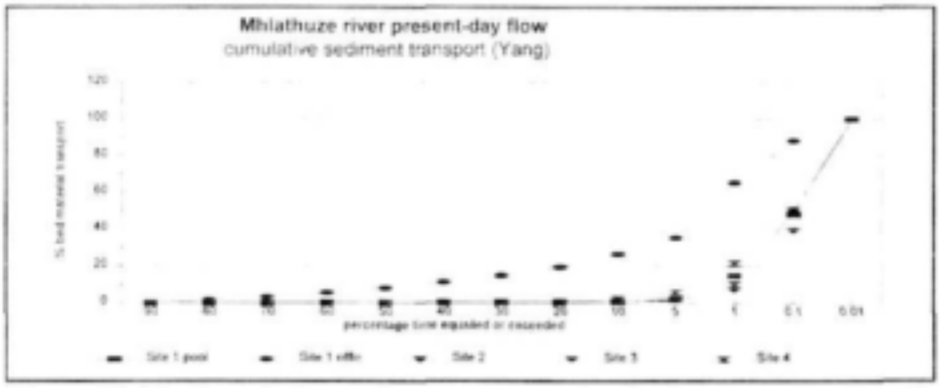

***Figure 10.10:** Cumulative sediment transport for the Yang equation for all sites for the present-day flow for the Mhlathuze River.*

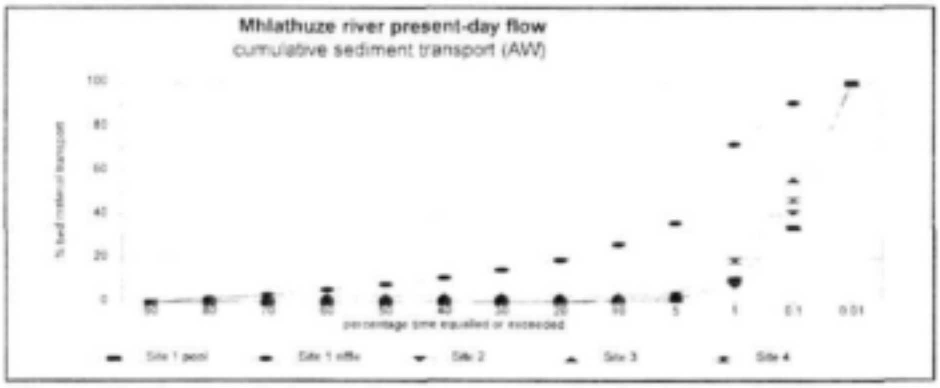

***Figure 10.11:** Cumulative sediment transport for the Ackers & White equation for all sites for the present-day flow for the Mhlathuze River.*

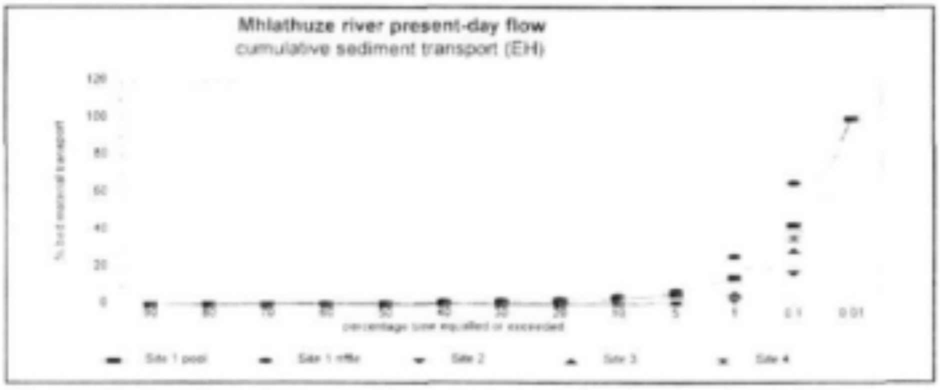

***Figure 10.12:** Cumulative sediment transport for the Engelund & Hansen equation for all sites for the present-day flow for the Mhlathuze River.*

Figures 10.10 to 10.12 display the distribution of the cumulative bed material transport under present-day conditions. The curves have all shifted to the right so that , other than for Site 1 riffle, 90% of the total bed load is transported by the top 5% of the flow, rather than the top 20% under virgin conditions. This represents a significant change in the effectiveness of the flow regime. Under the virgin flow conditions it appears that there was a more even distribution of the load between the flow classes. Under present-day flow environment, not only has the total load been reduced by a factor between 3.5 (the average for the three equations for Site 1 pool) and 1.54 (the average for the three equations for Site 4) (Table 10.9) but there has also been a clear change in the way in which the load is distributed around the duration curve. This is of significance in recommending flows for the Instream Flow Requirement (IFRs) and will be discussed further in Section 10.2.8.

For the Mhlathuze sand-bed sites, virgin flow conditions were more than sufficient to mobilise the entire bed (Figure 10.13). It should be noted that relative to the Mkomazi, the Mhlathuze sand-bed sites generate low unit stream power and shear stresses. This is a function of the low slope and the wide channel. For example, the unit stream power at the 0.1-0.01% flow class for sites 2, 3 and 4 is 260 Wm^{-2}, 86 Wm^{-2} and 65 Wm^{-2} respectively. At Site 1, the unit stream power is 280 Wm^{-2} at the pool section and 1073 Wm^{-2} at the riffle section. The higher values are the result of a narrower, deeper channel and a steeper slope. These low stream power values at sites 2, 3 and 4 would preclude the transport of coarse material, even at high flows. There is, however, no coarse material to transport.

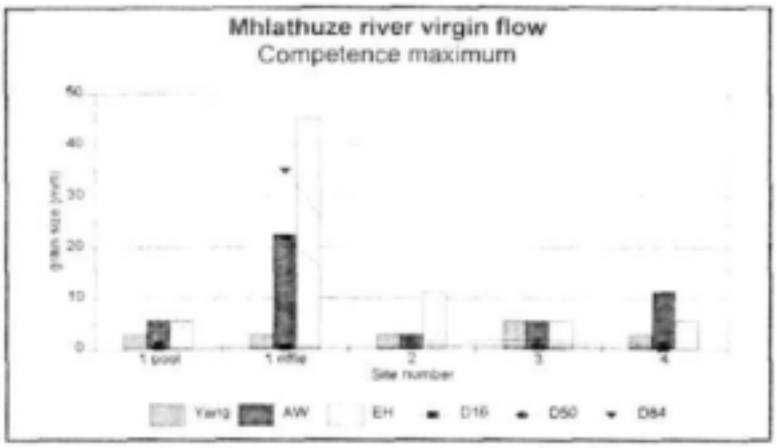

Figure 10.13: Maximum competence for the Mhlathuze River for virgin flow.

The regulated flow environment impacted significantly on the shear stress and unit stream power. The boundary shear stress and unit stream power has been reduced for the effective discharges. Figure 10.14 shows the unit stream power for the effective discharge for the Yang equation. The effective discharge for site 1 pool (1020 m^3s^{-1}) under virgin conditions produced a unit stream power value of 280 Wm^{-2} (Figure 10.14), while the effective discharge for the present-day conditions (595 m^3s^{-1}) produces a unit stream power of 181 Wm^{-2}. Thus, while the discharge under present-day conditions represents 58% of the virgin flow, the present-day unit stream power represents 65% of the virgin unit stream power. At site 1 riffle this is even more marked with the unit stream power declining from over 650 Wm^{-2} under virgin flow conditions to just over 200 Wm^{-2} under present-day conditions. At Site 2, the difference in unit stream power is small (260 Wm^{-2} for the virgin conditions and 202 Wm^{-2} for the present-day conditions). At sites 3 and 4 the difference is insignificant (86 Wm^{-2} for Site 3 virgin as opposed to 72 Wm^{-2} for Site 3 present-day, and 65 Wm^{-2} for Site 4 virgin and 54 Wm^{-2} for Site 4 present-day).

The reduced transport capacity of the regulated flow may be of limited significance, as long as there is a balance between the amounts of material transported into and out of the river system. However, where there are significant inputs of sediment from downstream tributaries (such as the Mfule and Nseleni for the Mhlathuze), it is likely that sediment accumulation will occur downstream of these tributary junctions, leading to channel aggradation. Under present-day conditions, due to the high mobility of the sand-bed the Mhlathuze is still competent to transport bed material at reduced (regulated) flows, but a reduced volume of material is being transported (i.e. the capacity of the Mhlathuze is reduced). There is no danger in this system of fine material filling the interstices of coarser material. Were the Mhlathuze River a heterogenous gravel- or cobble-bed river (such as the Mkomazi or Olifants), then a greatly reduced flow regime would be expected to have a different impact. This will be expanded on later in the chapter.

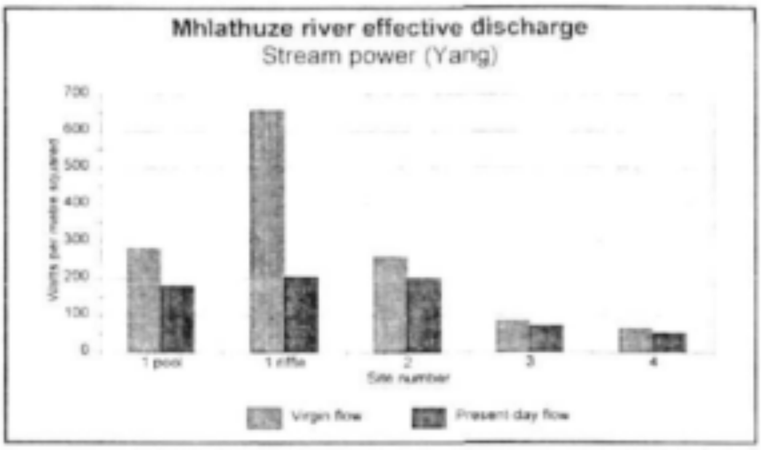

Figure 10.14: *Unit stream power for the Mhlathuze River using the Yang equation.*

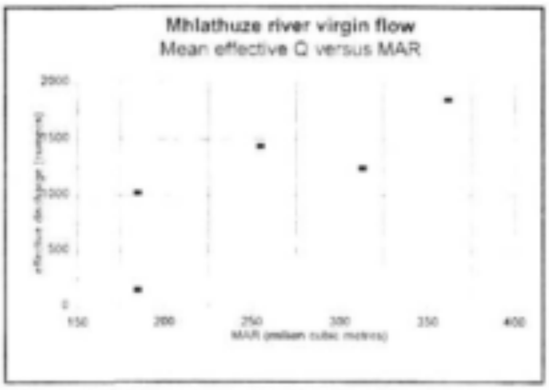

Figure 10.15: *Mean effective discharge versus MAR for the Mhlathuze River virgin flow.*

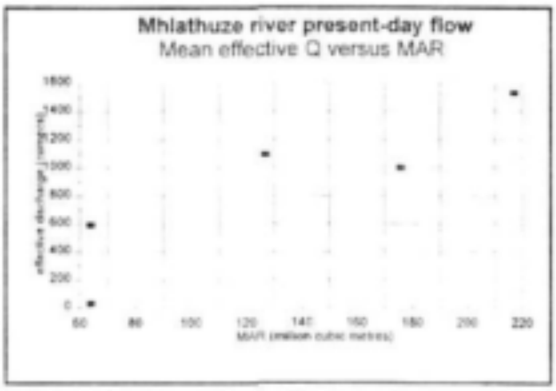

Figure 10.16: *Mean effective discharge versus MAR for the Mhlathuze River present-day flow.*

Figures 10.15 and 10.16 present the relationship between MAR and the mean effective discharge for the Mhlathuze for the virgin and present-day flow. The results suggest that effective discharge increases with MAR and thus with catchment size.

10.2.5 Effective discharge for sand and gravel

The effective discharge for sand and gravel was calculated using the same technique as outlined for the Mkomazi River. This was done for virgin and present-day conditions for the Mhlathuze River. Results from the virgin flow (Figure 10.17) indicate that the percentage bed material transported by the effective discharge for sand is generally less than that for gravel. This would suggest that the sand is being transported by a wider range of flow classes than the gravel, which is to be expected. Results from the present-day flow indicate that the percentage transported by the effective discharge for sand and gravel has changed (Figure 10.18). The percentage of bed material transported by the most effective discharge has increased for both sand and gravel. It is clear that not only has the volume of sediment being transported by the present-day flow changed, but so too has the proportion of sand and gravel being transported by the different flow classes. This result indicates that under present-day conditions less bed material is being transported and that the material that is being transported is being transported by a smaller range of flow classes. This finding is in agreement with the results presented in Section 10.2.4.1.

This has not, however, changed the effective discharge flow classes (Table 10.11). This would suggest that although the capacity of the flow has changed, the competence has not.

Table 10.11: *Effective discharge flow classes for the Mhlathuze River for sand and gravel for the Yang equation.*

Site	**Sand (flow class)**	**Gravel (flow class)**	**Sand (flow class)**	**Gravel (flow class)**
	Virgin flow		**Present-day flow**	
1 pool	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%
1 riffle	1-0.1%	1-0.1%	1-0.1%	1-0.1%
2	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%
3	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%
4	0.1-0.01%	0.1-0.01%	0.1-0.01%	0.1-0.01%

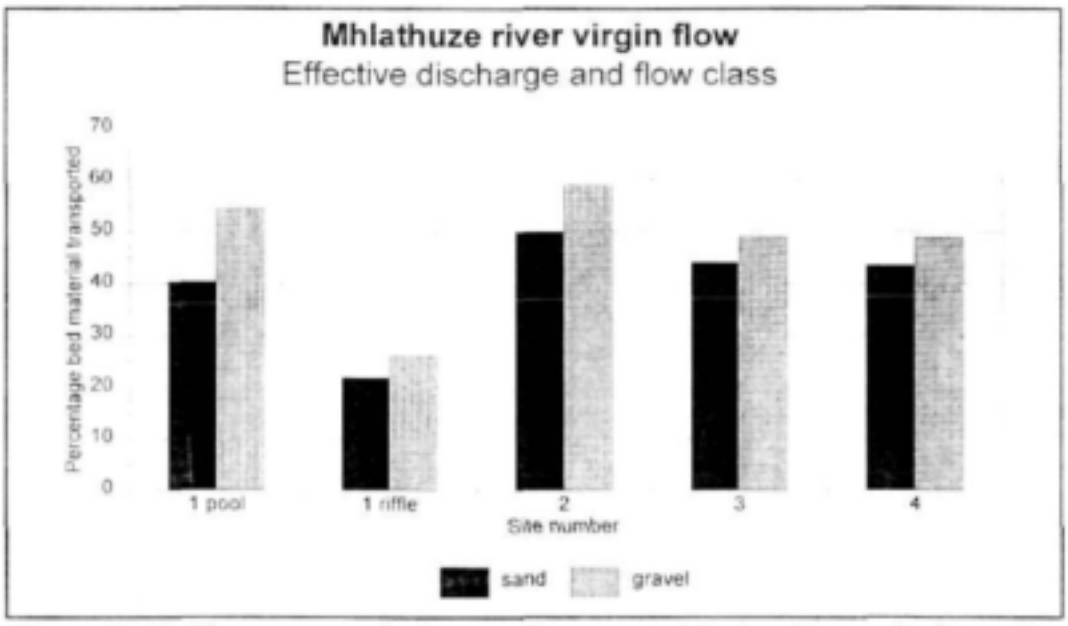

Figure 10.17: *The percentage bed material transported by the effective discharge for the Mhlathuze River virgin flow for sand and gravel.*

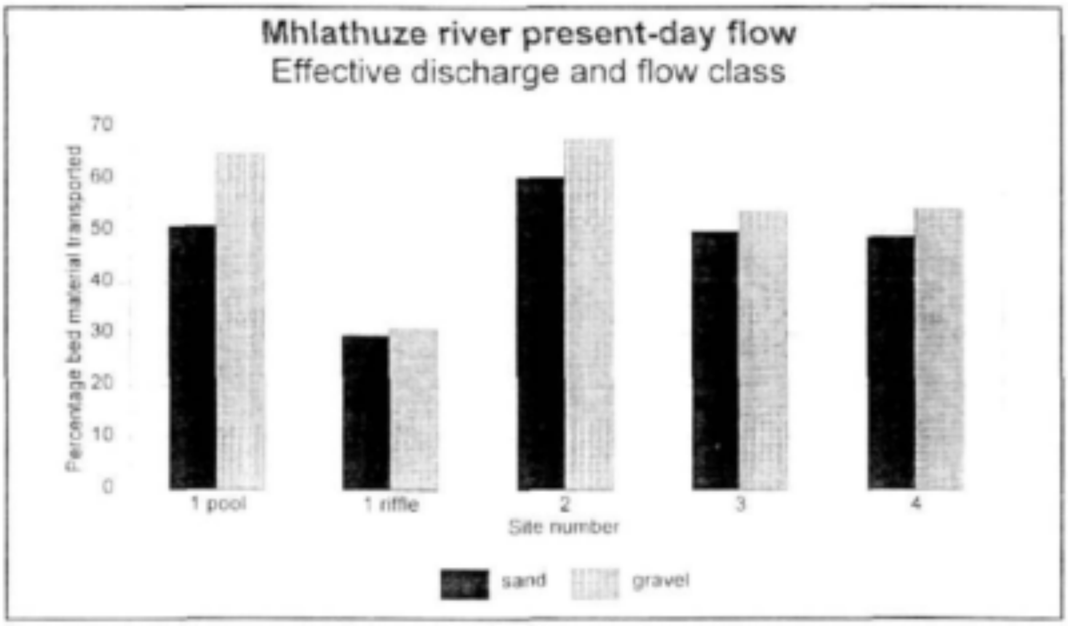

Figure 10.18: *The percentage bed material transported by the effective discharge for the Mhlathuze River present-day flow for sand and gravel.*

10.2.6 Synthesis

The Mhlathuze River is a sand-bed river and, as such, these findings demonstrate that some bed material transport occurs at even the lowest flow classes. It was also mentioned that the construction of the Goedertrouw Dam has had a significant impact on the flow regime, with a reduction of up to 60% of the MAR immediately downstream of the dam. The effective discharge has been reduced by almost 50% at all sites. While these reduced flows remain competent to mobilise the bed material, the volume of the transported material has been reduced due to a reduction in the transport capacity associated with a reduction in unit stream power. The cumulative sediment transport curves have shifted to the right under the present-day flow environment, which would suggest a higher percentage of the bed material is being transported by less frequent flows. This, however, points to the fact that under present-day conditions, the higher flows are of greater significance, as these are the flows that are more 'effective'. It is also clear that, under present-day flow conditions, the morphological features are inundated less frequently (approximately half the time) than would be the case under the virgin flow regime.

It should be noted that the effective discharges calculated for the Mhlathuze River are far higher than for the Mkomazi or Olifants Rivers. This is significant, as it illustrates the importance of the flow regime. The upper part of the flow duration curve displays a marked steepening due to the occurrence of tropical cyclones and cut-off lows which appear to occur on average every twenty years or so in northern KwaZulu-Natal. The high variability of the Mhlathuze increases the importance of the higher flows.

It is argued that due to the sand-bed nature of the Mhlathuze River, the channel can accommodate significant reductions in flow without crossing the threshold of instability, provided that the amount of sediment transported into the system is balanced by the amount of sediment that the channel can transport out of the system. However, this is not the case for the Mhlathuze River. The channel immediately downstream of the dam has narrowed and deepened in response to the regulated flow. It has effectively been stripped of its sediment and consequently a new channel form has developed. This impact is compensated in the downstream direction by the input of sediment and discharge from the Mfule and Nseleni tributaries. It is suggested that the input of sediment and discharge from downstream tributaries is likely to have resulted in channel aggradation. This would suggest that the impact of the regulation changes in the downstream direction. The results highlight a number of issues. First, the regulated flow regime has reduced the bed material transport capacity of the Mhlathuze River by nearly four times immediately below Goedertrouw Dam, and by approximately 1.5 times near the mouth. [This may have a number of indirect impacts, such as increased coastal erosion and degradation of beaches (cf. Cooper, 1991)].

It is argued that the Mhlathuze River has adjusted its channel morphology in sympathy with the regulated flow regime. There is evidence to suggest that a new set of in-channel features are developing, and that the present-day in-channel bench is in fact the new bankfull discharge. This is supported by the hydrological data. These findings suggest that methods used for setting a regulated Instream Flow

Requirement (IFR) on the basis of morphological features in the channel (e.g. the bankfull stage) may be inappropriate unless these bench features are taken into account.

If the above hypothesis is correct, then the following should also be true: under virgin flow conditions, the bench should have been absent and the estimated bankfull discharge should have been the equilibrium condition. If the bench is indeed a modern feature and related to modern flows, then the recurrence interval of the inundation should be approximately the same as the recurrence interval of the bankfull level under virgin flows. Furthermore, if the upper sites are incising then the recurrence intervals should be relatively high. If the lower sites are aggrading, then the recurrence intervals should be relatively low. The lack of a bench at Site 3 suggests that the present bankfull level may be the closer to the true bankfull level than at the other sites. The data therefore support this hypothesis.

