A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers

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EXECUTIVE SUMMARY

INTRODUCTION

South African rivers are under stress from a number of directions; direct abstraction of water, impoundments and associated interbasin transfers, gravel and sand abstraction, increased sediment inputs from eroded catchments and channelisation are amongst the actions which impact directly on the physical channel. The channel, together with the flow of water, sediment and nutrient, provides the physical habitat for aquatic ecosystems so that any disturbance of the channel morphology will also affect the availability of habitat. The study of channel form and channel forming processes is encompassed by the science of fluvial geomorphology, the application of which is fundamental to any assessment of the impact of river related developments, or attempts to redress former impacts through river restoration programmes. This project considers a number of relevant geomorphological concepts within a South African context and presents a geomorphological framework within which the impacts of water management on channel form and associated ecological processes can be assessed.

Geomorphological processes operate over a wide range of temporal and spatial scales, from the catchment to the channel bar and from geological time to the individual flood event. Although the channel and its associated habitats is the focus of ecological research, it is important to place the channel network in the context of the catchment which supplies the water and sediment which are conveyed through the channel, and hence the energy and materials necessary to form the channel. A hierarchical framework is presented which enables the linkages between the catchment and channel to be modelled over a range of spatial scales. Eexamples of how this model can be applied to river management include the Buffalo River in the Eastern Cape, the Sabie River in Mpumalanga and the Olifants River in the Western Cape.

PROJECT AIMS

The project aims as agreed in the original contract between Rhodes University and the WRC, and amended by the Steering Commitee for the project, are summarised below:

- To ascertain the important geomorphic and hydraulic criteria in terms of habitat.
- To develop a methodology for selected catchments for classifying the geomorphological components of lotic ecosystems.
- To extend this methodology to a wide range of South African river systems as a management tool for the assessment of conservation potential.

CHAPTER ONE: INTRODUCTION

This chapter provides a general introduction to fluvial geomorphology and its relevance to stream ecology. The aims of the research programme are outlined. A brief introduction is given to the three research catchments selected for this study together with their general characteristics. The research approaches selected for this study are outlined and a statement is made about potential management implications of the study. A statement is made about the status of Geomorphology in South Africa and the perceived need for further development to strengthen links between the physical and biotic components of river systems.

CHAPTER TWO: RIVER CLASSIFICATION

This chapter reviews the history of stream classification from both an ecological and geomorphological perspective. The chapter focuses on hierarchical models of stream classification which link large regional scales with small micro-habitat scales. The hierarchical approach is considered to be most appropriate for the development of a South African geomorphological system because the basic assumption is that the structure and dynamics of the stream are determined by the surrounding catchment.

Frissell *et al's* (1986) model is considered in detail and is used as a template for the development of a South African river classification system. The various nested levels of the hierarchy are considered separately, these include:

The Catchment -	the land surface which contributes water and sediment to any given stream network.
The Zone -	areas within a catchment which can be considered as homogenous with respect to flood runoff and sediment production.
The Segment -	a length of channel along which there is no significant change in the imposed flow discharge or sediment load.
The Reach -	a length of channel within which the local constraints on channel form are uniform, which has a characteristic channel pattern and degree of incision and within which a characteristic assemblage of channel morphologies occur.
The Morphological Unit -	the basic structures recognised by fluvial geomorphologists as comprising the channel morphology (either erosional or depositional).
Hydraulic Biotopes -	a spatially distinct instream flow environment with characteristic hydraulic attributes.

CHAPTER THREE: LITERATURE REVIEW: GEOMORPHOLOGICAL PROCESSES AND CLASSIFICATION

The hierarchical model promoted in this report describes the linkages between the catchment which supplies water and sediment to the channel network, the drainage network through which the sediment and water are routed, and the channel morphology at the reach scale which provides the habitat for stream organisms. This chapter considers the important geomorphological variables that need to be considered for each level of the hierarchy. The chapter outlines the important processes operating, the variables which control the rate and direction of those processes and the resulting channel morphology. The literature on fluvial geomorphology is vast and in a review such as this which encompasses a large range of scales it has not been possible to cover all pertinent literature, nor to explore all relevant concepts in detail. The most often cited and relevant literature for this review includes texts and edited volumes by Calow and Petts (1992), Knighton (1984), Morisawa (1985), and Richards (1982, 1987). It is hoped that the most important aspects have been covered and that the reader can be directed to the original sources for further information.