10.2.7. Implications for Instream Flow Requirements (IFRs)

In setting a regulated flow regime that would attempt to mimic the significant pre-impoundment discharges, it is necessary that the geomorphological objectives be clearly stated. In the case of the Mhlathuze River, where clear evidence exists that the regulated flow regime has had a significant impact on channel morphology and bed load transport capacity, it may be useful to set flow objectives that maintain certain aspects of the existing channel, rather than attempting to set flows to return the channel to a pre-impoundment state. It may be necessary, therefore, to set different flow requirements for Site 1 which is immediately below the Dam and which is incising and narrowing, as opposed to sites 2, 3 and 4 which are below the confluence of the Mfule and Nseleni tributaries, and are therefore probably aggrading.

Given the fact that the Goedertrouw Dam has a near 100% trap efficiency and that there are no major tributary inputs of sediment between the dam and Site 1, it is unlikely that channel aggradation will occur. It is more likely that the channel will maintain its downward trajectory and continue to narrow and deepen. To avoid this scenario, it may be useful to set an IFR that will ensure that the channel maintains its present width and topographic diversity. For this reason, channel maintenance flows should be recommended that seek to maintain the *status quo* of the channel, as it is clear that it is not possible to return to the pre-impoundment condition. Channel maintenance flows need to be set close to the effective discharge. It is important to note that the effective discharge also implies flow duration. It may be possible to manipulate the hydrograph of the dam releases (especially in mobile sand-bed channels) to optimise sediment transport and achieve a desired channel condition.

The sand-bed channels (sites 2, 3 and 4) are highly mobile. However, if the regulated flow regime does not have the capacity to transport the sediment input, then aggradation will occur. It is argued that the development of inset channel benches are probably a response by the Mhlathuze River to the regulated flow environment. Unless a balance between the input and output of sediment is achieved, the long-term trajectory for the Mhlathuze at these lower three sites is one of aggradation. This effect can be mitigated to some extent by flooding. However, given that the Goedertrouw Dam has had the effect of attenuating the flood peaks, present-day floods do not have the same transport capacity as they had in the past. However, they are of greater geomorphological significance, as they have become relatively more effective under present day conditions. In order for flooding to have the desired effect on the river channel, the high magnitude low frequency flows which are so significant in transporting the bed material need to be allowed through the channel reach.

For Site 1, the following objectives might be set:

- to remove fine sediment from the pool;
- to remove fine sediment from the gravel and cobble substrate in the riffle;
- to entrain the coarse material on the riffle, thereby exposing subsurface material to transport and maintaining a loose structure;
- to maintain the active channel width and topographic diversity; and
- to allow large floods to move through the reach.

For sites 2, 3 and 4 the following flow objectives might be set:

- to maintain the equilibrium of the channel by setting flows that transport the same amount of material entering the channel as that leaving the channel; and
- to allow large floods to move through the channel reach.

It is clear from the channel geometry of the Mhlathuze River that the river has adjusted to a highly variable flow regime. Flooding forms an important part of the operation of the system. As long as the system remains regulated, geomorphological responses are inevitable.

10.3 The Olifants River

10.3.1 Overview

The Olifants River is a highveld river in the Gauteng and Mpumalanga provinces of South Africa and is strongly controlled by bed rock and by numerous lineaments and faults that traverse the river (Chapter 5). The bed material is predominantly cobble-sized. The upper Olifants system consists of three main stems, the Wilge to the west, the Klein Olifants to the east and the Olifants proper, which have been impounded by a number of dams which have been in place for over 50 years and have had a major impact on the flow regime of the Olifants system. Four sites were selected in the Olifants system. Sites 3 and 4 were on the tributaries. Site 3 was on the Klein Olifants, approximately 45 kilometres downstream of Middelburg Dam and Site 4 was on the Wilge River, nearly 80 kilometres downstream of the Bronkhorstspruit Dam and 40 kilometers downstream of the Premier Dam. Sites 1 and 2 were on the main Olifants river. Site 1 was 15 kilometres downstream of Doornpoort Dam and Witbank Dam. Site 2 was the lowest site on the Olifants system and is thus regulated by five impoundments.

The flow classes calculated for the Olifants River are presented in Table 10.12. The methods for determining the bed material transport, effective discharge and dominant discharge were the same as those used for the Mkomazi and Mhlathuze Rivers. The sites on the Olifants River could not be related to any longitudinal downstream changes, as two of the sites are on tributaries of the Olifants They were, however, related to the Mean Annual Runoff (MAR).

It is important to re-emphasize that the hydrological data that were generated for the Olifants River relate to the virgin flow conditions. As explained in Chapter 6, this was due to the fact that no present-day daily data could be generated as information on the operational procedures of the controlling dams was not available. The field methods that were applied to the classification of the morphological features of the Mkomazi and Mhlathuze Rivers were also applied to the Olifants River.

10.3.2 Analysis of channel morphology

The estimated bankfull discharge for the Olifants River ranges from 62 m^3s^{-1} (Site 1) to 418 m^3s^{-1} (Site 2)(Table 10.13). On the annual series, these stages are inundated by flows ranging from a 1.6 to 9.5 year return period, with an average of 5.8 years (Table 10.14). The partial series ranges from 0.3 years to 4.2 years with an average of 1.7 years (Table 10.15). The results for the annual series other than for Site 1 are considerably higher than the conventional wisdom suggested by Leopold (1997).

The results indicate that good general agreement exists between the estimated bankfull discharge and the 1.5 and 2.44 year return period flows at Site 1 (Table 10.13). At Site 2, the estimated bankfull discharge is similar to the 2.0 year return period on the partial series. At Site 3, the estimated bankfull discharge is greater than any of the calculated return periods, while at Site 4 the estimated bankfull discharge is close to the 2.44 year return period on the annual series. It appears that no consistent agreement exists between the estimated bankfull discharge and any hydrological statistic for the Olifants system.

Table 10.12: *Flow classes calculated for the Olifants River. Values are in m^3s^{-1}. MAR is in million cubic metres.*

% time equalled or exceeded	**Q**	**Qm**	**Q**	**Qm**	**Q**	**Qm**	**Q**	**Qm**
	Site 1		**Site 2**		**Site 3**		**Site 4**	
	147 MAR		**449.3 MAR**		**81.6 MAR**		**166.9 MAR**	
99.99	0.010		0.206		0.025		0.120	
		0.047		0.518		0.068		0.291
90	0.225		1.304		0.187		0.708	
		0.259		1.55		0.220		0.834
80	0.297		1.835		0.258		0.982	
		0.336		2.11		0.292		1.11
70	0.381		2.41		0.330		1.258	
		0.448		2.79		0.368		1.42
60	0.527		3.23		0.411		1.604	
		0.663		3.88		0.467		1.81
50	0.833		4.65		0.530		2.048	
		1.09		5.77		0.639		2.37
40	1.42		7.16		0.771		2.74	
		1.90		9.11		0.993		3.29
30	2.53		11.6		1.28		3.93	
		3.50		14.9		1.71		5.05
20	4.85		19.2		2.28		6.49	
		7.36		26.7		3.38		9.29
10	11.2		37.2		5.01		13.3	
		15.0		47.2		6.81		13.4
5	20.1		60.0		9.25		22.7	
		32.8		94.6		15.4		37.6
1	53.4		149		25.6		62.22	
		111		278		52.4		122
0.1	229		520		107		238	
		361		722		186		379
0.01	569		1001		324		606	

Table 10.13: *Morphological data for the Olifants River. Values are in* m^3s^{-1}.

Site	**3**	**1**	**4**	**2**
Virgin MAR	185	255	313	362
$Q_{1.5}$	31	54	49	127
$Q_{2.44}$	41	75	73	190
$Q_{p\ 0.9}$	46	97	126	274
$Q_{p\ 2.0}$	81	178	192	440
Morphological flows				
Estimated Q_b	160	62	80	418
terrace 1	605	756	551	621
terrace 2	889		993	1245
terrace 3	1295	1899	1462	2598
Dominant discharge				
Yang	39	27	28	19
Ackers & White	64	32		29
Engelund & Hansen	63	32	43	27
Average	55	30	36	25
Effective discharge				
Yang	52	33	38	95
Ackers & White	52	111		95
Engelund & Hansen	186	111	379	278
Average	97	85	209	156

Furthermore, this does not appear to be related to channel type. Sites 1 and 2 are both multiple-channel types with partial bed rock control and a number of distributary channels. Yet Site 1 shows good agreement between the estimated bankfull discharge and the 1.5 and 2.44 year return period on the annual series, but Site 2 does not. Site 3 is strongly bed rock controlled, and the estimated bankfull discharge (160 m^3s^{-1}) is well in excess of any calculated hydrological statistic (Table 10.13). Site 4 is a cobble-bed channel, with the estimated bankfull discharge (80 m^3s^{-1}) almost twice that of the 1.5 year return period on the annual series (49 m^3s^{-1}), but considerably less than the 0.9 and 2.0 year return period on the partial series (126 m^3s^{-1} and 192 m^3s^{-1} respectively) (Table 10.12). The estimated bankfull discharge for the four sites for the Olifants system therefore display no consistent relationship with any calculated hydrological statistic.

This finding is also reflected in the relationship between the MAR and the inundation bankfull discharge. Figure 10.19 displays the relationship between the inundation discharge and MAR for the Olifants River.

The estimated bankfull discharge does not appear to increase with increasing MAR. Only terrace 3 displays a definite increase in the downstream direction (using MAR as a surrogate for downstream changes). Terraces 1 and 2 display no clear trend. This may reflect local conditions in that there is strong bed rock control at these sites and the channel boundary is not free to adjust to the flow regime, or the terraces may reflect the imprint of a relict flow regime.

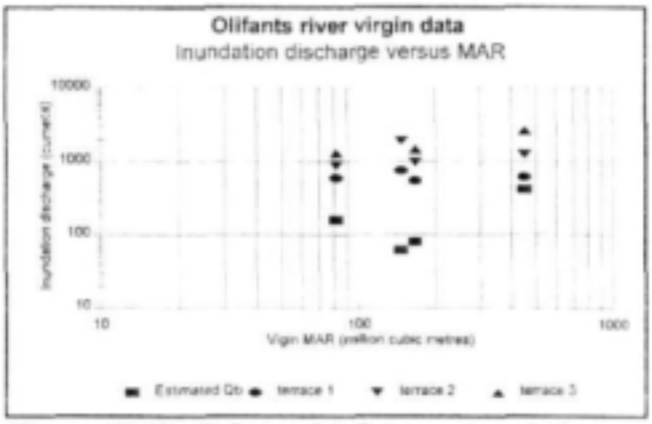

Figure 10.19: *Relationship between inundation discharge and virgin MAR for the Olifants River.*

10.3.3 Dominant discharge

The dominant discharge as calculated by the Marlette & Walker (1968) equation shows different values for each of the three bed material equations (Table 10.13). The dominant discharge values for the Yang equation range from 19 m^3s^{-1} (Site 2) to 39 m^3s^{-1} (Site 3). The values for the Ackers & White and Engelund & Hansen equations range from 29 m^3s^{-1} (Site 2) to 64 m^3s^{-1} (Site 3) and 27m^3s^{-1} (Site 2) to 63 m^3s^{-1} (Site 3) respectively (Table 10.13). No dominant discharge was calculated for the Ackers & White equation for Site 4, as the equation predicted that even under the highest flow class conditions no bed material transport would occur. The dominant discharge is generally lower than the 1.5 and 2.44 year return period on the annual series and the 0.9 and 2.0 year return period on the partial duration series (Table 10.13).

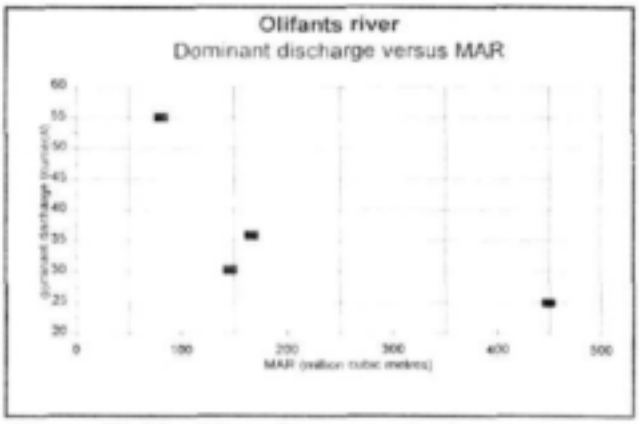

Figure 10.20: *Plot of average dominant discharge versus MAR for the Olifants River.*

Figure 10.20 displays the plot of the relationship between MAR and dominant discharge. Although not tested statistically, the result indicates that an inverse relationship exists between MAR and dominant discharge. The higher the MAR, the lower the dominant discharge.

10.3.4 Effective discharge

The effective discharges range from 33 m^3s^{-1} (Site 1) to 95 m^3s^{-1} (Site 2) for the Yang equation, and 52 m^3s^{-1} (Site 3) to 111 m^3s^{-1} (Site 1) for the Ackers & White equation. The Engelund & Hansen equation predicts significantly higher values ranging from 111 m^3s^{-1} (Site 1) to 379 m^3s^{-1} (Site 3)(Table 10.13).

Table 10.14: *Inundation frequencies for different morphological features for the annual data for the Olifants River.*

Site	Estimated Q_s return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}	Terrace 3 return period	Discharge m^3s^{-1}
3	9.5	160	>64	605	>64	889	>64	1295
1	1.6	62	>64	756			>64	1899
4	2.8	80	30	551	>64	993	>64	1462
2	9.2	418	15.8	621	>64	1245	>64	2598
Average	5.8							

Table 10.15: *Inundation frequencies for different morphological features for the partial series data for the Olifants River.*

Site	Estimated Q_s return period	Discharge m^3s^{-1}	Terrace 1 return period	Discharge m^3s^{-1}	Terrace 2 return period	Discharge m^3s^{-1}	Terrace 3 return period	Discharge m^3s^{-1}
3	4.2	160	>64	605	>64	889	>64	1295
1	0.3	62	>64	756			>64	1899
4	0.4	80	15	551	>64	993	>64	1462
2	1.9	418	3.8	621	>64	1245	>64	2598
Average	1.7							

Table 10.16: *Effective discharge flow classes for the Olifants River.*

Site	Yang (flow class)	Ackers & White (flow class)	Engelund & Hansen (flow class)
1	5-1%	1-0.1%	1-0.1%
2	5-1%	5-1%	1-0.1%
3	1-0.1%	1-0.1%	0.1-0.01%
4	5-1%		0.1-0.01%

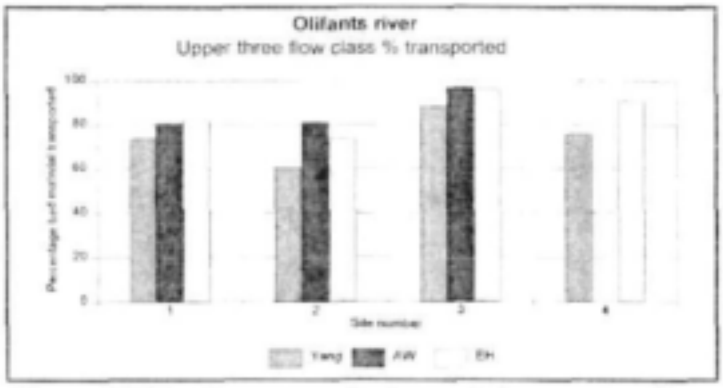

Figure 10.21: *Percentage bed material transported by the upper three flow classes (5-1%; 1-0.1% and 0.1-0.01%) for the Olifants River.*

Table 10.16 presents the effective discharge flow classes. These range from the 5% to 0.01% percentage exceedence. The Yang equation predicts effective discharge in the 5-1% range for sites 1, 2 and 4 and 1-0.1% range at Site 3. The Ackers & White equation predicts a range from the 5-1% class for Site 2, and 1-0.1% for sites 1 and 3. No transport is predicted for Site 4. Engelund & Hansen predicts higher transport values, with effective discharges in the 1-0.1% and 0.1-0.01% flow classes.

The upper three flow classes transport over 60% of the bed material load (Figure 10.21) while the effective discharge class transports between 32% and 51% of the bed material at the four sites (Figure 10.22). Figure 10.23 to Figure 10.25 display the cumulative sediment transport curves. According to the Yang equation, the upper three flow classes are responsible for over 60% of the bed material transported at each of the sites, while over 90% of the bed material for the sites is transported by flows that are equalled or exceeded by the 20th percentile and greater. Flows lower than this are not competent to transport significant quantities of bed material.

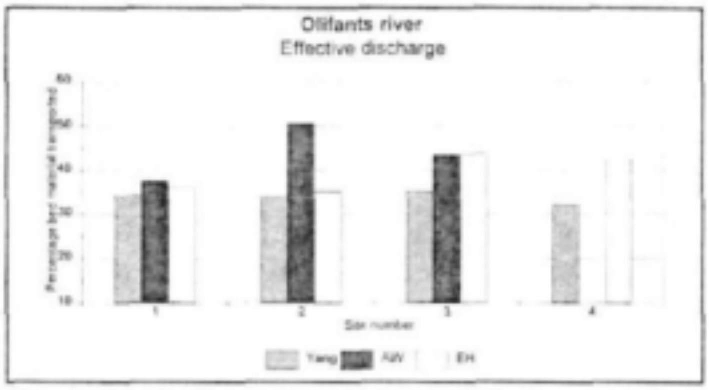

Figure 10.22: *Percentage bed material transported by the effective discharge for the Olifants River.*

Figure 10.26 demonstrates the relationship between the flow competence of the highest flow class and particle size distribution at the four sites. At sites 1, 2 and 3, the transport models predict that the D_{50} and below are moved at the highest flows. However, at sites 1, 3 and 4 the Yang and Ackers & White equations predict that the highest flow class does not have the competence to transport the D_{84}. In contrast, the Engelund & Hansen model predicts that the D_{84} is moved at the highest flow class. Field observation suggests that the Engelund & Hansen model over-predicts incipient motion. The Engelund & Hansen model is also designed for alluvial sand-bed rivers and, consequently, this model cannot be reliably applied to a coarse cobble-bed channel. It would appear that given the coarse nature of the bed, not all of the bed becomes mobile, even at the highest predicted discharges.

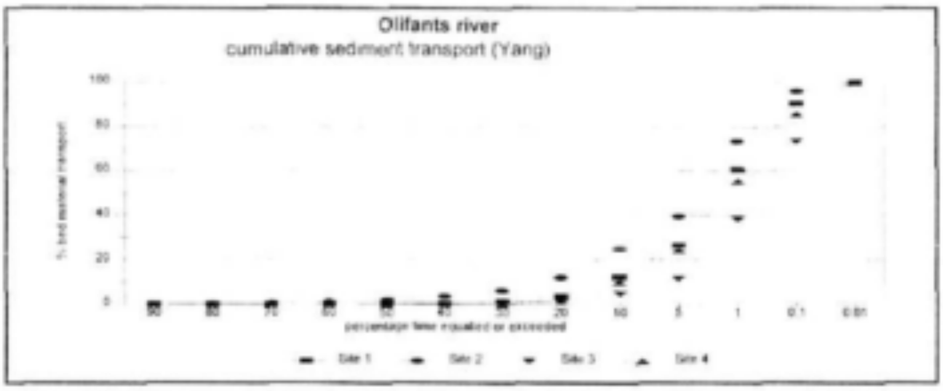

Figure 10.23: *Cumulative sediment transport for the Yang equation for the Olifants River.*

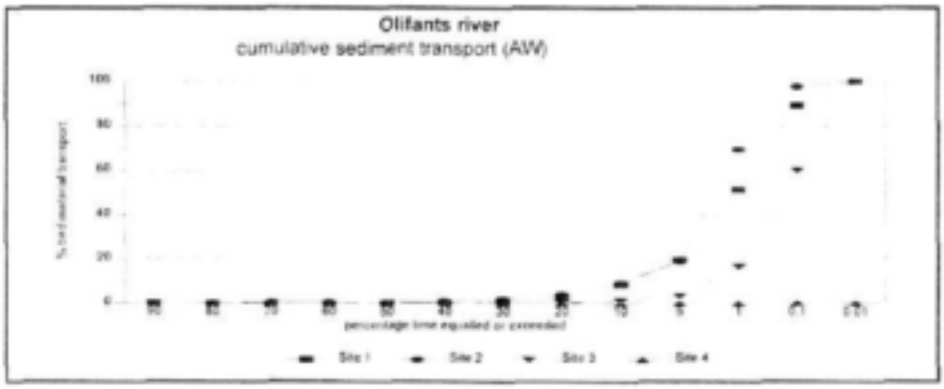

Figure 10.24: *Cumulative sediment transport for the Ackers & White equation for the Olifants River.*

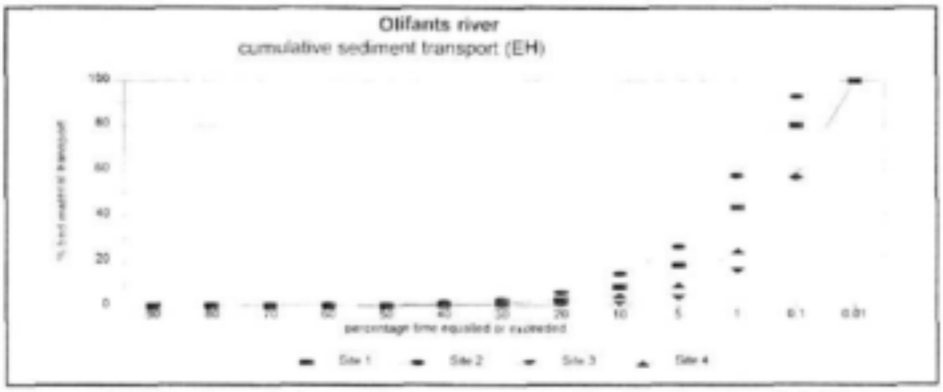

Figure 10.25: *Cumulative sediment transport for the Engelund & Hansen equation for the Olifants River.*

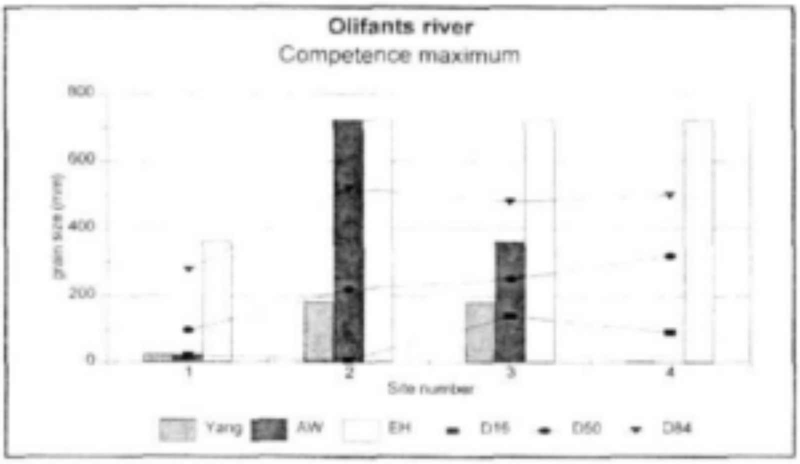

Figure 10.26: *Maximum competence for the Olifants River.*

The highest modelled flows generated for the Olifants River are not sufficient to inundate the upper two terraces. If flows of sufficient magnitude were able to inundate these terraces, however, the shear stresses and unit stream power generated would be sufficient to mobilise the entire bed. For example, the unit stream power generated at the terrace 3 inundation stage at Site 3 is calculted as 2683 Wm^{-2}. Similar, large values are generated at terrace 2 and 3 (2260 Wm^{-2} and 2018 Wm^{-2} respectively). Unfortunately, no historical flood data are available for the Olifants system, and hence it remains untested whether these terraces are inundated by high magnitude low frequency events.

10.3.5 Sediment-maintenance flushing flows

The same methods that were used to determine the sediment-maintenance flushing flows for the Mkomazi were applied to the Olifants River. Table 10.17 presents a summary of the results. It can be seen that at all sites, except Site 4 (Ackers & White equation), the Milhous β value predicts surface flushing and depth flushing at higher discharges than the equivalent transport equations for sand. The internal consistency of Mihous' approach was also tested. It was assumed that the β value of 0.021 (surface flushing of fines and sand) and 0.035 (depth flushing) would be equivalent to the discharge at which the d_{maxbl} and d_{50bl} (see Equations 8.25 and 8.26) would be 1.0 mm (sand) and 2.0 mm (gravel). Table 10.17 illustrates this relationship. It can be seen that in all cases, the β value predicts surface flushing and depth flushing at lower flow values than the equivalent flow at which motion begins for the 1.0 mm and 2.0 mm grain sizes.

Table 10.17 also shows the relationship between the maximum competence predicted from the Milhous equations (d_{maxbl} and d_{max50}) and the maximum competence calculated from the Yang, Ackers & White and Engelund & Hansen equations. It can be seen that for sites 1, 2 and 3, the d_{maxbl} predicts considerably lower competence than the three transport equations. However, at Site 4 the Milhous equations predict a higher competence maximum than the three transport equations. The comparison of the competence of the D_{50} and the maximum competence calculated from the three transport equations (Table 10.17) indicate the d_{max50} in most cases predicts a lower competence than the three transport equations. It appears that the d_{max50} is closer in value to the maximum competence predicted by the transport equations.

Table 10.17: *Comparison of the Milhous approach to the transport equations approach for the Olifants River.*

Site	β			β		d_{maxbl}			d_{max50}		
	^{1}Y	^{1}AW	^{1}EH	$^{1}d_{maxbl}$	$^{1}d_{50bl}$	^{2}Y	^{2}AW	^{2}EH	^{2}Y	^{2}AW	^{2}EH
1	H	H	H	L	L	L	L	L	L	L	L
2	H	H	H	L	L	L	L	L	L	L	L
3	H	H	H	L	L	L	L	L	L	L	L
4	H	L	H	L	L	H	H	L	L	H	L

1 L = β predicts surface flushing and depth flushing at lower flows than the equivalent for the transport equations, where Y is Yang, AW is Ackers & White and EH is Engelund & Hansen
H = β predicts surface flushing and depth flushing at higher flows than the equivalent for the transport equations, where Y is Yang, AW is Ackers & White and EH is Engelund & Hansen
2 L = d_{maxbl} and d_{max50} predict lower maximum competence than the equivalent for the transport equations
H = d_{maxbl} and d_{max50} predict higher maximum competence than the equivalent for the transport equations

Figure 10.27 provides the RBS values obtained for the Olifants River. The RBS values indicate that the Olifants River has an extremely stable bed. The RBS value predicts that sites 1 and 4 become unstable at the 99.99th percentile flow (i.e. the flow that is equalled or exceeded 0.01% of the time). At sites 2 and 3, however, the flow regime does not have the capacity to create the conditions necessary for channel instability, i.e. the RBS values predict that even under the highest flow conditions the D_{84} will not be mobilised.

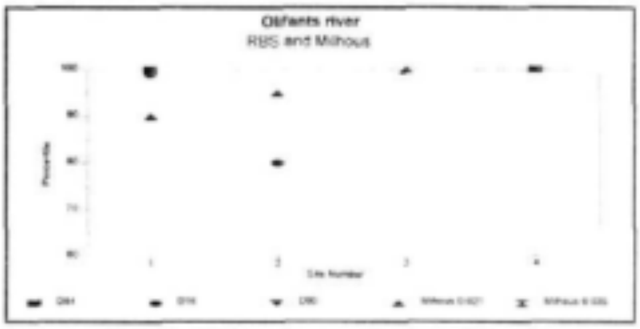

Figure 10.27: *RBS values calculated for the Olifants River. The β value calculated for the 0.021 (surface) and 0.035 (depth) flushing flows. These values represent the flow class at which the β value is 0.021 and 0.035 respectively.*

If the values for the RBS are compared with the effective and dominant discharges, the values show a distinct difference. The effective and dominant discharges are well below the RBS values. It has already been mentioned that the transport equations generally estimated a poor relationship between the β value and the sand and gravel competent flows.

These results support those from the three transport equations, these being that the Olifants River has an immobile bed and that there is unlikely to be any channel instability (based on the RBS calculations). However, the β index predicts that higher discharges are necessary to transport sand and gravel than the three transport equations and thus predict lower competence for the given flow classes than the three transport equations. It has been noted earlier, however, that these two sediment-maintenance flushing flow methods should be used with caution.

10.3.5.1 Effective discharge for sand, gravel and cobble

The effective discharge for sand, gravel and cobble was calculated in the same manner as for the Mkomazi and Mhlathuze Rivers. Figure 10.28 demonstrates that the percentage bed material transport for the effective discharge flow class is lower for sand, followed by gravel and cobble. Furthermore, it is only at Site 2 and 3 that the effective discharge transports cobble. The results indicate different effective discharges and different effective discharge flow classes for cobble, compared with the sand and gravel results, which are the same. (Table 10.18). Sand transport occurs over a wider range of flow classes than does gravel and cobble and the effective discharge for the sand class is generally the lowest.

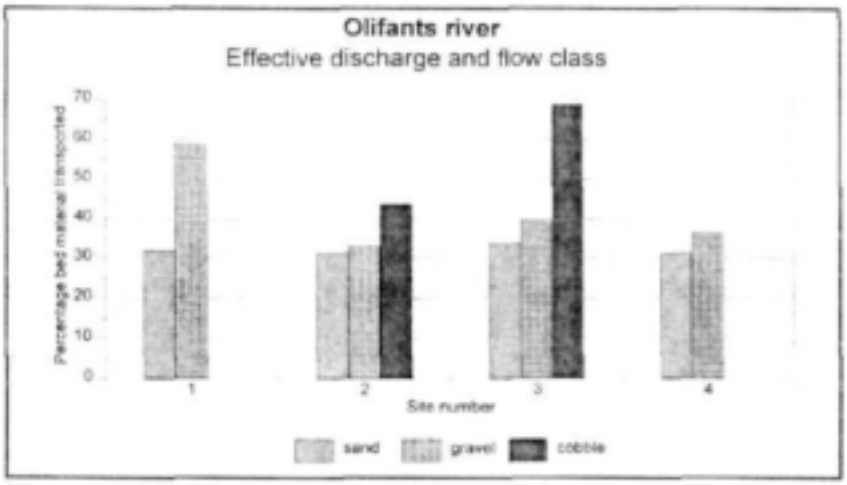

Figure 10.28: *The percentage bed material transported by the effective discharge for the Olifants River for sand, gravel and cobble for the Yang equation.*

Table 10.18: *Effective discharge flow classes for the Olifants River for sand, gravel and cobble for the Yang equation.*

Site	Sand (flow class)	Gravel (flow class)	Cobble (flow class)
1	5-1%	5-1%	-
2	5-1%	5-1%	5-1%
3	1-0.1%	1-0.1%	0.1-0.01%
4	1-0.1%	1-0.1%	-

10.3.6 Synthesis

The Olifants River is strongly controlled by bed rock, local hydraulic conditions and coarse bed material. The effective discharges are in the 5-0.01% range on the 1-day daily flow duration curve. It has been shown that the coarse fraction of the bed material (i.e. D_{84} and greater) remains immobile, even under the highest flow class, despite the high shear stress and unit stream power generated at a number of the sites. The material that is transported is mainly fine gravel. This results in the calculation of low effective discharges, as the flow in the lower flow classes is competent to transport significant quantities of the fine bed material, but is unable to mobilise the entire bed. It has also been demonstrated that should the flow reach the stage of the upper two terraces, sufficient stream power would be generated to transport the entire bed. Thus it could be argued that, like the Mkomazi, the Olifants has developed a channel architecture that is related to a highly variable, bi-polar type flood regime. It may therefore be erroneous to think of one 'effective discharge' for the Olifants. Instead a set of effective discharges may be of significance.

10.3.7 Implications for Instream Flow Requirements (IFRs)

The results generated from the analysis of the Olifants River can be used to make recommendations for IFRs for the Olifants system. It is argued that the Olifants system is strongly controlled by bed rock and that little channel change is likely to occur. It has also been pointed out that the coarse bed material is mobile only under the highest flow conditions. At some sites, the armour-layer remains immobile even under the highest flows generated by the predicted virgin flow conditions. This situation is almost certain to exist under the present-day regulated flow environment. This is despite the fact that all of the sites on the Olifants generate high unit stream power. The high unit stream power allows for transport of the finer portion of the bed material at lower flow classes, and hence the effective discharges are lower than those calculated for the Mhlathuze River. It can be argued that the regulated flow environment has had little impact on the channel morphology, and the channel maintenance flow is probably the 1 in 20 year flood which is able to mobilise the entire bed. The objectives of the IFR are therefore different to those stated for the Mhlathuze. The following flow objectives might be set:

- to periodically remove fine sediment from the gravel and cobble substrate;
- to periodically move gravel through the coarse cobble-bed; and
- to ensure that large flood events (1 in 20 years) are allowed to move through the system to ensure that the subsurface material is turned over and thereby maintain a loose bed structure.

It is important to point out that in a system such as the Olifants, where boundary resistance to flow deformation is strong, morphological features such as the estimated bankfull discharge should be used with caution in setting IFRs. In these systems the estimated bankfull discharge is not necessarily the same as the effective discharge or the dominant discharge. Given this scenario, it is probably wise to recommend two sets of effective discharge: first, an effective discharge that achieves the first two objectives outlined above; and second, a 'reset' discharge, a large flood event that serves as the channel forming discharge.

10.4 Summary and conclusions

The results presented have indicated that the approach that has been adopted in determining the magnitude and frequency of channel forming discharge and sediment-maintenance flushing flows can be applied in a meaningful way to regulated rivers. This section will consider the results in the light of the research questions posed at the beginning of the chapter.

Do the results obtained from the two regulated systems add to the understanding gained from the Mkomazi?

It is argued that the channel morphology and bed material transport in the Mhlathuze River have been considerably altered by the regulated flow environment imposed by the Goedertrouw Dam. This has resulted in channel narrowing and deepening immediately below the dam, and channel aggradation downstream of major sediment inputs from tributaries. The Olifants River on the other hand shows a high degree of resilience to change, probably due to the strong bed rock control of the channel boundary and the coarse heterogenous bed. Indeed little change is likely to occur other than possible further channel armouring or aggradation. Aggradation is unlikely given the high unit stream power generated in the Olifants system even under low flow conditions. It is probable that the Olifants system is supply-limited and that the coarse bed material is a reflection of this state.

What is the impact of flow regulation on the relationships, and are the observed morphological conditions related to virgin flow conditions or to the regulated present-day conditions?

It has been demonstrated that for the Mhlathuze, the present observed morphological relations are related to present-day flow conditions. It has also been suggested that the Olifants system is a more resilient system, and that the observed morphological conditions are likely to be more permanent given the strong bed rock control in the channel perimeter.

What lessons can be learnt for Instream Flow Requirements (IFRs)?

It is important to realise that fluvial systems may respond in different ways 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. Channel boundary conditions are of great significance in determining the impact of flow regulation. This must be taken into account when setting IFRs.

Given the results obtained, what flows should be recommended and why?

It has been suggested that, for the Mhlathuze, different flows should be recommended for the site immediately below the 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 was recommended that would ensure that fine material, sand and gravel would be flushed through the system thereby preventing fine material entering the interstitial zone. Second, it was recommended 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.

Section E: Short-term response: discharge related changes to hydraulic habitat

This research was based on field work and data analysis by Dr Roy Wadeson.

Chapter 11: The development of mapping techniques for the assessment of hydraulic biotopes

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11.1 Introduction

According to the new National Water Act (Act 36 of 1998), resource quality objectives must be set with respect to the following aspects of the water resource:

- the quantity, pattern, timing, water level and assurance of instream flow;
- the character and condition of the instream and riparian habitat;
- the water quality and
- the characteristics, condition and distribution of the aquatic biota.

With the exception of water quality, maintenance of instream and riparian habitat can be considered fundamental to the above objectives. From an ecological perspective, recommendations about the quantity, pattern, timing, water level and assurance of instream flow are based on criteria considered necessary to maintain adequate habitat conditions to safeguard the characteristics, condition and distribution of the aquatic biota.

Two important national initiatives are closely related to the protection of resource quality as defined by the National Water Act. One is the need to determine the ecological reserve for all significant water courses and the other is the River Health Programme, designed to establish and implement a national monitoring system. Assessment of aquatic habitat, and its relationship to the quantity, pattern, timing, water level and assurance of instream flow, has therefore become a priority.

International concern about the impact of dam construction and flow regulation on the ecology of regulated streams has prompted ecologists to quantify the flow patterns required for the survival of aquatic species and to build these flows into the instream flow requirements for regulated rivers (Gore & King, 1989; King & Louw, 1998). The relationship between discharge, flow characteristics and habitat availability provides the conceptual basis of most instream flow assessments. In South Africa these environmental flows form the basis of the ecological reserve as defined above. The aim of many overseas instream flow studies has been to assess the flow requirements of target species and to recommend flows needed to assure maintenance of the population (Stalnaker *et al.*, 1994). In South Africa, emphasis is put on the community rather than target species, so that the focus has been on the maintenance of overall habitat rather than on species management *per se*. Newson & Newson (2000, p.199) express a similar concern for British rivers: "Nevertheless, it is a valid working principle in ecology that diversity of habitat, if it can be described, paves the way for predictions of the potential diversity of biota." As more information becomes available on the habitat requirements of different species, however, it becomes easier to identify critical habitats in the different river systems (Weeks *et al.*, 1996 (vol1)).

Habitat is comprised of a number of components. Instream habitat, for example, 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 habitat also changes with discharge; wetted perimeter, depth and velocity all increase with discharge so that both the total available habitat and the quality of that habitat (the hydraulic biotopes) change. The nature of this relationship depends on the geomorphology characteristics of the channel at any given site, as has been demonstrated by Rowntree & Wadeson (1996), Padmore (1998) and Newson & Newson (2000).

Table 11.1: *Definitions of flow types (after Rowntree and Wadeson, 1999).*

Flow types	Definition
No flow	No water movement
Barely perceptible flow	Smooth surface, flow only perceptible through the movement of suspended matter
Smooth uniform flow boundary	The water surface remains smooth; streaming flow takes place throughout the water profile; turbulence can be seen as the upward movement of fine suspended particles
Rippled or surging flow	The water surface has regular disturbances which form low transverse ripples across the direction of flow; the degree of disturbance may vary from faint ripples to strong ripples
Undular standing waves	Standing waves form at the surface but there is no broken water
Broken standing waves	Standing waves present which break at the crest (white water)
Free falling	Water falls vertically without obstruction.

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. Hydraulic biotope mapping is suggested as a means of achieving this.

Table 11.2: *Definitions of hydraulic biotopes in terms of flow types. Further subdivision can be made in terms of substrate (modified form Rowntree and Wadeson, 1999).*

Hydraulic Biotopes	**Definition**
Trickle:	Very small volumes of flow trickling through cobbles or over bedrock. Trickles are characterised by ***barely perceptible flow***.
Backwater:	A backwater is morphologically defined as an area alongside but physically separated from the channel, yet connected to it at its downstream end or as slack water or dead zone: an area of ***no perceptible flow*** which is hydraulically detached from the main flow but is within the main channel. It may occur over any substrate.
Pool:	A pool is in direct hydraulic contact with upstream and downstream water but has ***no perceptible flow***.
Glide:	A glide exhibits ***smooth uniform flow***. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Glides exhibit no significant convergence or divergence.
Run:	A run can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. A run may be characterised by a ***rippled or surging flow*** type.
Riffle:	Riffles occur over potentially mobile, coarse alluvial substrates from gravel to cobble. A riffle may be characterised as having ***undular standing waves*** (or ***breaking standing waves***).
Rapid:	Rapids occur over a fixed substrate such as boulder or bedrock. Rapids are characterised by having ***breaking standing waves, chutes*** or limited ***free falling flow***.

Depth and velocity are widely seen by ecologists as the two flow variables which best describe aquatic habitat (Wadeson, 1994). While point depth measurements can be taken with relative ease using simple and inexpensive equipment, point velocity readings take considerably longer and require sophisticated and expensive current meters. An alternative method to classifying hydraulic habitat is to use the flow type in combination with the underlying substrate. The flow type (Table 11. 1) describes the surface appearance of the flow (smooth, rippled, broken standing waves etc.) and has been shown by Wadeson & Rowntree (1998) to be an acceptable surrogate for the flow hydraulics as characterised by such indices as the Froude number, Reynolds number or shear velocity, all of which are derived from velocity and depth measurements. Hydraulic biotopes can thus be defined in terms of the flow type, flow depth and substrate (Table 11.2). As the flow type is a visual manifestation of the flow hydraulics, it is a variable that is relatively straightforward to map. Hydraulic biotopes, however, tend to be distributed in a complex of small patches, especially in morphological units such as riffles and rapids, the area of focus in most reserve workshops. This makes mapping a time consuming process if conventional methods of surveying are used (King & Schael, 2001).

Wadeson (1996) used point sampling in order to evaluate the hydraulic characteristics of hydraulic biotopes. This information has been used to determine discharge related changes in the proportions of hydraulic biotopes present at any given discharge (Rowntree & Wadeson, 1996). The data displayed in Figure 11.1 shows how this relationship varies for three typical morphological units in the Buffalo River and indicates the potential application of this approach to reserve assessments. The next step is to move from point sampling to mapping the changes in areal extent and position of the various hydraulic biotopes within morphological units. As noted above, the time consuming nature of conventional mapping techniques to date has hindered the inclusion of habitat mapping as a standard component of reserve assessments.