CHAPTER FOUR: THE HYDRAULIC BIOTOPE CONCEPT

The term 'hydraulic biotope' is suggested as a more appropriate term than 'habitat', for the description of ecologically significant instream flow environments. A distinction is made between these temporally unstable features and the more stable channel form features recognised in fluvial geomorphology. A standardised terminology is introduced to describe the more common hydraulic biotope classes observed in South Africa. The problem of a standardised objective technique for biotope classification is addressed and a possible solution presented in the form of the hydraulic biotope matrix. It is envisaged that the biotope matrix will provide the initial impetus for the further development of a more rigorous technique.

An examination of the definition of geomorphological units and their associated biotopes shows that although there is often a coincidence of geomorphological and ecological terminology there are also significant discrepancies. Geomorphologists are concerned with broad scale features defined in terms of gross structure and form, which ecologists further subdivide on the basis of flow hydraulics and substrate availability. The subdivision of pools into pools and runs is a good example of this.

Ecologists not only subdivide morphological features into smaller spatial units, but also recognise temporal changes in biotope definitions because of biotic response to changes in physical conditions. To a geomorphologist a pool riffle sequence remains as such regardless of flow discharge. The biotope associated with each morphological unit may change as discharge changes. For example a pool with low flow velocities during base flow conditions may become a run as velocities increase during a flood event. Similarly riffles may be converted to runs as they are drowned out during high flows.

An important distinction made by geomorphologists, but not explicitly recognised by ecologists, is that between alluvial and bedrock features. The form and spatial distribution of alluvial features are closely related to discharge patterns and sediment supply so that upstream developments which alter these will also impact on the morphological units. In contrast, bedrock features, which are strongly controlled by the resistance of the geological strata and the long term erosional history of the river, respond more slowly and in a less predictable way to such disturbances. As ecologists become more concerned with the impact of channel change on the available in-stream environment it is important that they distinguish biotopes in terms of their likely response to change. The distinction between an alluvial riffle and a bedrock rapid therefore should be of significance to both geomorphologists and ecologists.

CHAPTER FIVE: FLOW HYDRAULICS AND THE INSTREAM FLOW ENVIRONMENT

The flow of water down a river channel due to gravity may be described as mean motion (Smith, 1975); it may be characterised by two numbers: the Reynolds number and the Froude number, both of which can be considered as indicators of flow conditions experienced within a column of water. The Reynolds number describes whether the mean flow is laminar or turbulent, and the Froude number describes whether the flow is subcritical, critical or supercritical. A particular feature of the Froude number is that, being based on the ratio of velocity to depth, it is independent of scale so that large and small features classify together if bulk flow conditions are similar. In contrast, the Reynolds number, based on the product of depth and velocity, is scale dependent and therefore is a measure of the magnitude of hydraulic variables.

By combining the Froude and the Reynolds numbers, mean flow may be classified as either subcritical-laminar, subcritical-turbulent, supercritical-laminar and supercritical-turbulent. Supercritical-turbulent and subcritical-turbulent are the most commonly occurring flows in streams and rivers (Chow, 1959).

The use of velocity and depth by lotic ecologists as defining variables to describe important instream habitats suggests that they have special significance to the aquatic biota living there. These two variables are the key components of the hydraulic indices describing mean motion of flow (the Reynolds number and the Froude number). The fact that both these indices are dimensionless and that the Froude number is independent of scale, allows one to hypothesise that these indicators of flow may be extremely useful indices for the characterisation of hydraulic biotopes.