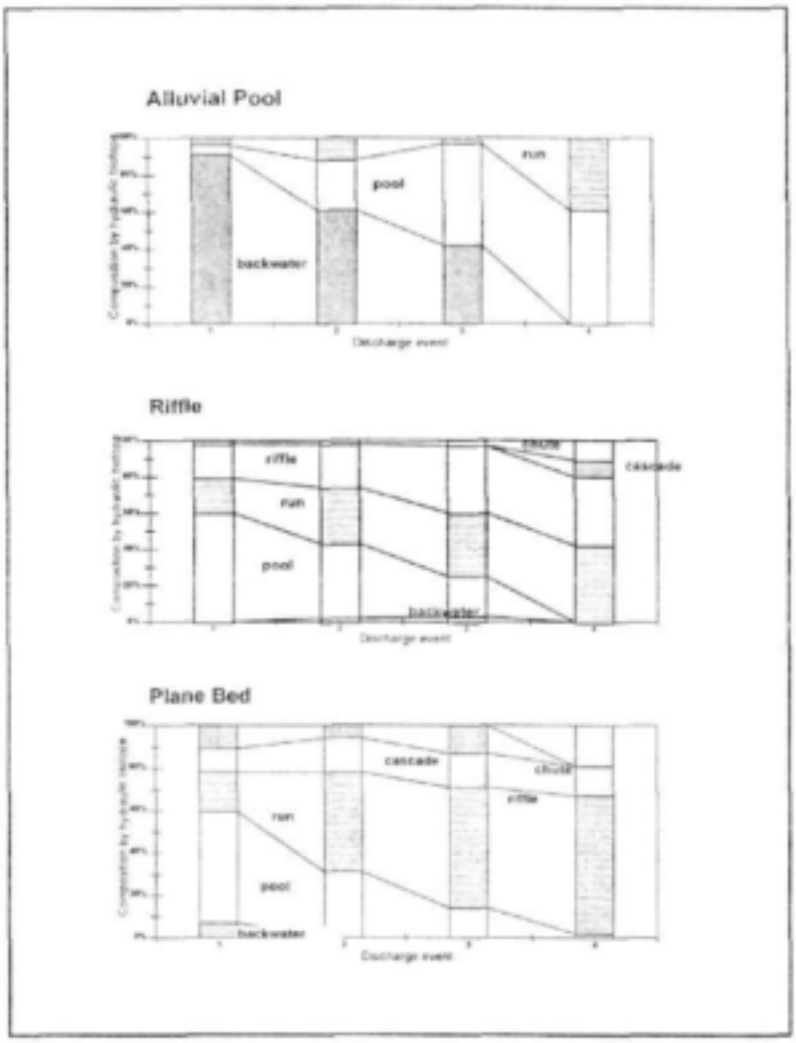


Figure 11.1: *Discharge related changes in hydraulic biotope composition for three morphological units in the Buffalo River, Eastern Cape. Percentage exceedence for discharge events as follows: 1-92%, 2-73%, 3-50%, 4-30%. Modified from Rowntree and Wadeson (1996).*

Two approaches to the habitat mapping problem are considered in this report. The first utilises digital photography which is then manipulated using Geographical Information System software (GIS). The second requires a detailed survey of the area of interest. This data set is also manipulated using GIS software to create a three dimensional digital terrain model (DTM).

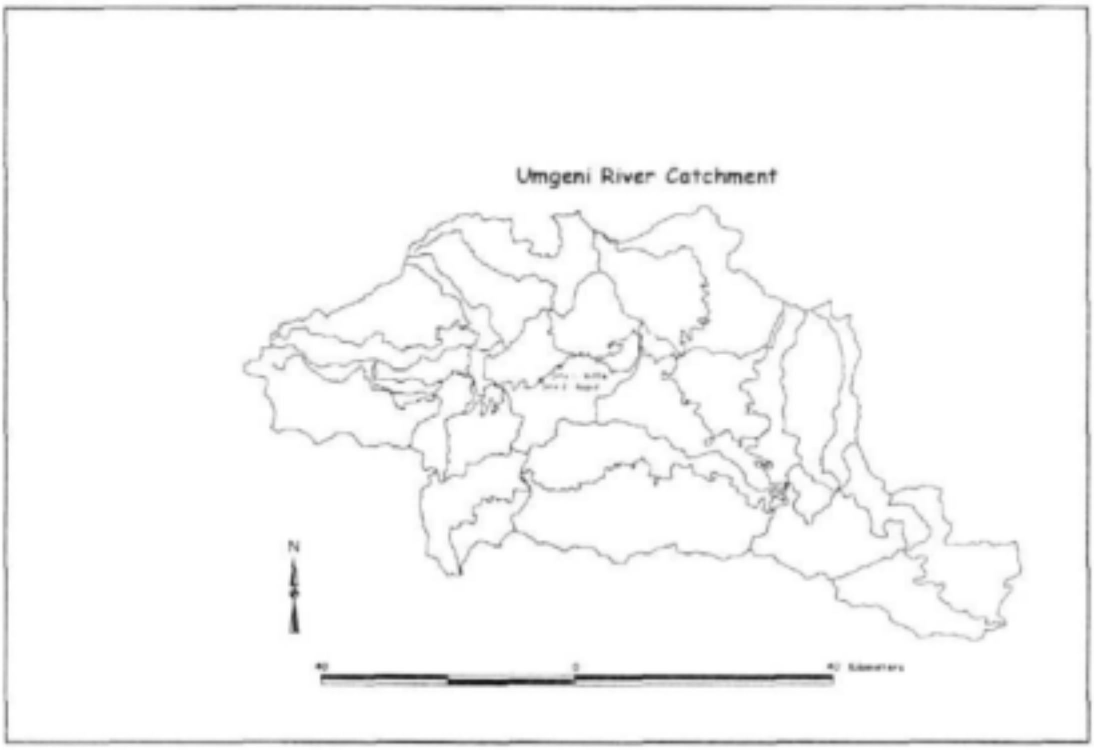


Figure 11.2: *Overview of the Umgeni River Catchment showing research sites.*

11.2 Digital Photography

11.2.1 The Research Area and Study Sites

The Umgeni River is a relatively steep coastal river system, fairly typical of those draining the eastern escarpment of South Africa. From its headwaters in the Drakensberg Mountains at an altitude of more than 3000 metres it flows in a south-easterly direction for 160 km before discharging into the Indian Ocean just north of the city of Durban. The location of research sites used to develop a hydraulic biotope mapping technique are shown in Figure 11.2. The research reach is situated between Midmar Dam and Albert Falls. Although the river is naturally perennial at this site, flow is now dependent on dam releases. The research reach is situated downstream of a bedrock gorge with a geomorphology characteristic of a rejuvenated foothill type zone, that is, a steepened section within the middle reaches of the river caused by uplift. Bed material is dominated by boulder, cobble and gravel with a pool-riffle and pool-rapid morphology. A compound channel is present with a narrow active channel (30 metres width) contained within a macro-channel (80 metres width).

The main requirements for this study were that the study reach was easily accessible, could be related to a stage plate nearby for discharge readings and that a diversity of channel morphology was present. The study sites represent different channel types and different channel morphology. Site 1 (Plate 11.1) has a pool-riffle morphology. Riffles are composed of cobble and boulder interspersed with gravel. Pools have beds dominated by similar size material which has been covered by a thin layer of fine material (silt and mud). Substratum is well rounded and relatively lose in the riffle but stable in the pool (channel width approximately 30 metres). Site 2 (Plate 11.2) has a pool-rapid morphology. Rapids are composed of channel spanning deposits of large boulders interspersed with cobbles and gravels. Pools are relatively small and shallow. Particle shape is rounded but well-packed giving rise to a stable bed (channel width approximately 20 metres).

11.2.2 Methods

11.2.2.1 Data Collection

The aim of this study was to develop and test a technique for the mapping of hydraulic biotopes within different morphological units over a range of discharges. The two sites described above provide a range of different morphological units: riffle and pool at Site 1 and rapid and pool at Site 2. For the purpose of this study the units that represent the most diverse and complex array of hydraulic biotopes were selected for mapping, that is the hydraulic controls at each site (riffle and rapid). Unfortunately, due to low summer rainfall, dam levels remained low during the field work period and no high flows were observed in the river. The results therefore relate only to one discharge, 0.76 m^3s^{-1}. Discharge data were obtained from an upstream gauging weir at Midmar Dam wall.

At each site an elevated digital photograph was taken of the riffle and rapid. Various techniques were examined to best ensure that photographs could be replicated for different flow conditions. The most satisfactory technique used to date has been the use of a 1.7m aluminum step ladder. The step ladder is positioned at a known location (using a GPS and marked features) and photographs taken using a hand held Kodak DC 210 camera. The height of the photographs above the water level were approximately 6m for Site 1 and 3m for Site 2. The lack of standardisation for height *between* different sites is not a problem. It is important however to standardise height for repeat photographs at a site. The photographs cover an area of at least 100m^2. In the examples given here, the entire channel width was photographed but not the entire length of the morphological unit (approximately 35%).

Early attempts used a 3.5 m fibreglass pole with a tripod attachment and the self-timer option on the camera. This was largely unsuccessful because of the inability to closely replicate photographs when one cannot see reference points through the view finder.

A photograph taken at each site was downloaded to a notebook computer and a black and white print was produced with a portable printer. This image provided the template for the mapping of hydraulic biotopes in the field. The identification and demarcation of hydraulic biotope boundaries was carried out using the concepts and ideas which are formalised in Tables 11.1 and 11.2. The hydraulic biotype for each mapped unit was classified according to the surface flow type and the underlying substrate. A minimum of three random depth measurements were then taken within each different biotope and these values were also recorded on the template.

Plate 11.1: *Umgeni River Site 1 - Riffle*

Plate 11.2: *Umgeni River Site 2 - Rapid*

In order to transfer qualitative hand-sketched boundaries on the template into quantitative areas of measurement, the information was digitized and analysed using the software package ArcView. The original digital photograph was used as a background template for digitizing.

The process of transferring hydraulic biotope boundaries onto a hard copy template is relatively simple if one is familiar with the different substrate and flow type classes as outlined in Tables 11.1 and 11.2. The time taken at each site is dependent on the complexity of the area, accessibility, flow conditions etc. Site 1, which is a fairly complex site, took approximately 1 - 2 hours to map in the field, this time includes the recording of flow depth in each biotope unit. The production of GIS covers in the laboratory takes somewhat longer and again is determined by the complexity of the site and the familiarity with the software (approximately 3 - 4 hours).

Equipment needed to carry out the hydraulic biotope mapping procedure as discussed in this report include:

Digital Camera
Notebook Computer
Portable Printer
Depth Measuring Stick
Aluminum Step Ladder
ArcView software

11.2.2.1 Data analysis

For each site, maps were prepared showing the distribution of hydraulic biotopes at the given discharge (Figures 11.3 and 11.4). The maps give a good visual impression of both the diversity of hydraulic biotopes and their distribution within a morphological unit. The actual area of the hydraulic biotopes was calculated in ArcView. This information was exported to a spread sheet for further analysis.

Habitat extent was further described by means of simple histograms (Figure 11.5). Each histogram demonstrates both the diversity and aerial extent of hydraulic biotopes for a given discharge. To give an indication of depth within each hydraulic biotope at a given discharge, the modal value of the measured depths was plotted as simple histograms (Figure 11.6).

11.2.3 Results

The map of hydraulic biotope distribution within the riffle is shown in Figure 11.3. This map clearly demonstrates that at this site, with a flow of 0.76 m^3s^{-1}, there was a high degree of habitat diversity. All seven of the hydraulic biotopes were present. A visual interpretation of the map shows that there was a limited area out of the water and that the habitats were patchy but well-connected. The map of hydraulic biotope distribution within the rapid is shown in Figure 11.4. This map clearly demonstrates that there were fewer habitats available in the rapid (five instead of seven). The map also shows the presence of more areas out of the flow. The habitats still appeared to be well-connected at this flow.

The percentage aerial extent of different habitats is shown in Figure 11.5. It is interesting to note that at this discharge the riffle was dominated by trickle flow (37 %) and that this, together with riffle flow (22 %), run (15 %) and pool (15 %), made up 89 % of the available habitat. Only 3 % of the available 'active channel' was dry. The rapid morphology showed a somewhat different picture, with rapid (34 %), run (24 %), and trickle (21%), making up 79 % of the available habitat. A further 18 % of the 'active channel' was dry at this discharge.

Depth of habitat plays an important role for some ecological elements in the river. Fish are particularly reliant on depth for feeding, migration and so on. Figure 11.6 shows changes in the modal depth of different hydraulic biotopes in two separate morphological units. The graph shows that, at a flow of 0.76 m^3s^{-1}, considerably more depth is available in the dominant hydraulic biotopes of the rapid than the riffle.

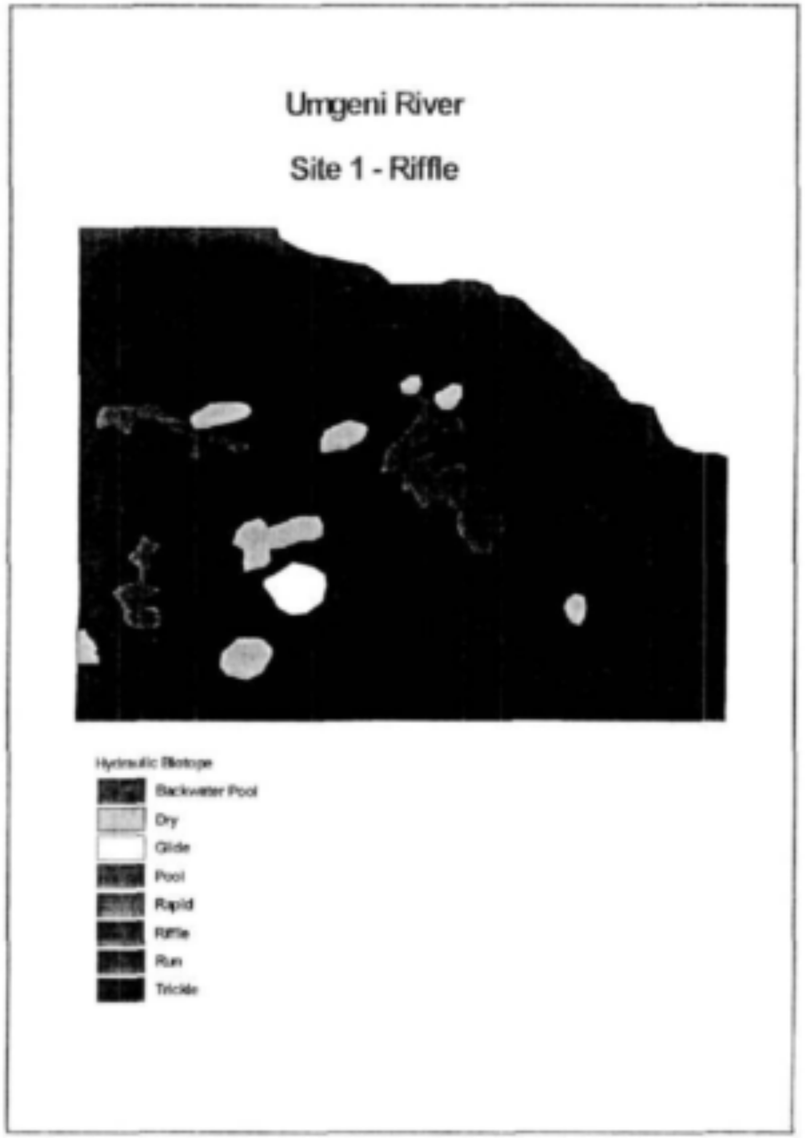


Figure 11.3: Hydraulic biotope distribution - Site 1: Riffle

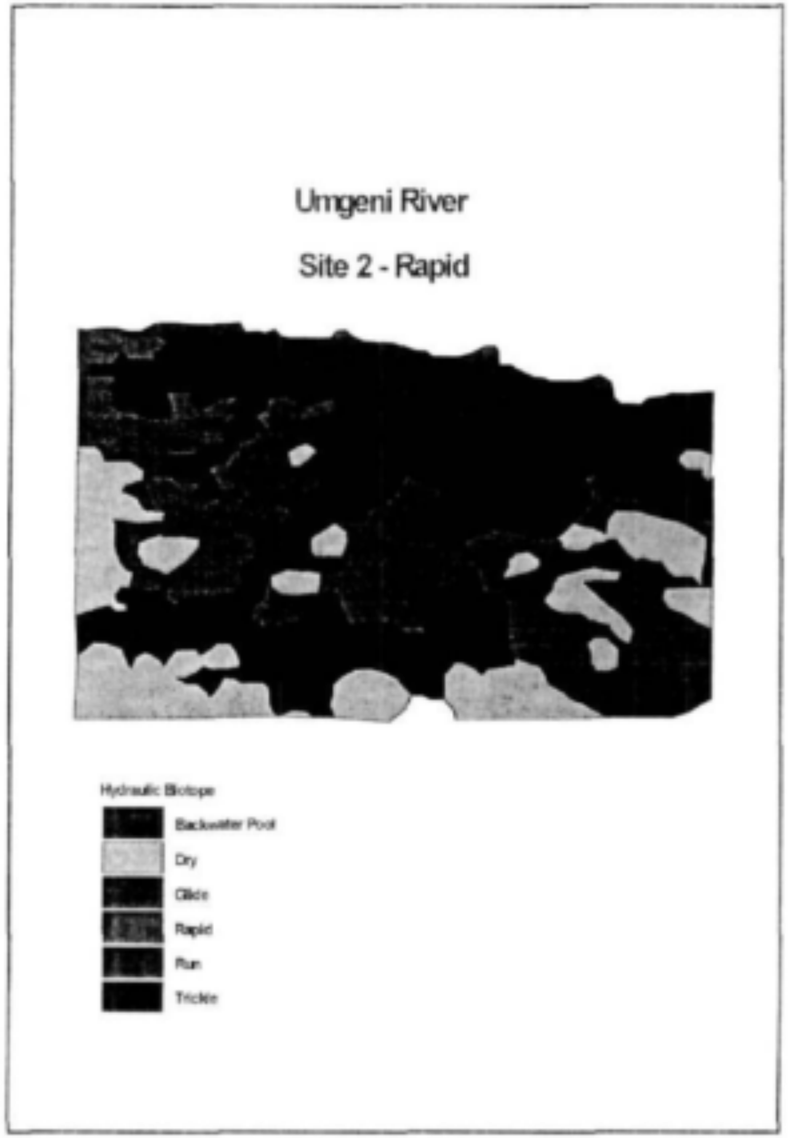


Figure 11.4: *Hydraulic biotope distribution - Site 2: Rapid*

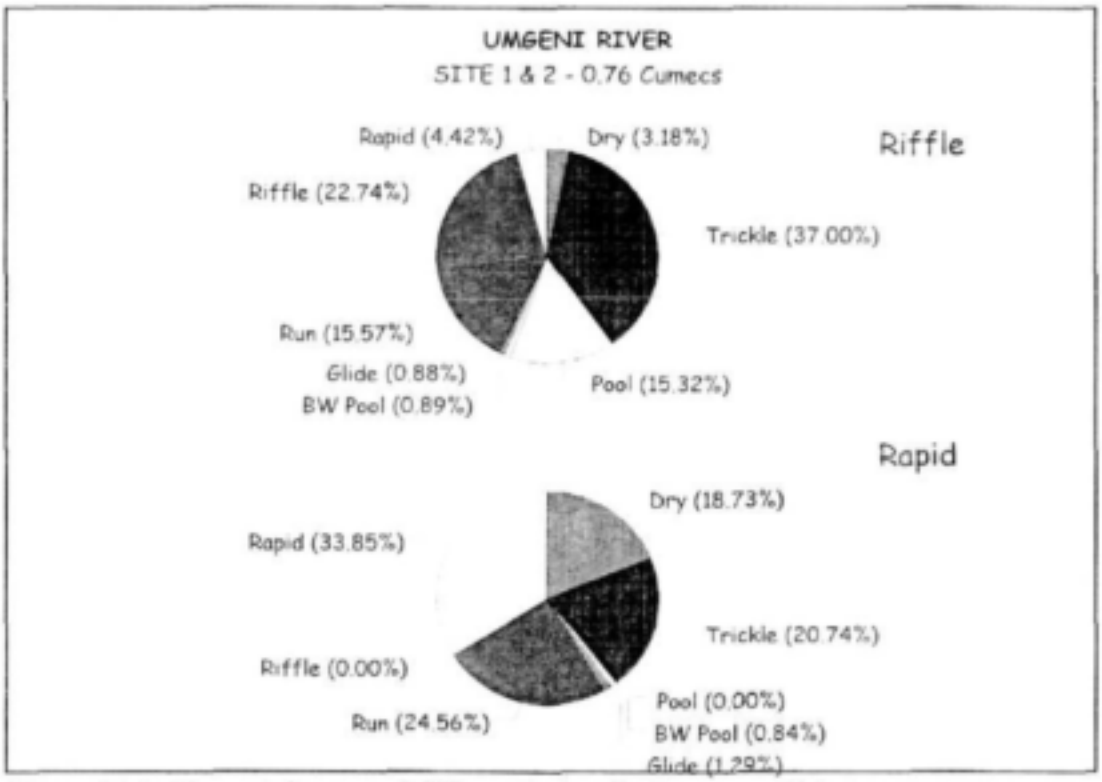


Figure 11.5: *The aerial extent of different hydraulic biotopes within two separate morphological units.*

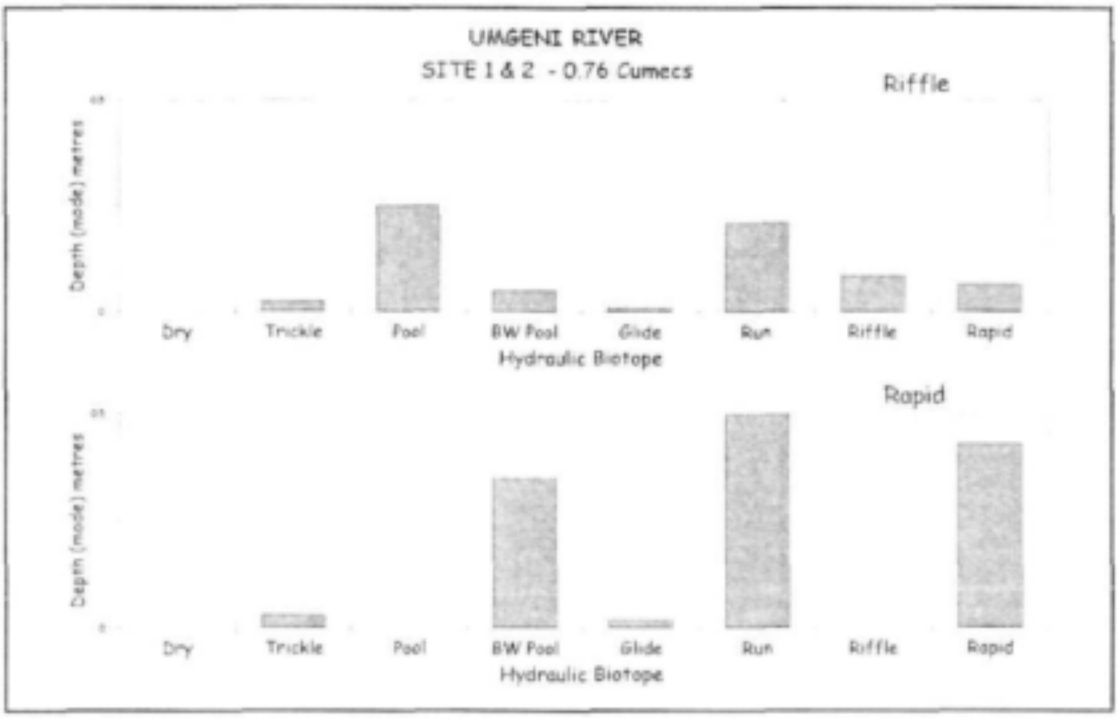


Figure 11.6: *Modal depth of different hydraulic biotopes within a riffle and a rapid.*

11.2.4 Discussion

A habitat mapping technique utilising digital photography provides a relatively quick and easy method for the quantitative assessment of changes in hydraulic biotope condition. The results presented here show the pattern of hydraulic biotopes at two sites for one discharge only. Clear differences can be seen between the two sites. If the method is to be linked to flow requirements, it clearly needs to be repeated for a range of discharges. Lack of flow variability over the study period precluded any comparative measurements being undertaken. Nonetheless it is concluded that the method will provide a useful supplement to the procedures presently used in assessing the ecological reserve.

In response to changes in the flow regime and catchment condition there are likely to be concomitant changes in the physical makeup of the river. The River Health Programme has been initiated to monitor these changes. The mapping technique described here may provide a useful tool in this programme for the assessment of habitat change over a long period of time. In this case it is envisaged that measurements could be linked to a particular flow level or flow duration, probably those characteristic of wet- and dry-season base levels.

Assuming that the researcher has access to the equipment listed above, a hydraulic biotope map for any site can be produced in four to six hours. Approximately two of these hours are required in the field; the balance in the laboratory. There is a limited amount of training required to carry out the procedure. The field worker needs to know how to use the field equipment and needs to be familiar with the information given in Tables 11.1 and 11.2. A certain degree of competency is required in the use of the software package Arc View to create the finished maps, but again this is a relatively simple exercise.

Some limitations which need to be recognised are as follows:

- The procedure requires expensive technology (digital camera, notebook computer etc).
- Some specialised training is required.
- Only a limited area can be mapped at any one time (dependent on the focal range of the camera and the height of the photograph above the site).
- The biggest problem encountered is standardisation for repeat photographs, i.e position of photographer, angle, height, scale etc.
- The technique is not suitable for high flow mapping as one cannot enter the channel for classification and field verification.
- For best results the photograph should be taken from at least 6m above the area of interest and in the middle of the channel. Using the present technique, this is not possible.
- Clearly recognisable landmarks (above the flood line) must be visible within each photograph so that repeat photographs can be taken for different discharges.
- The validity of the procedure needs to be tested for a series of different discharges, unfortunately this was not possible in this study.
- It is a two dimensional technique and would be strengthened if it was coupled to a three dimensional procedure such as digital terrain modeling (DTM), as described in the following section.

11.3 Digital Terrain Modelling (DTM)

11.3.1 Introduction

As pointed out above, channel dimensions for any site of interest (IFR sites) have been obtained to date by a series of two dimensional cross-sectional surveys. These surveys have been used to determine the channel hydraulics for a site, that is the relationship between depth, discharge, velocity and wetted perimeter. The cross-sectional surveys (with the associated hydraulics) are used by ecologists in an attempt to determine the ecological flow requirements of selected species.

Several problems have been recognised in the use of this two dimensional technique. Site selection for a survey section is critical; it must be representative, at a hydraulic control and preferably through the lowest point on that hydraulic control. Scientists involved very often have no idea as to the degree of connectivity between the survey site and other sections across the hydraulic control.

The advent of more sophisticated survey equipment (Total Station) has allowed the efficient collection of numerous data points distributed throughout an area of interest. Each point has an attribute of latitude, longitude and elevation (X, Y and Z coordinates) with respect to a fixed datum. These data points can be imported into a GIS software package (ArcView Spatial) and manipulated using interpolation techniques to produce a continuous three dimensional surface. The major components of physical habitat (excluding water quality) are hydraulics, substrate and aquatic vegetation cover. Hydraulics can be modelled for a single cross section using conventional techniques. The hydraulic characteristics can then be added to the DTM in the form of a water surface for each specified discharge. This water surface has associated variables of wetted perimeter (at a cross-section) and average velocity (at a cross-section).

11.3.2 The Research Area and Study Sites

As part of a consultancy project to determine the potential environmental impact of two dams on the Tugela River, three sites were surveyed to allow the creation of three dimensional topography of the river bed. The data from two sites are presented here to demonstrate the potential application of DTM techniques to habitat modelling.

The Tugela catchment drains an area of 29 039 km^2, rising on the escarpment of the Kwa-Zulu Natal Drakensberg range and flowing approximately 512 km through the eastern slopes until it discharges into the Indian Ocean 80km north of the city of Durban (Figure 11.7). Two sites selected for a habitat assessment include an area on the Bushmans tributary upstream of the town of Weenen, and a site on the main Tugela River at Jamesons drift.

Site 1 on the Bushmans River

Site 1 is fairly representative of the pool/riffle type morphology found in this section of the Bushmans River and incorporates considerable habitat diversity as demonstrated in Plate 11.3. The active channel is confined by low banks which form benches within a deeper macro-channel.

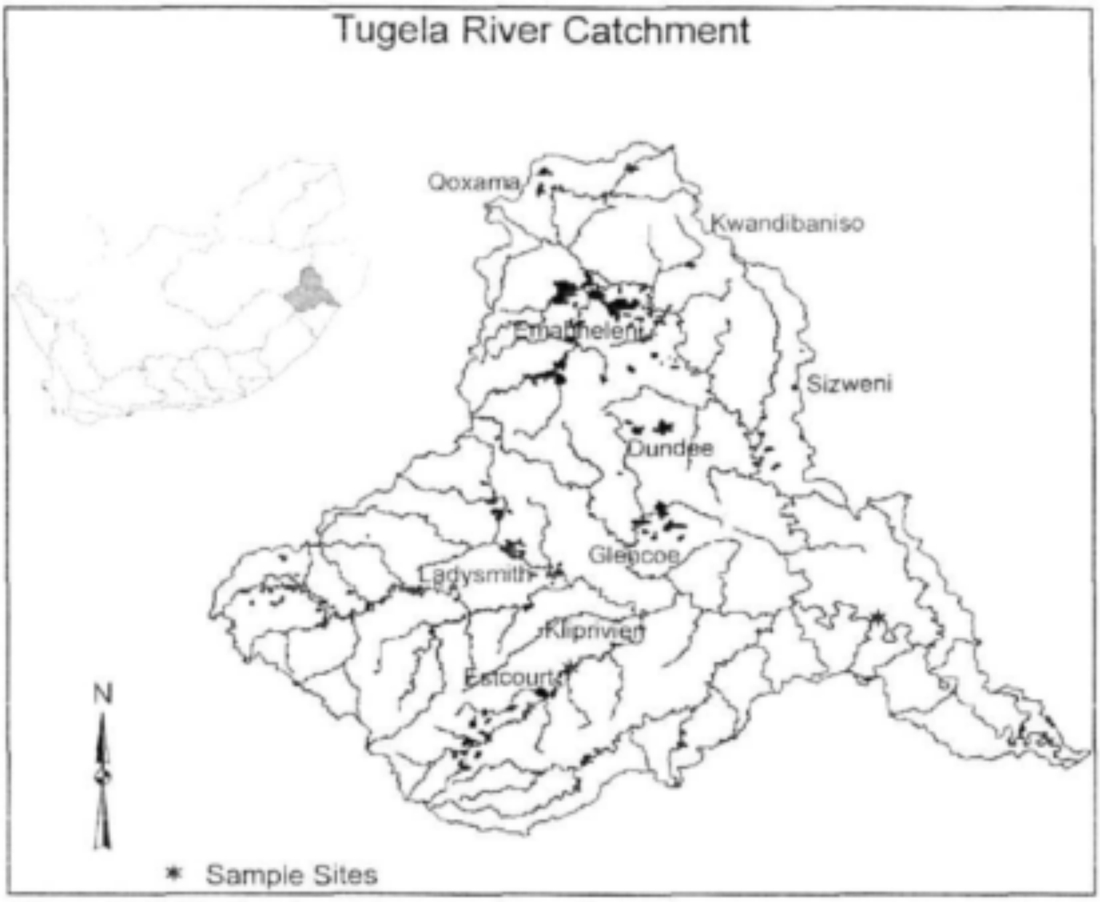


Figure 11.7: *The Tugela catchment and sampling sites.*

Site 2 on the Tugela River (Jamesons Drift)

Site 2 is downstream of all the major tributary inputs in the Tugela catchment. It consists of a well defined channel which is dominated by large cobbles and boulders. The morphology can be described as pool/rapid because the bed material is considered to be immovable under normal low conditions (Plate 11.4). A well defined low flow channel flows between lateral bars of large cobble and boulder.

Plate 11.3: *Site 1 on the Bushmans River.*

Plate 11.4 *Site 2 on the Tugela River, Jamesons Drift.*

11.3.3 Methods

Surveying:

A grid pattern for data collection was used by laying out two parallel lines (ropes) on opposite banks of the river. A third rope was fixed perpendicular to these two lines to mark the first survey transect and guide the prism holder. This rope was moved after the completion of each transect. The number of transects at each site was determined by the physical complexity and time constraints. As a standard procedure, two metre intervals were used between transects and approximately 15 - 20 transects surveyed.

Table 11.3: *Adapted sediment key for field capture.*

SEDIMENT	SIZE (mm)	ADAPTED KEY
Silt	< 0.06	1
Sand	0.06 - 2	
Gravel	2 - 16	2
Coarse Gravel	16 - 64	3
Cobble	64 - 128	
Large Cobble	128 - 256	4
Boulder	512 - 1024	
Large Boulder	> 1024	5
Bedrock	not applicable	

The survey instrument was set up at a fixed point so that all transects could be completed without having to move the instrument. A field worker walked the transect lines across the river carrying a survey prism and a modified sediment key (Table 11.3).

The aim of this survey was to capture as accurately as possible the change in bed topography. The complexity of the river bed in these surveys required approximately 90 points to be captured along each transect. Each point was numbered and a record made of the bed material sediment size and presence or absence of vegetation. The flow type (hydraulic biotype) was also noted on one occasion, at a discharge of 0.9 m^3s^{-1}. These data were later manually captured in a spread sheet and linked to the survey data. An example of the linked data sheet is given in Table 11.4.

Table 11.4: *Example of data sheet for the collection of elevation and sediment data.*

no.	X (m)	Y (m)	Z (m)	substrate	vegetation	habitat
A1	101.32	99.38	99.79	1	yes	riffle
A2	103.01	98.70	99.81	2	yes	cascade
A3	104.07	98.30	99.74	2	yes	cascade
A4	106.36	97.40	99.82	3	no	glide
A5	106.87	97.16	99.99	3	yes	rapid

ArcView GIS:

The GIS programme ArcView, together with spatial analyst and 3D analyst, were used to manipulate the data. Data were imported into ArcView as a text file consisting of rows and columns (x, y, z, substrate and vegetation). Note that elevation data had been corrected for slope by taking the bed slope and then flattening it over the transects. The survey points were converted to a raster data base. These points were interpolated using an IDW (Inverse Distance Weighted) method in ArcView Spatial to create a complete surface of topography and sediment distribution.

11.3.4 Results

Bed Topography

Figure 11.8 illustrates the three dimensional topographical surfaces modelled from point data at Site 1 on the Bushmans River and Site 2 at Jamesons Drift on the Tugela River. Dotted lines illustrate the 8 and 7 transects respectively along which point data were collected.

The topographic maps give a clear picture of the different morphology of the two channels. Whereas Site 1 has a relatively wide, flat bed, Site 2 has a more v-shaped morphology giving rise to a narrow low- flow channel. Extensive lateral bars are present at Site 2, whilst the presence of lateral channels and backwaters separated from the main channel by low islands is apparent for Site 1.

Sediment

Point data of sediment size were used to produce the frequency curves shown in Figure 11.9. The channel material at Site 1 has a fairly heterogenous size distribution, with a significant area of silts and sands and of gravels. Site 2 generally has coarser bed material with much of the bed characterised by coarse gravel and larger, with significant areas of large boulder and bed rock.

Figure 11.10 illustrates the modelled two dimensional maps of sediment distribution at the two sites. The coarser material at Site 2 is again apparent.

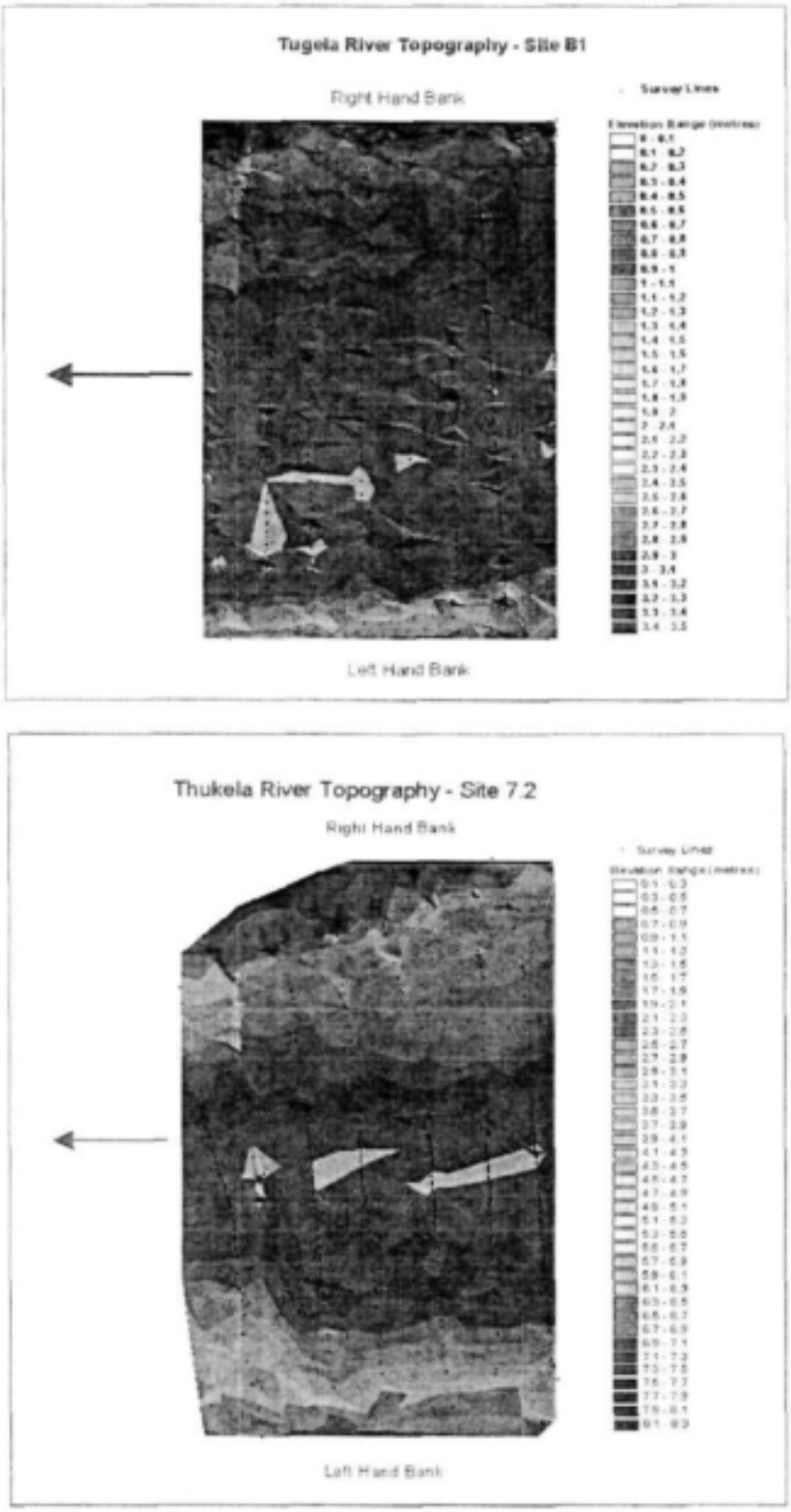


Figure 11.8: *Topographical surface modelled from point data for Site 1, Bushmann's River (Site B1) and Site 2, Jamesons Drift (Site 7.2).*

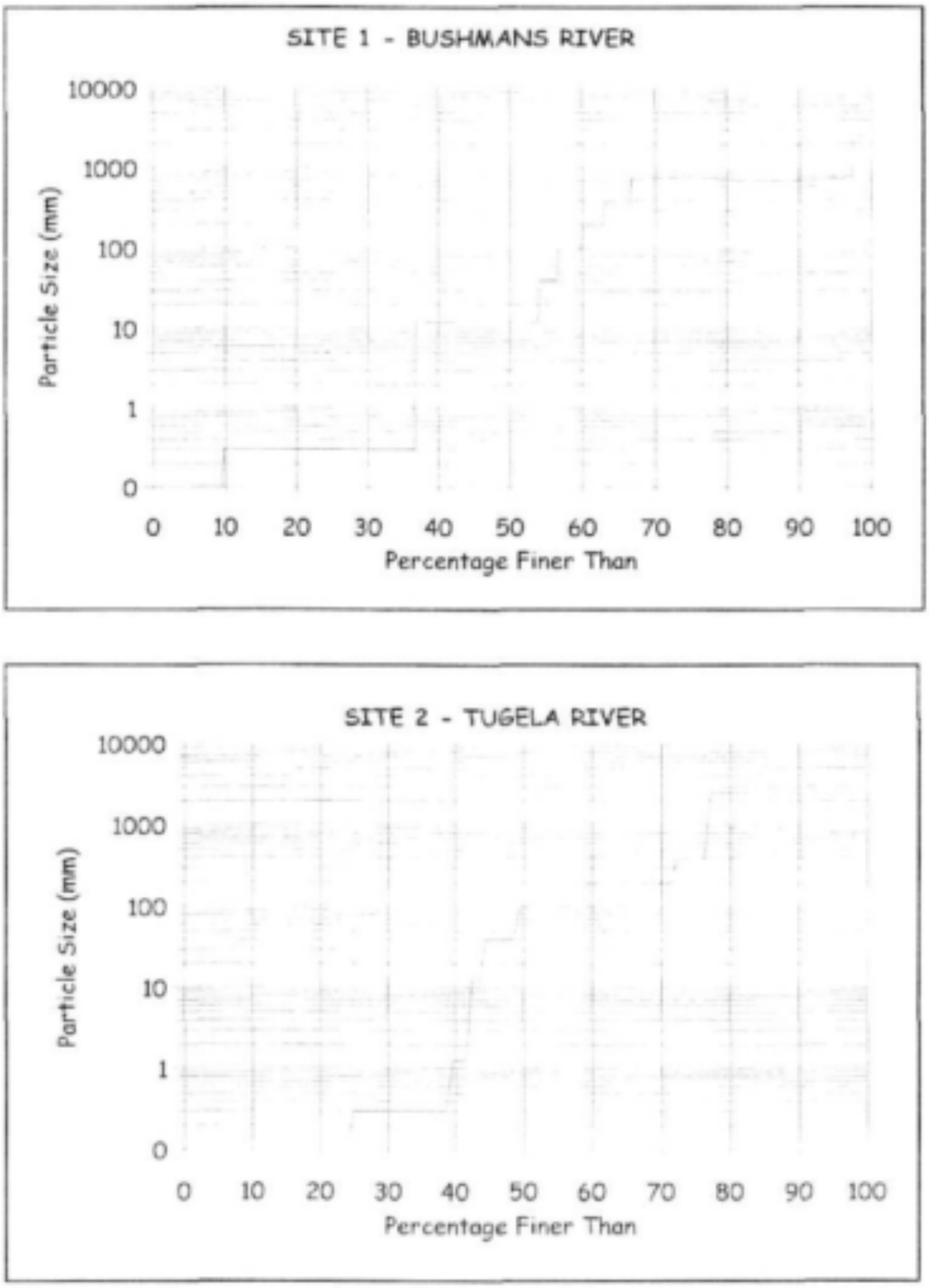
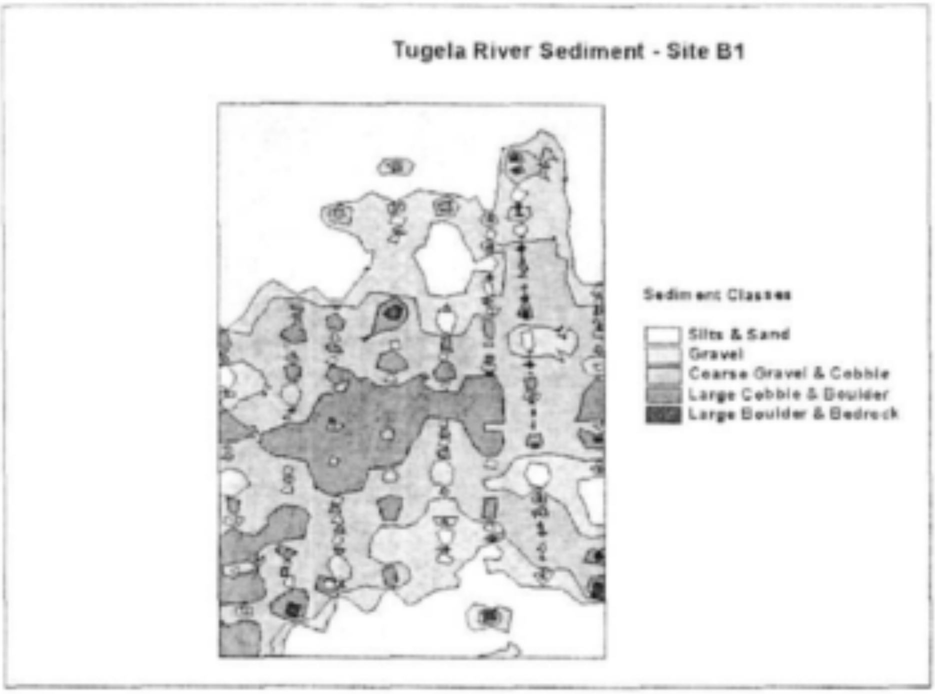