The patterns of flow within the microenvironment form an important component of the physical habitat for aquatic organisms. A number of simple measures are available to describe the flow conditions near river beds. Hydraulic indices which are likely to have special significance to the aquatic biota, and hence the classification of near bed hydraulic biotopes, are the shear velocity (as it relates to the laminar sub-layer) and the 'roughness' Reynolds number. It is hypothesised that if relationships are shown to exist between the hydraulic indices describing mean motion (Reynolds and Froude numbers), and the hydraulic biotope, so too might there be relationships between the hydraulic indices describing the microflow environment and the hydraulic biotope.

Davis and Barmuta (1989) after Morris (1955), recognised five near bed flow regimes; they may be either hydraulically rough or hydraulically smooth. Hydraulically rough flow can be further classified as either chaotic flow, wake interference flow, isolated roughness flow or skimming flow (Figure 5.5 & 5.7). These flow classes are largely based on measures of bed topography and as such are less likely than surface flow conditions to show good relationships with the hydraulic biotopes described in Chapter 4.

The hypothesis that the indices describing both mean and near bed flow conditions may show associations with hydraulic biotopes needs to be tested. If such associations are found it is envisaged that these hydraulic indices may provide a quantitative basis for the classification of hydraulic biotopes. This classification will assist the comparison of similar features both within and between different fluvial environments.

CHAPTER SIX: CLASSIFICATION OF HYDRAULIC BIOTOPES

Analysis of results in this chapter suggest that we can define the hydraulic biotope as an instream flow environment which has specific mean and near bed variability of flow. Useful hydraulic indices to describe these flow conditions are the Froude number and velocity-depth ratio (mean), 'roughness' Reynolds number and shear velocity (near bed).

The hydraulic biotope matrix as a tool for the identification of different hydraulic biotope classes appears to be extremely useful as it has been shown to be valid at a number of different spatial and temporal scales. Statistical analysis of results supported the hypothesis that hydraulic biotope classes recognised at different sites and at different discharges do not show significant difference in their hydraulic characteristics as defined by the Froude number, 'roughness' Reynolds number and shear velocity.

Specific associations appear to exist between channel morphology and hydraulic biotope class distribution. Various patterns of class progression occur as a dynamic responses to changes in discharge. Both the greatest diversity of hydraulic habitat and the optimum combination of different flow types was observed at intermediate discharges. Very low discharges resulted in extensive pool hydraulic biotope in all morphological units, with little diversity, whereas at the highest discharge hydraulic biotope diversity was also lost as local hydraulic controls were drowned out.

The relationships described here are for a localised selection of morphological units in one river system. The next challenge is to extend this research to a wider range of morphological units and river environments to see if general relationships can be found. This would provide an important step forward in formulating models which predict available habitat from channel geomorphology and could prove invaluable to future instream flow assessments.

CHAPTER SEVEN: THE GEOMORPHOLOGICAL HIERARCHY: METHODS

This chapter presents, in detail, all methods used to carry out a full hierarchical classification of the Buffalo River, Eastern Cape. The chapter serves as a handbook of instruction for a user who wishes to carry out a geomorphological classification of any South African river system. Certain prerequisites need to be met for the classification to take place. The user must have a working knowledge of the geographical information system software *ArcInfo* together with *Arcview*. An important source of information necessary for part of the geomorphological classification is the national digital data base of the WR90 Report (Pitman *et al*, 1994). A certain degree of geomorphological training or understanding is required for the analysis of results.

CHAPTER EIGHT: APPLICATION OF THE HIERARCHICAL MODEL TO RIVER MANAGEMENT

The geomorphological model presented in this report provides a conceptual framework which can be used to support the decision making process in catchment management. Two examples have been given as to how this can be achieved; inputs to the Building Block Methodology used in the IFR procedure and inputs to a National Biomonitoring Programme for riverine ecosystems.

To provide effective answers for river management any model needs to be linked to process models which estimate the hydrological and sediment response of the catchment and river system. The level of sophistication of the chosen models depends on our level of understanding of the processes themselves, the availability of the necessary data, and the financial and time constraints of the manager. In a management context the latter two constraints tend to be the limiting ones. The proposed hierarchical geomorphological model lends itself to the application of both simple process models appropriate for the rapid assessments often needed in decision making and also the more complex research models which scientists strive for in their long term goal of predicting system response to management decisions and catchment developments.

CHAPTER NINE: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The final chapter presents an overview of the project and makes recommendations for further research. Tangible research products are described as, firstly, a set of techniques for describing and classifying components of river systems within a framework which conceptualises the links between different scales in the catchment system and, secondly, the development of the hydraulic biotope concept and associated classification as the finest spatial scale at which geomorphologists, hydraulic engineers and ecologists can conveniently work together. The conclusion also points to a number of other less tangible but equally significant outcomes of which the most important has been the strengthening of links between river ecologists and geomorphologists and the recognition of geomorphology as an essential component basic to our understanding of river processes and ecological functioning.

Directions for future research were given as follows:

- improved catchment scale modelling of sediment source areas and sediment yield,
- research into channel forming flows and the dominant discharge concept,
- further work on the relationship between hydraulic biotopes, morphological units and discharge and the ecological validation of the hydraulic biotope classification.

There is also thought to be considerable scope of developing the hierarchical model as a decision support tool for management situations. Finally there is a need for a national geomorphological inventory of South African rivers.

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CHAPTER ONE
INTRODUCTION

1.1 INTRODUCTION

Fluvial geomorphology is the study of landforms shaped by the action of running water. In scope it ranges from the scale of morphological units at a single location on the channel to the drainage basin which is the landscape unit that integrates the channel network and its catchment area. Fluvial geomorphology encompasses both the description and classification of form and the study of the dynamic processes which effect both short term and long term change in the system. The search for an understanding of changes in channel morphology through time and space therefore underlies the development of concepts and theory in fluvial geomorphology.

South African river systems are strongly impacted by anthropogenic disturbances such as impoundments, interbasin transfer and land use changes which alter the flow and sediment regime. This problem is likely to escalate as South Africa strives to meet its future water needs. The morphology of the river channel reflects this imposed regime so that anthropogenic disturbance in the catchment can lead to adjustment of channel morphology. This morphology provides the physical habitat for lotic ecosystem and hence channel habitat and associated biota (Petts, 1980). Whereas the magnitude of the disturbance is likely to be a function of the characteristics of the impacted catchment, the mode and extent of channel adjustment, or the sensitivity to disturbance, is a function of local channel geomorphology described in terms of gradient, substrate type, bank materials and vegetative cover (Knighton, 1984, Schumm, 1979, Chang, 1984, 1986).

If our rivers are to be managed so as to conserve their ecological integrity[1] it is important that river managers are provided with a system by which rivers can be categorised or classified with respect to their geomorphic characteristics at both the catchment and the channel scale. Such a system would firstly contribute to our knowledge of the present state of rivers in this country and, secondly, aid the prediction of channel adjustment and associated habitat transformation in response to changes in the flow and sediment regime. For example, methods such as Instream Flow Incremental Methodology (IFIM) used for the assessment of habitat availability under changed flow conditions (Gore and King, 1989) assume a stable channel cross-section whereas in fact the channel morphology and substrate conditions are likely to be modified along with the flow. The classification would aid the identification of stability thresholds beyond which direct application of IFIM would be unjustified.

The relevance of geomorphological concepts to stream ecology requires little justification. At the local scale, geomorphological processes shape the channel form which determines instream micro-habitat. At

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[1]Ecological integrity is defined by Kleynhans (1996) as the ability of the river to support and maintain a balanced, integrated composition of physico-chemical habitat characteristics, as well as biological components, on a temporal and spatial scale, that are comparable to the natural characteristics of ecosystems of the region.

the drainage basin scale, channel catchment linkages determine the macro-habitat in terms of the flow regime, water quality, temperature, nutrient cycling and so on. The development of stream ecology as a science will therefore be enhanced by an understanding and application of geomorphological concepts.