***Figure 11.9:** Frequency analysis of bed material size.*



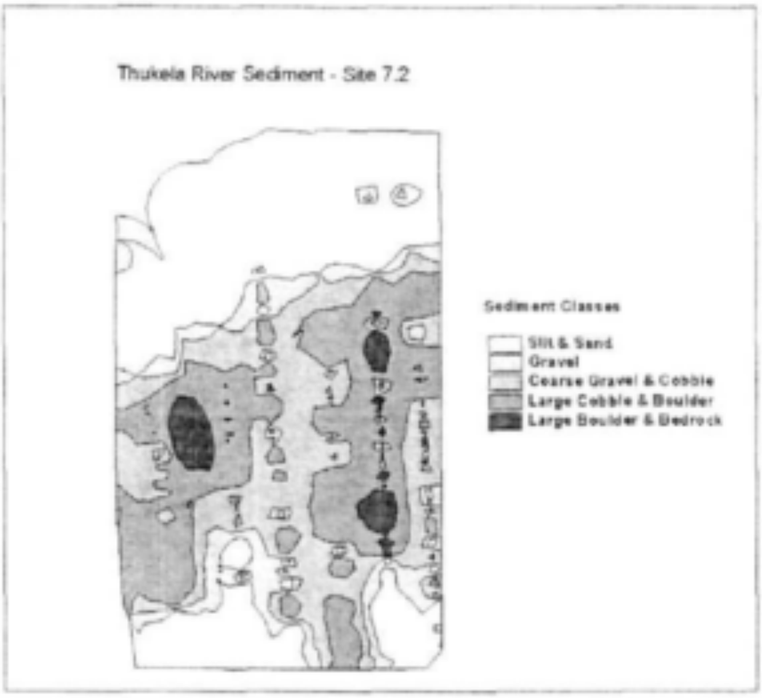


Figure 11.10: *Modelled sediment distribution at Site 1, Bushmann's River (Site B1) and Site 2, Jamesons Drift (Site 7.2).*

Flow depth

A rating equation relating depth to discharge was developed for each site as part of the IFR exercise. The rating equation ($d = 0.457Q^{0.308}$) was applied to Site 1 and ($d = 0.508Q^{0.296}$) to Site 2. The rating equation can be used to equate a specified maximum depth to a discharge for the site. This depth can be applied to the DTM to demonstrate the area of flow in the channel and the degree of connectivity at the site.

The distribution of flow depth at Site 2 is shown in Figure 11.11 for maximum flow depths of 0.4 m, 0.5 m, 0.6 m & 0.7 m respectively. From the rating equation these depths equate to discharges of approximately 0.6 m^3s^{-1}, 1.2 m^3s^{-1}, 2 m^3s^{-1} & 3 m^3s^{-1}. The darker blue areas illustrate the lowest points on the bed from which flow depth is measured and therefore the deepest water. Figure 11.12 shows the equivalent flow depth distributions at Site 2 for maximum flow depths of 0.7 m, 1.1 m, 1.5 m & 1.8 m. From the rating equation these maximum flow depths equate to a discharges of approximately 3 m^3s^{-1}, 10 m^3s^{-1}, 40 m^3s^{-1} & 70 m^3s^{-1}.

The differences in channel morphology at each site have a clear influence on the way that the flow is distributed across the channel bed. At Site 1, as discharge increases, the water spreads laterally across the bed from the right hand side. At the lowest flow there are a number of small isolated pools detached from the main flow. These are incorporated into the main flow as the discharge increases. It can be seen that even at the highest specified discharge there is no water flowing through the lateral channels although small isolated pools appear. At the lowest flow at Site 1 it can be seen that there is no continuous flow, but rather a series of isolated pools. These join up at the second discharge. As flow increases, the main increase is in depth rather than wetted area as the flow is confined in the v-shaped channel. There is a potential for isolated pools to form at higher discharges as a result of water seeping laterally through the cobbles and boulders into depressions.

Wetted Area

The changes in wetted area and depth distribution were explored further using the summary statistic function of ArcView. This was used to determine the change in surface area for each depth as a function of change in discharge. Figures 11.13 and 11.14 illustrates the change in surface area of the bed covered by different depths of water as discharge increases for Site 1 and Site 2 respectively. At Site 1 the modal depth values tended to be in the shallow flow classes (0 - 10 cm) at all discharges, and the area of bed covered by less than 10 cm of water remained close to 200 m^2. As discharge increased, the area covered by greater depths increased. The shape of the distribution was markedly different at Site 2. At low discharges there was a symmetrical distribution with modal values of between 10 - 40 cm. The heterogeneity of the depth classes increased with discharge until at the highest discharge the distribution became bi-modal, with large areas of shallow flow between 10 - 20 cm as well as the deeper flows of between 90 - 110 cm.

The graphs can also be used to determine what area of the bed is covered by a specific depth. For example at Site 1 at a discharge of 0.6 m^3s^{-1} (maximum depth of 0.4m) a depth of 20cm covers an area of approximately 125m^2. At a discharge of 3 m^3s^{-1} (maximum depth of 0.7m), a depth of 20cm covers an area of approximately 275 m^2. At Site 2 at a discharge of 3 m^3s^{-1} (maximum depth of 0.7 m), the area of the bed covered by a depth of 20 cm is approximately 50m^2. At a discharge of 70 m^3s^{-1} (maximum depth of 1.8 m) the area of the bed covered by a depth of 20 cm is approximately 550 m^2. For the four flows considered, the greatest area of the bed covered by 20 cm of water is at 2 m^3s^{-1} of flow (approximately 950 m^2).

Sediment Cover as a function of discharge

Utilising the "union" function of ArcView maps of depth and sediment were combined to determine the loss or gain in area of different sediment sizes as a function of discharge. Figure 11.15 illustrates the change in percentage cover of different sediment sizes at two separate discharges for the two sites.

Once again the two sites portray differences that are related to the channel morphology. At low flows the wetted area of the channel bed is characterised by coarse gravel, cobble and boulder. As the water spreads out across the channel bed at the higher discharge there is a significant increase in the percentage of sand and silt covered by water. At Site 2, discharge changes have relatively little effect on the bed material class inundated by water. The water remains concentrated in the area dominated by large cobble and boulder. The amount of gravel and finer material that is inundated remains insignificant even at the higher discharge.

Hydraulic Biotopes

A map of "habitat" was produced using the hydraulic biotope data collected at a discharge of 0.9 m^3s^{-1} at Site 1 and 2.7 m^3s^{-1} (Figure 11.16). As with many of the other maps in this study, ArcView Spatial was used to interpolate between surveyed points to produce a continuous surface of habitat. It is important to note that the map is valid only for the observed flow condition at the time of the survey.

It can be seen that the pattern of hydraulic biotypes is quite different for the two sites. There is a high diversity of flow types at Site 1; these have a patchy distribution. The hydraulic biotypes have a more continuous linear pattern at Site 2. There is a clear progression from backwater at the channel margin, through pool and run to riffle in the centre of the channel. Small patches of faster more broken flow types disrupt the riffle flow.

Hydraulic biotopes shown in Figure 11.16 are identified on the map in terms of flow type. It would be possible to use the 'union' function in ArcView to combine flow type and bed material size class, but the resulting map would be complex and the many different polygons would be difficult to separate by eye. A qualitative assessment of habitat can be obtained by visually integrating the maps of flow type, sediment size class and flow depth.

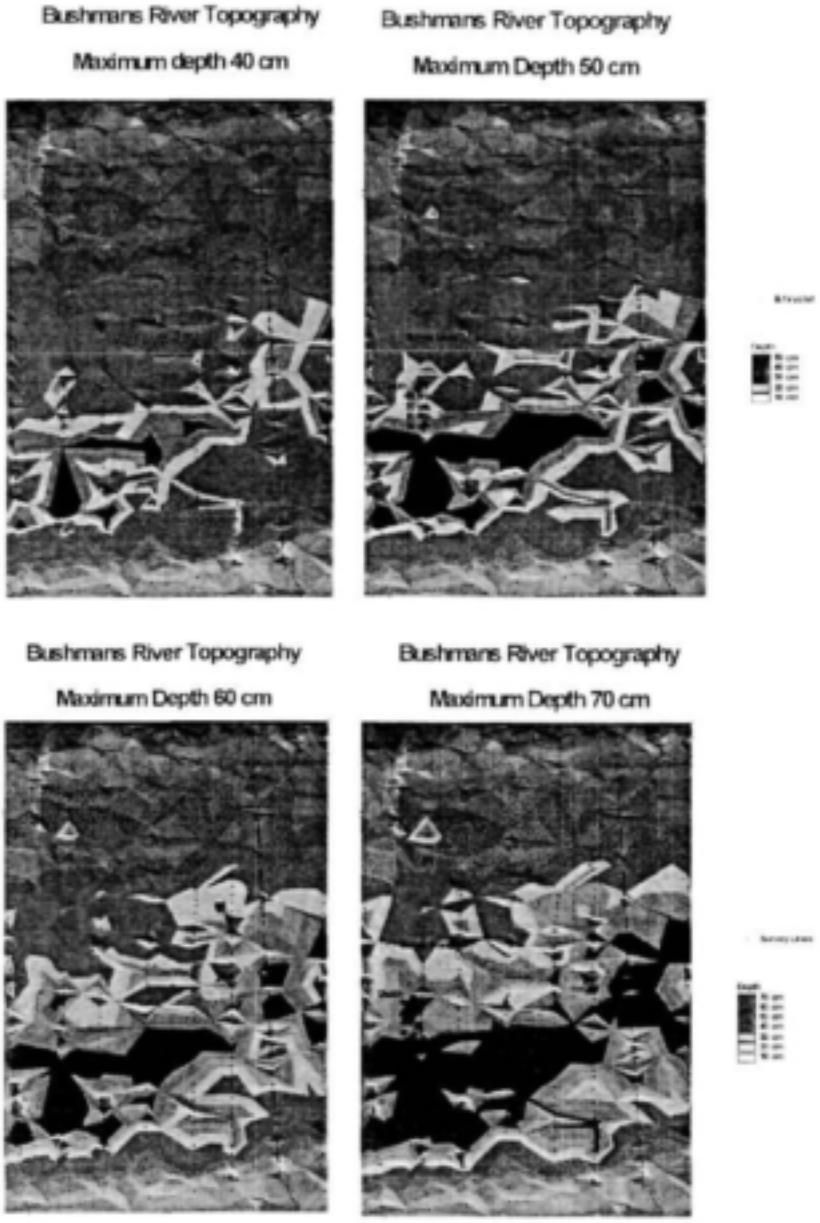


Figure 11.11: *The extent of water cover for discharges of 0.6, 1.2, 2 and 3* $m^3.s^{-1}$ *at site 1 on the Bushmans River.*

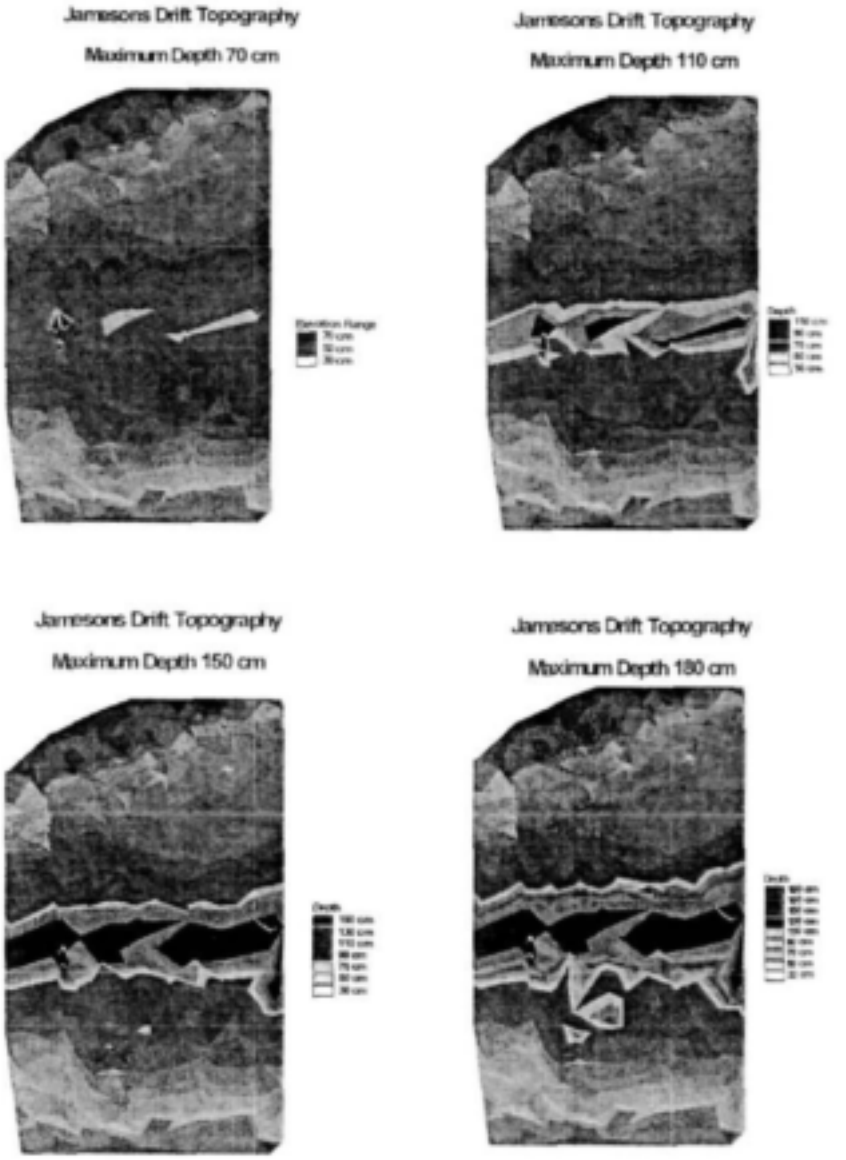


Figure 11.12: *The extent of water cover for discharges of 3, 10, 40 and 70 m^3s^{-1} at site 2 on the Jameson Drift, Tugela River.*

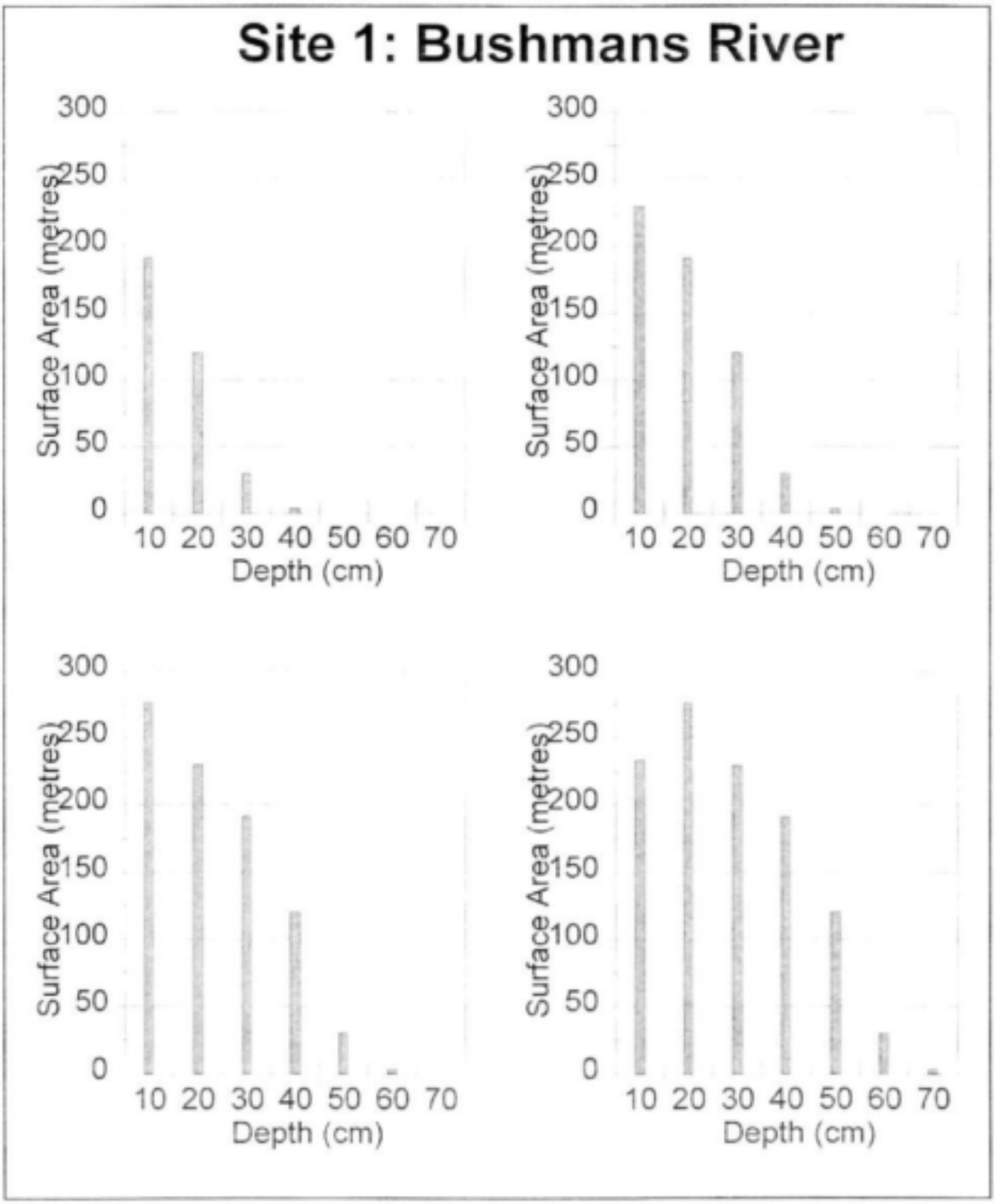


Figure 11.13: *Change in surface area for different depths as discharge increases. Site 1. Bushmans River, for discharges of 0.6, 1.2, 2 and 3* m^3s^{-1}.