In South Africa, fluvial geomorphology has been a neglected discipline and it is only in the last decade that significant research has been initiated to study contemporary fluvial systems. An examination of South African river literature shows that it is the ecological community which has carried out most research on the physical characteristics of the country's rivers (Ferrar 1989; Davies *et al.*, 1993). While to some extent this has been based on globally accepted geomorphological concepts, there has also been a tendency to create an idiosyncratic South African eco-geomorphology. There is a need to integrate ecological thinking with a sound understanding of geomorphological theory and to develop a common terminology to allow better communication between river practitioners.

This project was initiated in order to address the need to integrate ecological and geomorphological thinking through the development of a classification system that would describe geomorphological features across a wide range of scales in a manner that was both relevant and meaningful to ecologists. The research was based on a hierarchical classification framework using spatially nested levels of resolution to provide a scale based link between the channel and the catchment. A number of similar schemes which incorporate geomorphological concepts have been developed as tools for effective water management. Many of these classifications are based on Frissell *et al.*'s (1986) framework which addresses form and pattern within a number of hierarchical levels.

In this research Frissell's model has been adapted as the basis of a classification of South African river systems and a tool for river basin management. The South African model has six nested levels: the catchment, the response zone, the stream segment, the reach, the morphological unit and the hydraulic biotope. This is a cascading system in which each level provides the input into the lower one. This framework provides, firstly, a scale-based link between the channel and the catchment so as to account for catchment dynamics and, secondly, allows a structured description of spatial variation in stream habitat. This hierarchical model thus provides the spatial framework for the classification of physical features upon which process models of catchment hydrology, flow hydraulics and sediment transport can be based.

It is believed by the authors that the hierarchical system described in this report represents a number of advances beyond previous systems. Firstly, by detailing a standard procedure for developing each level of the hierarchy, it goes considerably further than merely providing a conceptual research framework as presented by Frissell *et al.* (1986). Where available, comprehensive classification systems are presented, enabling researchers to describe channel features according to a common system. Secondly, in developing the system, due attention was given to all levels of the hierarchy. In a number of extant classifications which claim to be based on a hierarchical system, the focus has clearly been at one or two scales placed within an ill defined hierarchical context. Having said this, in this project particular attention has been paid to developing the lowest level of the hierarchy, the hydraulic biotope. The hydraulic biotope describes the instream habitat for stream biota and is a function of the interaction between flow and channel morphology. It thus represents the fundamental link between stream ecology and geomorphology. Developing the hydraulic biotope concept and validating a classification system for hydraulic biotopes became a major focus of the research. It was not possible, given the time constraints of the project, to develop all levels of the hierarchy to their full extent. It is felt, however, that the system provides both a working model for immediate application to river management issues and a sound framework which can be developed further as the need and the capability arises. The system has been widely applied by the authors to a number of practical issues such as Instream Flow Assessments and has been adopted as the standard framework for describing the geomorphology of the river systems for which assessments are to be made.

1.2 AIMS

The aim of the research programme was to provide ecologists and river managers concerned with conserving ecosystem health or integrity with a relevant geomorphological framework to aid the explanation of ecosystem processes and biotic distributions and contribute to a decision support system for management. Specific aims of the project were set out in the original proposal as follows:

- To ascertain the important geomorphic criteria which determine habitat sensitivity to natural or anthropogenic disturbance.

- To develop a methodology for selected catchments for classifying the physical habitat of lotic ecosystems (running water).

- To extend this methodology to a wide range of South African river systems as a management tool for the assessment of conservation potential.

The main product of the research has been a hierarchical geomorphological model or classification framework. This model should provide a useful tool for all those involved in catchment or river research, be they river scientists such as ecologists and geomorphologist or river managers. It is envisaged that the model could provide:

- a description of the physical framework which regulates many of the natural ecological processes,
- standard terminology so that features of different scales can be described and linked,
- a spatial framework for river research,
- a basis for classifying rivers for the development of management guidelines.

1.3 RESEARCH CATCHMENTS

The development of the hierarchical geomorphological model as proposed in this report took place in the context of research based in three catchments, the Sabie, the Buffalo and the Olifants. These three rivers have separately been the focus of ecological research; they were also deemed to represent three systems in very different hydrological and geomorphological environments.