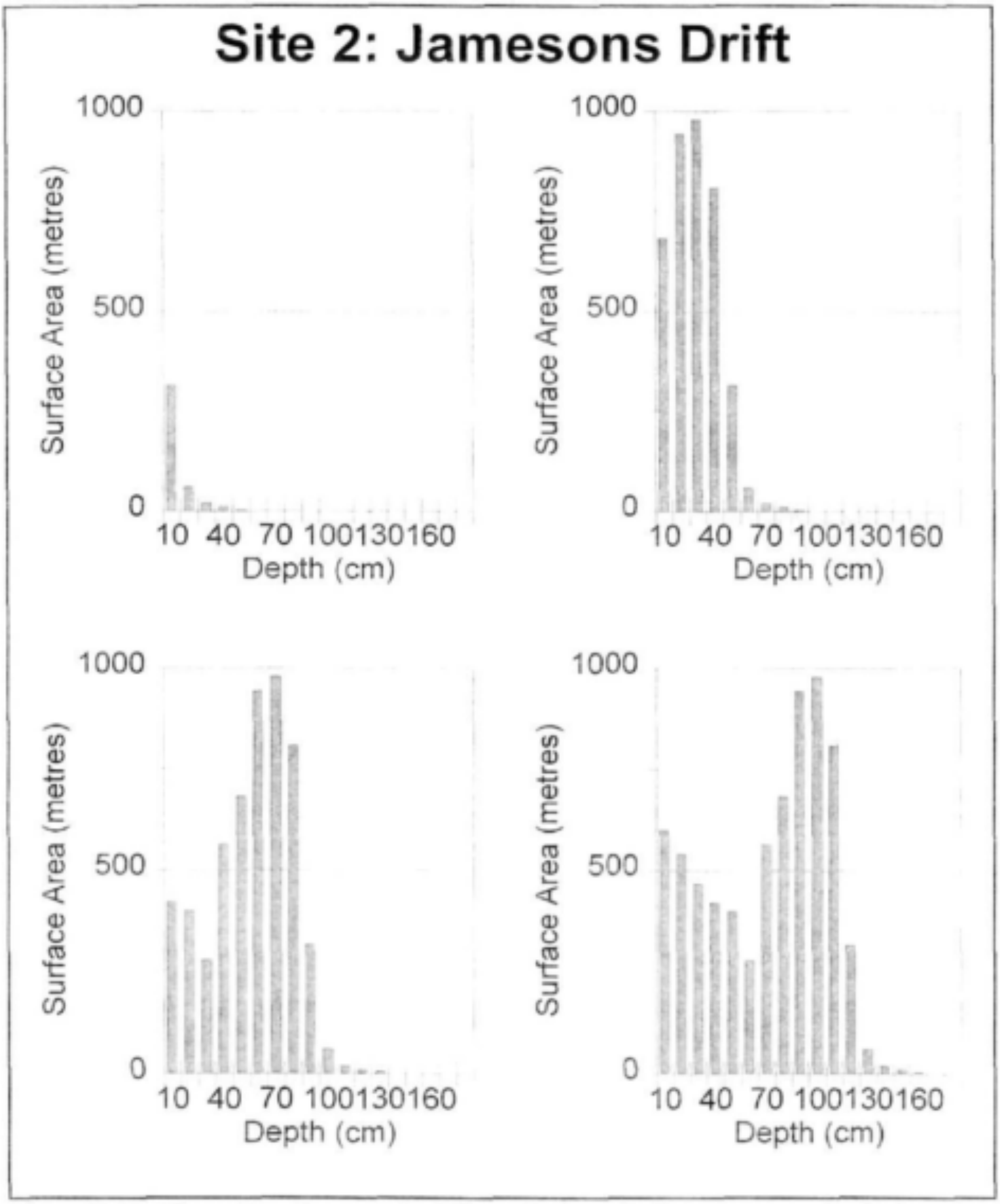


Figure 11.14: *Change in surface area for different depths as discharge increases, Site 2, Jamesons Drift, Tugela River, for discharges of 3, 10, 40 and 70 m^3s^{-1}.*

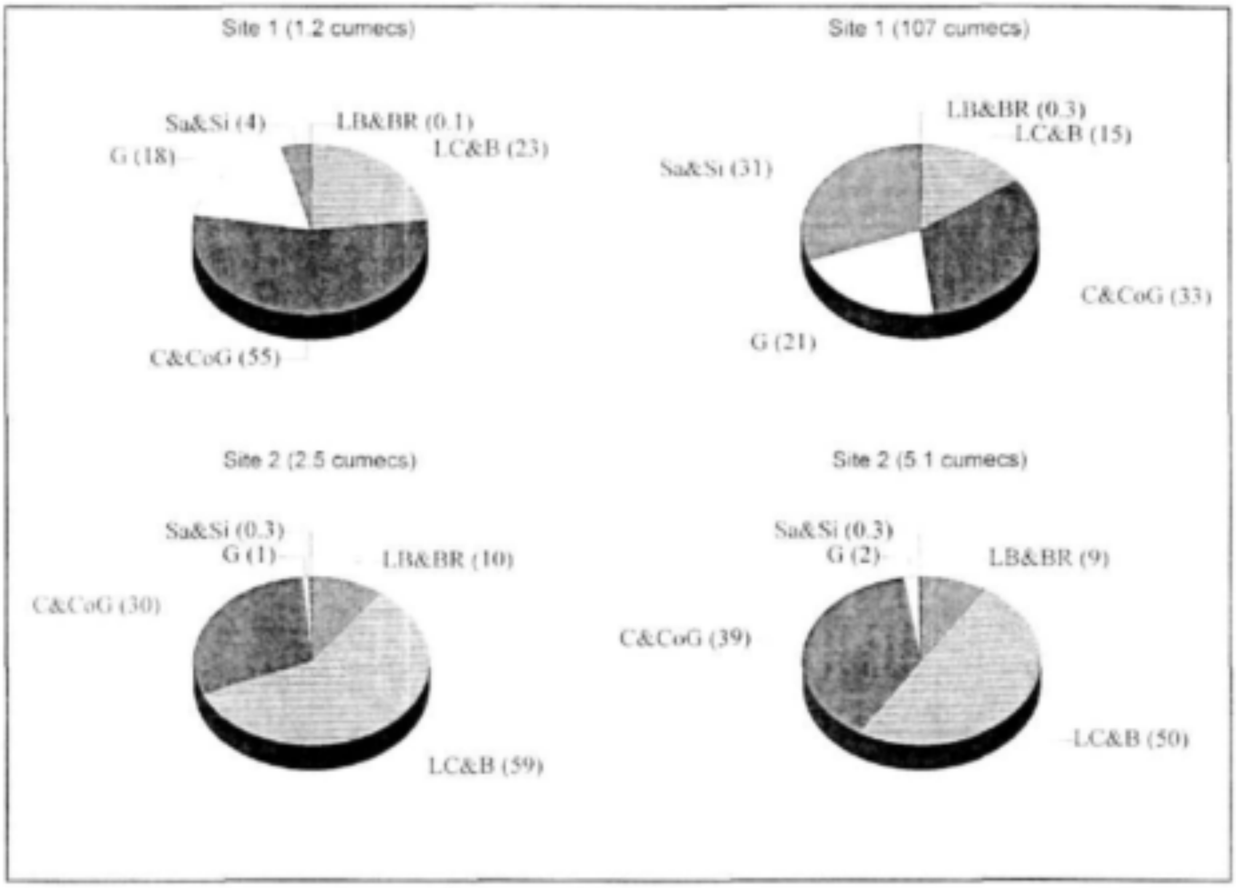
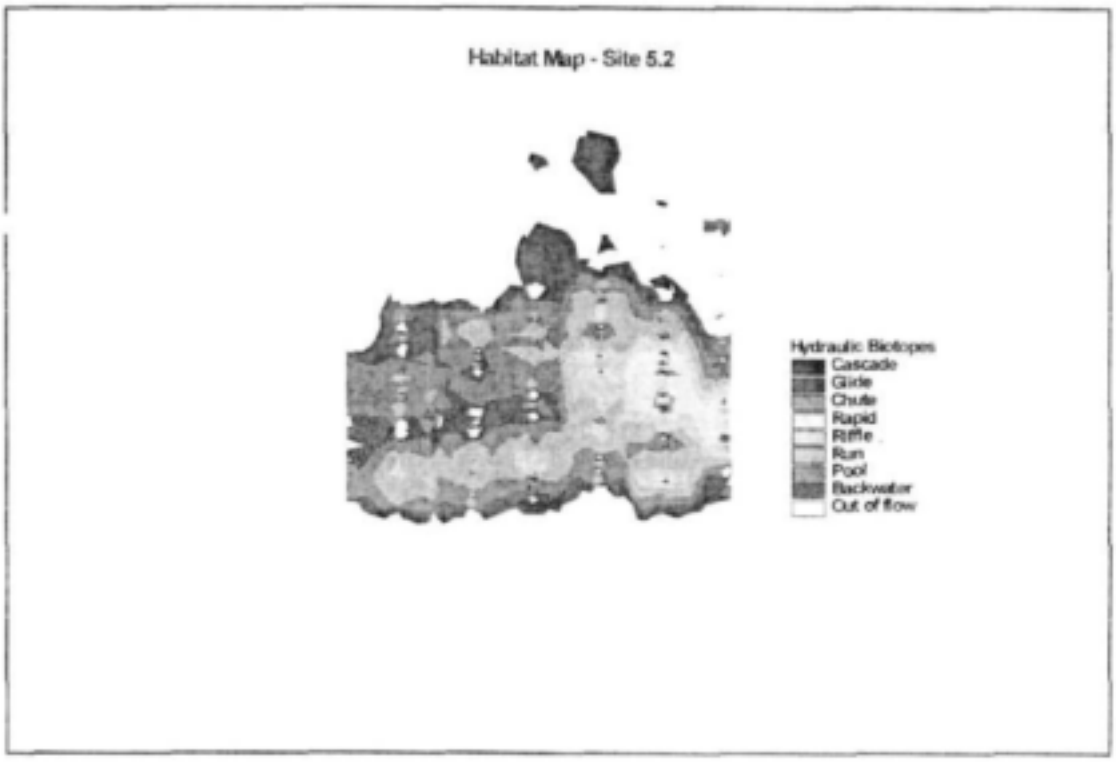


Figure 11.15: *Changes in size class of substratum with changes in discharge. (LB&BR large boulder and bedrock; LC&B large cobble and boulder; C&CoG cobble and coarse gravel; G gravel; Sa&Si sand and silt; percentages in brackets.)*

a) Site 1, Bushmans River at 0.9 $m^3.s^{-1}$



b) Site 2,Jamesons Drift, Tugela River, at 2.7 $m^3.s$

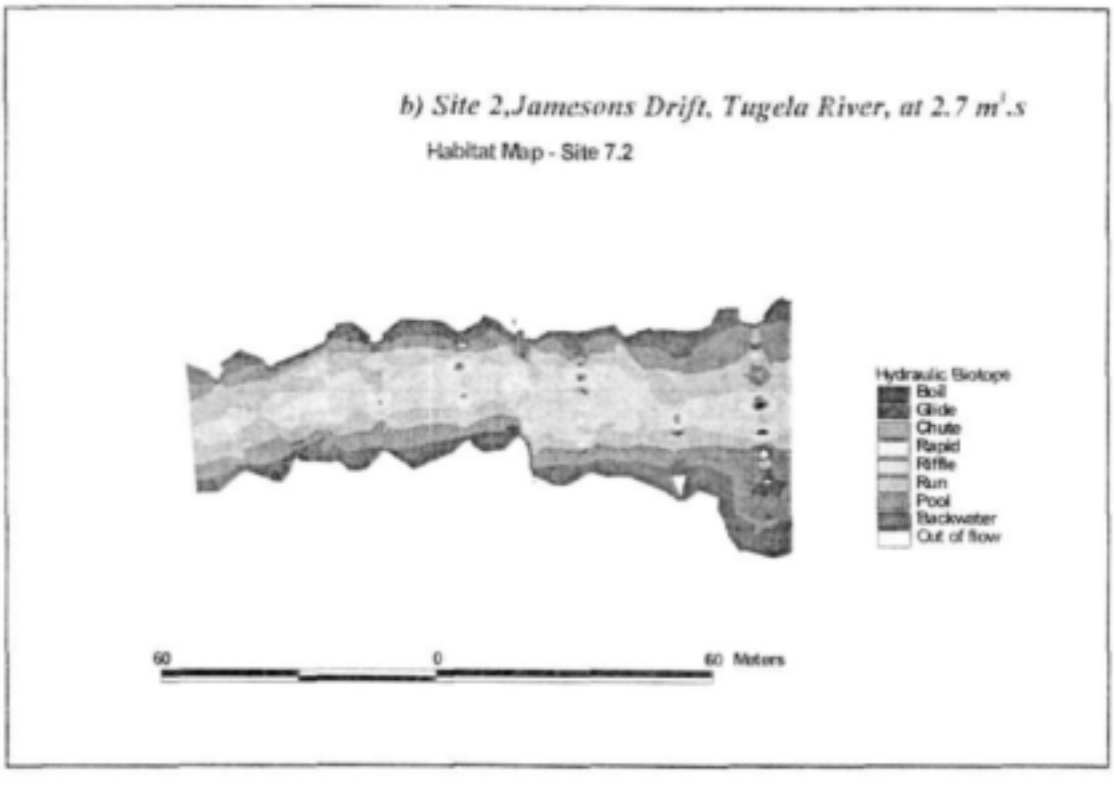


Figure 11.16 Habitat maps showing distribution of hydraulic biotopes at one specified discharge

11.3.5 Discussion

The use of DTM techniques has considerable potential to assist aquatic scientists in decision making processes such as Instream Flow Requirement (IFR), the Reserve and general biomonitoring. The application to data collected from the Bushmans and Tugela Rivers presented in this chapter is an indication of the potential use of the method for mapping habitats in river channels.

The two examples taken from the Tugela catchment clearly show a number of differences between the instream components of channels with different morphology. The analysis has demonstrated how different channel morphology creates different levels of habitat complexity in terms of discharge related changes to flow depth, bed sediment and flow types. These changes were graphically illustrated using maps modelled from point data along 7 or 8 closely spaced transects at each site. There is a significant increase in the effectiveness of the information compared to that obtained from the one standard IFR transect. The maps give a measure of both downstream variability and of habitat connectivity that is not available from a single transect.

From discussion with aquatic ecologists it has become apparent that these scientists often use the variables of flow depth and bed substrate as important indicators of habitat suitability for specific species. The technique presented here provides a relatively simple and accurate method for mapping changes in available water depth and substrate composition. One very important variable for the assessment of habitat condition is a measurement of turbulence. This is a result of the interaction of bed roughness, water depth and velocity. The method demonstrated in this chapter has not yet dealt with the issue of velocity, but it is believed that it can be addressed in part through the addition of habitat mapping as illustrated in Figure 11.16.

11.4 Conclusions

The information in this report aims to demonstrate the potential for two different methods to carry out habitat mapping. The following description aims to provide a summary of the two techniques together with advantages and disadvantages of each.

Digital Photography

Advantages:	Relatively quick (6 hours per site), relatively cost effective (if technology is available), intermediate accuracy, gives a continuous cover for the sample area.
Disadvantages:	Difficult to re-survey because of problems with standardisation, heavily reliant on advanced technology, requires specialist skills, scale dependant by size of image, two dimensional surface does not allow the overlay of water levels.

D.T.M

Advantages:	Relatively accurate, no problems with standardisation, easy to train a field worker for objectivity, scale independent, can return to the site at any interval after the initial survey (fixed bench marks) and carry out an accurate re-survey of water depth, substrate and flow type without any specialised equipment, allows the easy overlay of different water levels on a three dimension surface for assessment of connectivity, inundation etc.
Disadvantages:	Time consuming for initial survey (1 day for a site), requires expensive survey equipment (Total Station) and a qualified surveyor, requires specialist skills for computer manipulation of data. Results depend on extrapolation from line transects.

As a simple habitat mapping tool, the use of digital photography appears to have enormous potential. Problems of standardisation need to be solved before this technique will realise its full potential. DTM modelling appears to be considerably more versatile for habitat mapping and has immediate visual impact. The ability to produce a three dimensional surface with different water levels is very useful for determining instream flow requirements. Although the method is more time consuming and expensive, the results appear to be more accurate and more useful. The ability to accurately assess changes in habitat with changes in flow is a big advantage to this technique.

The advantage of the DTM technique in the Tugela catchment is that a re-survey is likely to be easier and more accurate because of the number of fixed benchmarks. This technique does not have the same problems of differences in height, angle, scale and so on which are associated with the use of digital photography. The latter technique also avoids the need for digitising as the points are fixed by the field survey.

One disadvantage of the technique is that it relies on interpolation between a number of line transects. The effect of this can be seen on the various maps presented above. One solution might be to use a combination of the techniques, overhead digital photography to capture the flow type distribution for small sample areas, point-transect survey to capture topographic, sediment and flow type data over a larger area.

11.4.1 Further development

It is felt that the full potential of digital terrain modelling will not be realised until it has been scrutinised and used by aquatic ecologists in real management scenarios. It is hoped to apply this technique as standard procedure in the IFR forum as part of the comprehensive reserve and to build in specific ecological requirements to the procedure as it develops.

To date the technique has been used only once in a full IFR workshop (Middle Olifants). One site was mapped in the middle Olifants River as an exercise to determine the potential use of the technique to assist the setting of ecological flow requirements. Extensive use was made of the three dimensional maps for different flows, particularly in to determine attributes such as connectivity of flow, connectivity of flow depths, innundation of marginal vegetation and so on. The visual impact of the DTM maps proved particularly impressive. Feed back from the workshop was extremely positive, so much so that ecologists were hesitant to try and set IFR requirements for the lower Olifants River until a habitat model was available to assist them.

11.4.2 Further research

To develop a predictive habitat mapping tool it will be necessary to carry out repetitive surveys of the same area at different discharges. This will demonstrate trends of habitat change in response to changes in discharge. If enough data are gathered it may be possible to develop 'rules'of change for different channel morphology. This work is presently underway as part of a follow up Water Research Commission project.

Section D: Overview: Geomorphology and Management.

Chapter 12: Overview: Geomorphology and management

12.1 Overview of research objectives

This research project set out with the primary aim of implementing geomorphological research as an integral component of multidisciplinary approaches to the management of southern African river systems and conservation of their ecological integrity. Specific objectives were to:

Refine the geomorphological component of the IFR methodology

Develop geomorphological indices and monitoring procedures to assess channel condition

Further assess the hydraulic biotope concept and its application to the assessment of habitat condition

As noted in the introduction, the development of a geomorphological index and assessment of channel condition was taken up in a project funded through the Department of Water Affairs and Forestry and preliminary developments were published as reports under the River Health Programme (Rowntree and Ziervogel,1999; Rowntree and Wadeson, 2000). 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.

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. Previous research funded by the WRC (Rowntree and Wadeson, 1999) demonstrated the validity of hydraulic biotopes as a means of identifying homogenous hydraulic environments. 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 the relationship between flow and habitat availability.

Reserve determinations and associated IFRs have commonly been carried out in conjunction with major water development schemes that involve flow regulation. Flow regulation can be the result either of building dams that impound and store water or interbasin transfer schemes (IBTs) that transfer water from a doner to recipient stream. Both developments can seriously alter the flow regime of the impacted rivers. Impoundments absorb floods, particularly the moderate events, while IBTs increase the base flow of the receiving stream, often to magnitudes equivalent to the annual flood.

McGregor in Chapter 2, Volume 1, has highlighted the geomorphological changes commonly observed below dams as documented in international literature. She presents a model that demonstrates the interaction between resultant changes to the flow regime and sediment load. McGregor emphasises that downstream changes to channel morphology must be considered in relation to tributary inputs that change the balance of flow related and sediment related impacts. Moreover, her own field research (McGregor, 2000) demonstrated that geomorphological change is often localised, often at tributary junctions.

While the downstream effects of dams has received world wide attention, there has been a remarkable lack of research into the geomorphological impact of interbasin transfer schemes. An investigation by Du Plessis on the impact of an interbasin transfer on the semi-arid Skoonmakers river highlights the magnitude of changes that can take place and point to a need for further research in this area. The regulated flow in this river has had a major impact on the erosive power and sediment transport capacity of this river, resulting after 20 years in a greatly widened and deeper channel in its upper riches. The geomorphological impact was shown to have a strong spatial dimension, with the upper reaches being subjected to massive erosion, and the lower reaches to deposition. Changes to channel structure were closely linked to changes in riparian habitat and to species composition of the riparian vegetation. An increasing number of interbasin transfer schemes are proposed as components of South Africa's water resource development schemes. Experience from the Skoonmakers River shows that the geomorphological impacts of such schemes must be carefully assessed before such schemes go ahead.

While it is widely acknowledged that dams and other water developments impact on geomorphological processes and can change the downstream channel morphology, it is more difficult to make accurate predictions of what those changes will be. As a first step we need to understand the relationship between the flow regime and channel morphology in un-impacted rivers. The magnitude-frequency debate provides a useful context for evaluating this relationship (Chapter 3, Volume 2). Fundamental to this debate is the idea of a dominant or channel forming discharge that is the discharge to which the channel form is related. In many alluvial rivers this has been equated to the bankfull discharge - the discharge at which the flows just fill the channel before spilling out onto the flood plain (if present). Research in the 1950s and 1960s by American geomorphologists (Leopold *et al.* 1964) demonstrated that the bankfull discharge was also the most effective discharge for sediment transport in that over the long term it carried the most sediment. Thus the bankfull discharge was seen to have both morphological and sediment transport significance. It has been widely used as the independent variable to develop predictive equations for channel features such as channel width, channel depth, pool and riffle spacing or meander wavelength (Leopold *et al.* 1964). It would seem logical therefore to apply this thinking to understand geomorphological processes in South African rivers and to the determination of the geomorphological flow component for the Reserve.