The Sabie drains the Eastern Escarpment of Mpumalanga, flowing through the Kruger National Park in its lower reaches. The Sabie River is the only perennial river flowing through the Kruger National Park. It remains one of the least impacted of the major river systems and therefore has a high conservation status. Through the Kruger National Park Rivers Research Programme there is an ongoing research effort looking at the instream flow requirements of this system, including the geomorphological flows. To date there are no major impoundments on the Sabie River, but the upper catchments are impacted by commercial forestry and irrigated farmland which together place a high demand on water either on the upper catchment slopes or from the river itself.

The Buffalo River drains the Amatola Mountains in the Eastern Cape. Although relatively pristine in its upper reaches, its lower reaches are impacted by urban developments and dense peri-urban and rural settlement. Four impoundments supply water to King Williamstown and East London. The Buffalo provided a convenient river for field study as it lies reasonably close to Grahamstown.

The Olifants River drains the Ceder Berg in the Western Cape. Its source lies on a relatively flat plateau which has been developed for agriculture. The upper-middle reaches are confined within a gorge or narrow valley so are relatively undisturbed, the flood terraces of the lower middle and lower reaches are under intensive irrigated citrus orchards and vineyards. There are two impoundments in the middle reaches of the Olifants, upstream of these direct abstraction by irrigators places a severe demand on low flows. The lower reaches of the Olifants are controlled by releases from ClanWilliam and Boelshoek dams which are determined by irrigation demand rather than environmental needs.

It is clear that the ecological integrity of all three rivers is under threat from developments in the catchments. It was anticipated that by focussing on these three rivers they would firstly provide three contrasting systems on which to test the viability of the model and, secondly, provide a geomorphological data base which could be used in a management context as the need arose.

1.3.1 General characteristics of the Sabie, Buffalo and Olifants rivers

The three rivers represent distinct geomorphological environments. The Sabie rises above1700 m in the high veld of the Great Escarpment and flows across the semi-arid low veld, traversing the Kruger Park before entering Mozambique. The total length of the river up to its confluence with the Mkomati in

Mozambique is 210 km. The Buffalo is a shorter river (125 km) which rises above1300 m in the forested Amatola mountains of the Eastern Cape, crossing the coastal plateau before reaching the sea at East London. The Olifants river rises in the Cederberg mountains of the Western Cape above 700 m. It flows northwards through the well defined Olifants valley before meeting with its much larger Karoo fed tributary, the Dorings. The Olifants then crosses a coastal plain before reaching the sea near Vrehdendahl, a total river length of 280 km.

All three rivers are characterised by a concentration of rainfall over the head water areas and sub-humid to semi-arid lower catchments. Rainfall over the Sabie catchment varies from 2000 mm to 450 mm, the Buffalo from 2000 mm to 500 mm and the Olifants from 1300 mm to less than 300 mm.

Both the Sabie and the Buffalo have been affected by significant uplift and rejuvenation. The Sabie below the Great Escarpment crosses three planation surfaces of Partridge and Maud (1987), the African surface of the early Cretaceous, the Post African surface of the Early Miocene and the Post African II surface of the late Pliocene. Uplift in this area was probably around 300 m in the Miocene and somewhat less than 600 m in the Pliocene. The lower Buffalo river crosses the Post African I surface and the marine platform of the earlier African surface. Uplift in this area was in the order of 200 m and 800 m in the Miocene and Pliocene respectively. In contrast, the western coast experienced much reduced uplift, 150 m and 100 m in the Miocene and Pliocene respectively in the catchment area of the Olifants river. The Olifants is largely confined to dissected mountainous country and only crosses small remnants of the African and Post African I erosion surfaces near the coast.

The geology of the three areas is also significantly different. Much of the Sabie is underlain by intrusive rocks - gneiss, tonalite and granites. These rocks tend to produce coarse sands and gravels on weathering. The Buffalo catchment is largely underlain by Karoo sediments, predominantly mudstones, shales and sandstones, which give rise to fine textured sediment. Dolerite dikes are frequent and outcrop along the length of the channel, providing local inputs of fine sediment. The geology of the Olifants catchment is complex. The upper catchment is comprised of fine grained shales, mudstones and sandstones. The middle catchment is dominated by sandstones and quartzites of the Table Mountain Group. The lower catchment is underlain by carbonaceous shales and limestones of the Malmsbury Group. The predominant sediment producing rocks in the upper Olifants are sandstones and quartzites which produce a sandy bedload. Even in flood conditions the water of the Olifants remains clear.

1.4 RESEARCH APPROACHES

1.4.1 Review of Classification Methods

Rivers have been a frequent subject for classification by scientists from a wide range of disciplines including both ecologists and geomorphologists (Mosley, 1987). The review presented in this report

(Chapter 2) focus on the geomorphological classification of rivers, but attention is paid to the relationship between geomorphological and ecological classifications where appropriate. Classification systems are described under separate groups: whole river systems, zonal classifications, morphological classifications and hierarchical classifications.

The classification system presented in this report closely follows recent research trends in stream categorization (Bailey, 1978; Lotspeich, 1980; Brussock *et al*., 1985; Rosgen, 1985; 1994; Frissell *et al*., 1986; Cupp, 1989 and Kellerhals and Church, 1989): a system whereby the characteristics of the stream are defined on several spatial and temporal scales according to the geomorphological processes operating within the catchment.

1.4.2 Geomorphological Variables for Stream Classification

The hierarchical model promoted in this report describes the linkages between the catchment which supplies water and sediment to the channel network, the drainage network through which the sediment and water are routed, and the channel morphology at the reach scale which provides the habitat for stream organisms. For each level of the hierarchy, Chapter 3 outlines the important processes operating, the variables which control the rate and direction of those processes and the resulting channel morphology.

1.4.3 Development of the Hydraulic Biotope Concept

The term 'hydraulic biotope' is suggested as a more appropriate term than 'habitat' for the description of ecologically significant instream flow environments. A distinction is made between these temporally unstable features and the more stable channel form features recognised in fluvial geomorphology. A standardised terminology is introduced to describe the more common hydraulic biotope classes observed in South Africa. The problem of a standardised objective technique for biotope classification is addressed in Chapter 4 and a possible solution presented in the form of the hydraulic biotope matrix.

1.4.4 Flow Hydraulics

Stream ecologists frequently use velocity and depth to describe or define important instream habitats. This suggests that these two variables are thought to have special significance to the aquatic biota living there. These two variables may act independently, but may also act in combination through a number of hydraulic indices which describe either the mean flow (average conditions in the water profile) or near-bed conditions. For example they are the key components of the hydraulic indices describing *mean motion of flow*, the Reynolds number and the Froude number. They are also related to near-bed hydraulic indices such as the shear velocity (as it relates to the laminar sub-layer) and the 'roughness' Reynolds number.

Chapter 5 reviews the different hydraulic measures and indices which are thought relevant in describing instream habitat conditions. It is hypothesised that quantifiable relationships may exist between hydraulic biotopes, described in terms of surface flow characteristics and bed substrata, and the various hydraulic indices describing mean motion (Reynolds and Froude numbers) and the near-bed environment. These relationships are tested through research described in Chapter 6.

1.4.5 Experimental Studies

The research on hydraulic biotopes undertaken in the present project progressed through a number of pilot studies during which ideas on classification and measurement developed. These finally came together in an in-depth study based in the Buffalo River.

Preliminary studies were carried out in the upper and middle reaches of the Sabie River. This research provided useful insights into classification approaches and helped to draw attention to the need to distinguish between morphological units and the hydraulic biotopes themselves. The results themselves were not in a suitable format for presentation in this report. Four further studies are described. The first was at a single site in the Great Fish River, where flow regulation enabled the study of hydraulic biotope dynamics at a range of discharges (Wadeson, 1994). A second study in the Molenaars River, Western Cape, used cell classifications in order to study the spatial variability within different morphological units located in four separate reaches. This study was a useful exercise in underlining the need for standardised data collection methods which were used in subsequent surveys. A third study was carried out in the Olifants River in the western Cape, focussing on a sand bed reach. This provided a useful comparison to the Buffalo River study which included boulder, cobble and bedrock reaches.