Much of the research presented in Volume 2 of this report has focussed on developing magnitude-frequency concepts for South African rivers, specifically the Mkomazi and the Mhlatuze (KwaZulu Natal) and the Olifants (Limpopo Province). Much geomorphological research is empirical in its approach, and therefore is derived for a specific geographical context. Empirical relationships need to be carefully tested before they can be applied elsewhere. The South African fluvial environment was described in Chapter 2, Volume 2. South Africa rivers, particularly those draining the Great Escarpment, are steep and strongly influenced by bedrock exposed in their beds and banks. They are not true alluvial rivers and in place of a flood plain tend to have an active channel incised within a macro channel bounded by terraces. The natural flow regime of South African rivers is highly variable with a steep flood frequency curve, meaning that extreme floods are many times larger than annual flood events. Moreover, research on South African palaeoflood hydrology has shown that periods of above and below average flooding occurred, with concomitant changes in sedimentation patterns in the recent past. Long term cycles have been shown to be related to Quaternary glacial and interglacial cycles, but shorter term cycles occur within stadia and inter-stadia periods (Dollar and Goudie, 2000). This variability is likely to find expression in the channel morphology in a manner that may be quite different from that related to the more equitable flows of temperate humid areas where much of the early research on magnitude and frequency was developed.

It is clear from the preceding discussion that an indigenous understanding of how southern African fluvial systems function is of importance, as the approach taken to understanding fluvial systems has major implications for management. A classic example of this is the previously stated legal case in the United States (Gordon, 1995), where Luna B. Leopold and Stanley M. Schumm presented conflicting evidence regarding the water requirements of the Platte River in Colorado. Their approaches to assessing the river's water requirements differed fundamentally and therefore the methods that each applied and the answers that were subsequently generated were inconsistent (see Table 11.1). This highlights the danger that unless fluvial systems are understood in their proper context, within appropriate spatial and temporal time-scales, an inadequate understanding of their physical functioning will be developed, resulting in the systems being poorly managed.

Research presented in this report has attempted to examine our theoretical and applied understanding of the magnitude and frequency of channel forming discharge for selected southern African rivers. Two approaches to the problem was developed, an empirical approach that related channel form indicators to discharge and a theoretical approach based on the effective discharge for sediment transport. In alluvial channels, morphological features are made up of sediment that is in temporary storage in the channel, representing the balance of erosion and deposition within the reach. In theory there should therefore be a relationship between the sediment transport capacity of the flow and channel morphology in an alluvial reach. As noted in Chapter 4, Volume 2, actual rates of sediment transport are notoriously difficult to measure in natural channels. It is somewhat easier to derive an estimate of the transport capacity of the flow at a given discharge using hydraulic principles. This approach was followed in this research to estimate the effective discharge for the Mkomazi, Mhlatuze and Olifants rivers. The methods developed and results achieved using the magnitude-frequency approach have been presented in Chapters 5 to 10.

Table 12.1: *Summary of points made by the United States and Opposition on sediment movement in mountain streams (modified after Gordon, 1995).*

United States (Leopold position)	Opposition (Schumm position)
Sediment supplied were of sufficient quantity to fill in the channels if maintenance flows were not provided.	The amount of sediment supplied by the mountain streams was very small and mostly wash load. Only small flows, if any, were needed to move this sediment.
Materials forming the stream boundaries were able to be moved at bankfull flows or less.	The stream boundaries were composed of coarse materials which would not move at bankfull flow.
The streams were hydraulically controlled, meaning that a unique relationship exists between discharge and the amount of sediment transported. If flows were reduced, but sediment supply remained the same, then aggradation would occur.	The streams were supply-limited, meaning there was less sediment available than the streams could carry. Flows could be reduced and the streams would still be able to carry the sediment load.

12.2 A magnitude frequency model of channel adjustment for South African rivers

Theories of channel formation and maintenance discussed in Chapter 3 fall within two basic models: the 'Leopold' model and the 'Structural' model. The first arises from the hydraulic geometry approach as applied to sand and gravel-bed alluvial rivers and has been developed by the 'Leopold' school of thought. It argues that 'rivers are the authors of their own geometry', and that over time rivers will adjust their dimensions to convey the intermediate flows and associated sediments within their banks i.e. those which occurred a few times a year on average. Very large flows occur too infrequently and very small flows carry too little sediment to shape the active channel. This model considers the bankfull flow, that flow that just reaches the level of the floodplain, to be the channel forming discharge. This approximates to the effective discharge, the flow that carries the most sediment over a long period of time. Bankfull flow was found to occur with a frequency of 1 to 2 years on average for many humid area alluvial rivers. This first model rests on the assumption that an alluvial river can be considered to be in quasi-equilibrium. Over a reasonable period of time, a river in quasi-equilibrium will deliver the same amount of sediment downstream as is supplied to it from the upstream catchment. If this balance is upset, then the river would be in disequilibrium, and hence instability and channel adjustment will occur.

The second model, the 'Structural' model, is one which has been applied to bed rock or partially bed rock controlled rivers, to steep mountain rivers, or to dryland type rivers with a highly variable climate and hydrological regime. These types of rivers are not fully adjustable and are unlikely to be in equilibrium with the imposed flow. Their dimensions and form are often influenced by non-fluvial factors including bed rock, large boulders, or structural features such as faulting. The structural model postulates that these rivers are formed by floods much larger than the 1 to 2 year 'bankfull' event (as suggested by the Leopold model). In the Platte River in the United States, Harvey (cited in Gordon, 1995) has referred to 'courses of convenience' and 'relic channel' to describe a channel with bed material that is immobile under frequently occurring flows. Smaller material that is washed into streams during storm events can easily be transported by relatively low flows. It is argued that these streams do not carry a high bed material load relative to their transport capacity and are therefore supply-limited. In these channels no relationship exists between the dimensions of the channel perimeter and the frequently occurring flows. This may be because the rivers were shaped by some past event, such as a mega-flood or glacial action.

River managers should be aware of these contrasting process-response models as applied to alluvial and non-alluvial channels. The response to flow regulation or to a change in sediment load is likely to differ in each channel type. In alluvial channels, any change to the flow regime is likely to result in channel adjustment as the system adjusts to a modified discharge. Where the flow regime is regulated such that the magnitude and frequency of flows are reduced, and yet sediment continues to enter the channel from upstream areas and tributaries, it is likely that sediment will accumulate and vegetation will encroach into the channel, thus creating a reduced channel capacity adjusted to the less frequent flood flows. This will in turn exacerbate the impact of flooding by high magnitude events. When high flows do pass through the impacted sites, accelerated stream channel erosion, deposition, lateral migration and/or avulsion may result.

Non-alluvial channels are less likely to adjust their channel form in response to flow regulation. A regulated flow environment which reduces the magnitude of the annual and more frequent floods will not have a major impact, as these smaller flows are simply not 'effective'. Channel maintenance is performed by large floods which are less likely to be affected by flow regulation. In this sense, these channels can be regarded as being resilient as, within threshold limits, the river is able to accommodate changes in the flow and sediment regime without experiencing major alterations.

An awareness of these two contrasting models is of critical importance to understanding and managing southern African fluvial systems. The above discussion begs the question, which model best applies to southern African fluvial systems? Results from the Mkomazi River have shown that no relationship exists between the bankfull discharge and either the hydrological regime, the effective discharge or the dominant discharge. However, there does appear to be good agreement between the inundation stage of the in-channel bench and the 0.9 year and 2.0 year return period on the partial duration series, and the in-channel bench and both the dominant discharge and effective discharge as calculated by the Yang equation. A number of studies have pointed to the difficulty of identifying the bankfull level (cf Williams), a problem that may have arisen in this research. As described above, effective discharges related more closely to the lower bench, which may represent contemporary channel adjustment.

The effective discharge as calculated by the three transport equations for each of the sites for the Mkomazi is shown to be in the 5% to 0.1% range on the 1-day daily flow duration curve. This range of flows accounts for the bulk of the bed material transported (>80%). It can be argued that rather than specify a single effective discharge it is more appropriate to think of a range of discharges that are responsible for bed material transport.

While the effective discharge with respect to the total long term sediment transport was shown to fall within the 5% to 0.1% range on the 1-day daily flow duration curve, only large floods with average return periods of around 20 years generate sufficient stream power and shear stress to mobilise the entire bed. It was estimated that these large floods would inundate the terraces. It has therefore been suggested that, for the Mkomazi River, it may be instructive to think in terms of two sets of effective discharges: first, a range of discharges that transport the most bed material over a long period of time and approximate a 'bench-full' discharge, and second, a 'reset' discharge, i.e. large floods with return periods in the 20 year range that are able to mobilise the entire bed and serve as channel maintenance discharges for the entire bed as well as the macro-channel.

Thus for the Mkomazi both models of channel adjustment appear to play a role. The 'Leopold' model is appropriate if applied to the lower in-channel benches rather than the bankfull level itself. A range of discharges in the 5-0.1% range on the 1-day daily flow duration curve are responsible for the bulk of the bed material transport. These discharges approximate to a range of stages that bracket the bench. The second 'structural' model also applies as it is the largest floods, with a frequency of once in 20 years, that are able to mobilise the entire bed and reset the whole channel. It is argued that this bi-polar type flood frequency curve may be responsible for the gross channel architecture. The macro-channel is maintained by the large flood events, and the active channel is maintained both by the range of effective discharges and the 'reset' discharges. These are the geomorphologically 'effective' flows.

The techniques and methods that were developed for the unregulated Mkomazi River were then applied to two highly regulated systems, the Mhlathuze and Olifants Rivers. Results from the Mhlathuze River have indicated that the Goedertrouw Dam has had a considerable impact on the downstream channel morphology and bed material transport capacity and consequently the effective and dominant discharges. It has been suggested that the Mhlathuze River is now adjusting its channel geometry in sympathy with the regulated flow environment. Utilising the present-day flow regime, it was noted that there appears to be a good relationship between estimated bankfull discharge and dominant discharge. This is a function of the hydrological regime of the Mhlathuze which has a markedly skewed flood frequency curve due to the occurrence of cut-off low pressure systems which cause regular flooding in northern KwaZulu-Natal. Under the present-day regulated flow environment, the discharge volumes and peaks have been reduced. This has resulted in an increase in return period inundation levels (for example, the estimated bankfull discharge average return flow is 3.7 years under present-day conditions as opposed to 2.6 years for virgin flow conditions), but a reduction in the effective discharge with concomitant reductions in unit stream power and boundary shear stress. Under present-day conditions it has been demonstrated that the total predicted bed material load has been reduced by up to three times, but there has also been a clear change in the way in which the load has been distributed around the duration curve. Under present-day conditions, over 90% of the total bed material load is transported by the top 5% of the flows, whereas under virgin flow conditions 90% of the total bed material load was transported by the top 20% of the flows.

It appears that the Mhlathuze River fits neither the 'Leopold' nor the 'Structural' model. There appears to be no relationship between the estimated bankfull discharge, the dominant discharge and the effective discharge. The effective discharge is in excess of the estimated bankfull discharge and dominant discharge. The Mhlathuze does not fit the second model either, in that the river is not controlled or semi-controlled by bed rock, all flows are competent to transport the bed, and the channel perimeter is capable of freely changing its form in response to the imposed discharge and sediment regime. This disequilibrium is probably a function of the regulated flow regime.

The Olifants River is a steep bed rock controlled system with coarse bed material. The estimated bankfull discharge has an average return period of 5.8 years on the annual series, which is considerably higher than the conventional wisdom suggested by Leopold (1997). Furthermore, there appears to be no relationship between the estimated bankfull discharge and any hydrological statistic. The effective discharge range falls between 5%-0.01% on the 1-day daily flow duration curve. This accounts for over 60% of the bed material transported at each of the sites, while a further 30% of the mobile bed material is transported by flows that lie between the 20% to 5% range. It has also been pointed out that even the highest flows simulated for the Olifants River do not generate sufficient energy to mobilise the entire bed. It is useful to consider the Olifants River as being adapted to a highly variable bi-polar type flood regime.

The importance of thresholds and initiation of motion in assessing the impact of flow regulation should not be underrated. Where coarse gravel- or cobble-bed rivers occur, even minor reductions in flow may be sufficient to retard bed material transport if shear stress or stream power fall below a critical level. Critical shear stress and stream power may not be as significant in mobile sand-bed channels such as the Mhlathuze, but they are highly significant in coarse-bedded channels. It is thus instructive to consider the significance of flow reduction not only in terms of volume and duration, but also in terms of magnitude.

It would appear from the results of research on the Mkomazi, Mhlathuze and Olifants Rivers that neither model of channel adjustment on its own adequately reflects the southern African situation. There are a number of reasons why this may be so. Many of southern Africa's fluvial systems are bed rock or partially bed rock controlled and flow within confined macro-channels with an inset active channel. Within the active channel is often a channel bench (Figure 2.3). It is argued that this channel form is a response to climatic history, tectonic history and a highly variable flow regime. It is possible that some highveld rivers, such as the Olifants, have an immobile coarse armour or pavement that may have been a response to a previously wetter climate with larger, more frequent floods.

It may be more useful to develop a third model for southern African rivers, one placed somewhere between the 'Leopold' alluvial model and the 'Structural' model. This model would argue that two sets of effective discharges are of significance. 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.

This complex channel morphology leads to problems when applying morphologically related criteria such as the bankfull discharge as the channel forming discharge. The classic 'equilibrium' morphology of temperate alluvial systems will be more difficult to achieve in controlled or semi-controlled systems (those with a strong bedrock influence) or where channels are continually adjusting to a highly variable flow regime. In these systems all morphological features, including inset benches, must be considered in the light of recent events in the channel and the likelihood of recovery from major floods.

There are parallels between the morphology described for these three rivers and the category of two-stage channels (macro-active channel) described elsewhere - the rivers draining the lowveld of southern Africa (cf. van Niekerk & Heritage, 1993; Rowntree & Wadeson, 1999), the seasonal tropics in India (cf. Gupta, 1995) and those in eastern Australia (cf. Erskine & Warner, 1998). These rivers all have in common a nested channel pattern with a clear distinction between the active and macro channel. Gupta (1995) argues that this nested channel pattern is linked to the highly variable flow regime of Indian tropical rivers. There is need for further research which aims to link form and process in these systems, evaluating the relative effects of boundary resistance and flow variability.

12.3 Implications for river management

These results have a number of implications for river management in southern Africa. The impact of engineering type water development schemes on downstream channel processes has been highlighted by the research on impoundment and IBT impacts presented in Volume 1. Currently, protection of the river resource against these impacts is sought through application of the Resource Directed Measures of the Department of Water Affairs and Forestry, operationalised through the Ecological Reserve determination process. For large developments this has been achieved through defining the Instream Flow Requirement (IFR) of a river using the Building Block Methodology (BBM). The BBM seeks to determine the flow regime required to maintain the river at some pre-determined conservation status (King & Louw, 1998). The BBM method is based on the concept that the stream ecosystem is adapted to a range of flows that are categorised into three groups: low flows, freshes, and floods (King & Louw, 1998). As mentioned earlier, Rowntree & Wadeson (1999) have suggested that three basic problems require information for IFRs: flows that maintain the spatial and temporal availability of habitats, the maintenance of substratum characteristics, and the maintenance of channel form. Rowntree & Wadeson (1999) have developed the hydraulic biotope concept to account for the information needs of the first problem. Chapter 11 explores ways in which this could be put into practice. The latter two information requirements can be achieved by utilising the magnitude-frequency approach. These two information needs are related to the freshes and flood flow groups for the BBM.

It has been suggested that the geomorphologist's first task in the IFR assessment is to estimate the range of flows necessary to maintain channel form and to predict the morphological changes that are likely to occur (cf. Rowntree & Wadeson, 1997). This 'channel maintenance' flow has been difficult to predict, as no information has been forthcoming in southern African. In the past, common practice has been to apply the alluvial model, defining the channel forming discharge as that which equates to the bankfull level, often taken as the bench where this is clearly the most active feature. It is argued that data can be generated to satisfy this information requirement by applying the technique whereby the relationship between effective discharge, dominant discharge and channel morphology is determined. The most effective range of flows are in the 5-0.1% range. This implies a magnitude as well as a duration. It is also argued that it is necessary for large floods to be allowed to move through the system as a 'reset' discharge, for the reasons mentioned above.

The second way in which this research contributes to southern African river management is through identifying the range of flows that are necessary for the maintenance of substratum characteristics. This information requirement is closely linked to the maintenance of channel form, and the two are difficult to separate. However, in this report the maintenance of substratum characteristics refers to the seasonal flushing of finer sediments from the bed. A number of methods have been tested for the Mkomazi, Mhlathuze and Olifants Rivers. It was been shown that the use of these methods in isolation can generate meaningless results, as they have often been developed for one channel type (alluvial for example) and thus cannot be applied to other channel types (gravel or cobble-bed for example). It is important that these methods are used circumspectly, and that each method is used in rivers similar to those from whence they are derived.

12.4 Methodological issues

A number of considerations arise from the methods used for this research. These relate to the nature of the bed material transport equations used, to the determination of sediment-maintenance flushing flows, to the relevance of using the dominant discharge and effective discharge approach, and to the significance of morphological features. Each of these will be addressed in turn.

Three bed material transport equations were used in this research. The rationale behind choosing them has been given in Chapter 8. The data requirements to run these models are fairly intensive and costly to procure, and the computation procedures are long. The equations all generate different absolute values, but often show similar trends. It is recommended that attention is paid to these trends rather than assigning precision to the results.

It was pointed out in Chapters 4 and 8 that a number of assumptions need to be made when using these equations and the user must be aware of the limitations of the models. Moreover these equations should be used only in the physical environment (i.e. channel type) for which they were developed. The Engelund & Hansen model, for example, is unsuitable for anything other than sand-bed rivers. It is recommended that either the Yang or the Ackers & White model be applied for rivers which have a coarse gravel-bed. The Yang model can also be applied to sand-bed rivers. Calibration of all models for southern African rivers is required before results can be accepted with confidence, but this requires measured bed load data which does not exist at present.

The second important consideration is that the methods used for determining sediment-maintenance flushing flows should be used with extreme caution. The Milhous and RBS approaches were developed for individual rivers, thus limiting their extrapolation potential. It is recommended that the sediment-maintenance flushing flows are calculated using the effective discharges for different grain-sized classes using the bed material transport equations. This is recommended for two reasons. First, they were developed from a broader data set and, second, the flushing flows for different grain-sized classes account for incipient motion as well as duration.

The third point of discussion is the relevance of the dominant discharge and effective discharge approach. It is argued that the effective discharge provides a useful approach to identifying those flows which are significant for particular channel types. The dominant discharge of Marlette & Walker (1968) is computed from the flow classes, and although it provides a useful average discharge that transports 50% of the bed material, it does not account for the fact that there are a range of flows that can be considered to be effective. Therefore it can be argued that the effective discharge approach which considers the effect of each flow class separately is perhaps more appropriate. The use of the cumulative curves for displaying the flow range over which most bed material is moved is particularly effective in this regard.

The fourth consideration is the significance of morphological features. One of the limitations of the research was correctly identifying the in-channel morphological features. Of particular significance is the refinement of the definition of in-channel features in an objective way and then to associate them with flow and process. Of great importance is the correct identification of the bankfull discharge and the benchfull discharge. With more data it may be possible to relate particular features to salient channel characteristics (degree of bed rock influence, channel gradient etc) both within a river and between rivers. In regulated systems, or in systems recovering from a major reset event, the bench is probably the new bankfull stage. Active channel incision or widening may result in an exaggerated estimate of the bankfull event. It is thus evident that the discharge related significance of morphological features identified in the field is often unclear. It is recommended that, in setting IFRs, a combination of an interpretation of the morphological features present and calculation of the effective discharge is used. This provides a useful means of identifying whether the river under consideration has in fact adjusted its geometry in sympathy with the regulated flow. Flow objectives can then be set depending on whether restoration to the 'natural state' is required, or whether maintaining the status quo is acceptable.

12.5 Research products and recommendations for future research

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. McGregor (2000) studied downstream impacts of the Sandile Dam on the Keiskamma and, more recently, a WRC funded projected has been completed (Beck and Basson, 2002). 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 imminent 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 Limpopo 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. The effective discharge model developed in this project was based on the concept of transport capacity and assumed that the transport process was transport limited. Although the model took account of the available sediment present within the study reach, it was unable to account for the sediment supply from upstream. 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 monitoring devises such as bedload traps. The pitfalls of making such measurements are well recognised and most field research has been located in small gravel bed streams. Problems are compounded in large rivers.

or in rivers with a coarse bedload or a bedrock pavement. Non the less 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.

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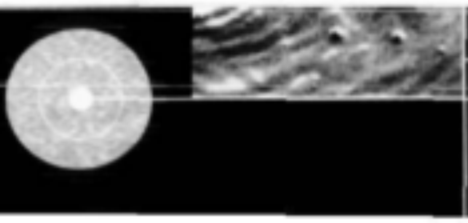

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