1.4.6 Methods

The methods used for a complete hierarchical classification system are discussed in Chapter 7. This chapter forms the basis for an operation manual. Practical examples for each level of the hierarchy are given based on work carried out in the Buffalo River.

1.4.7 Management Applications

The geomorphological model presented in this report provides a conceptual framework which can be used to support the decision making process in catchment management. Two examples have been given as to how this can be achieved; inputs to the Building Block Methodology used in the IFR procedure and inputs to a National Biomonitoring Programme for riverine ecosystems.

1.5 TERMINOLOGY

An important outcome of this research has been the development a common language to faciliate communication between geomorphologists and stream ecologists. Many geomorphological and hydraulic terms have been introduced which will undoubtedly be unfamiliar to most ecologists. These have been explained as far as possible in the text. For further explanations the reader is referred to the numerous dictionaries of physical geography such as the Penguin Dictionary of Physical Geography published by Penguin (Whittow,1984) or The Encyclopaedic Dictionary of Physical Geography (Goudie *et al*.,1991)

CHAPTER TWO
RIVER CLASSIFICATION: APPROACHES & FRAMEWORK

2.1 INTRODUCTION

Classification, in the strictest sense, means ordering or arranging objects into groups or sets on the basis of their similarities or differences (Platts, 1980; Gauch, 1982). It is a tool which has been used in virtually all sciences, particularly in their early stages of development.

Rivers have been a frequent subject for classification by scientists from a wide range of disciplines including both ecologists and geomorphologists (Mosley, 1987). Motivations for identifying different types or classes of river have varied widely, from the desire of the scientist to enhance his or her understanding of river behaviour and morphology by highlighting common characteristics of a given river type, to the need of an engineer or freshwater fishery manager to extrapolate experience and knowledge of a given river to rivers which behave in a similar fashion (Mosley, 1987). Classification and the development of a consistent terminology is also necessary as the basis of communication between scientists, both within and between disciplines. In the field of stream ecology, where geomorphological features provide the physical framework within which ecosystems exist, this is particularly important. Despite the pressing need, the classification of fluvial systems remains in a formative stage because of the dynamic changes that occur over broad spatial and temporal scales (Salo, 1990), and because classification systems only reflect the current state of knowledge on river function (Frissell *et al.*, 1986).

Implicit in the endeavour to classify any natural feature or ecological system is the assumption that relatively distinct boundaries exist and that the boundaries may be identified by a set of discrete variables. The classification of streams is complicated, however, by both longitudinal and lateral linkages, by changes that occur in the physical features over time, and because boundaries between apparent patches in fluvial systems are often indistinct (Naiman *et al.*, 1988; Pringle *et al.*, 1988). Connectivity and variability are fundamental for the long-term maintenance and vitality of stream systems, and become essential but complicating factors in developing an enduring classification scheme (Naiman *et al.*, 1992).

The history of stream classification from an ecological view point has been reviewed comprehensively by Macan (1961); Illies and Botosaneanu (1963); Hawkes (1975); Wasson (1989) and recently Naiman *et al.* (1992). The present review focuses on the geomorphological classification of rivers, but attention is paid to the relationship between geomorphological and ecological classifications where appropriate. Classification systems are described under separate groups: whole river systems, zonal classifications, morphological classifications and hierarchical classifications.

2.1.1 Whole river system classification

The drainage system is composed of a complex system consisting of the drainage network and its catchment area. It is only at the level of the entire river system that the linkages between the catchment and the channel network, and between the upstream and downstream channel, can be effectively considered. These considerations are important to concepts of zonation or the river continuum concept of Vannote *et al.* (1980). It is, however, difficult to impose a classification system at this level because of the uniqueness of river systems.

River systems are composed of a hierarchy of catchments with small catchments nested within larger ones as indicated in Figure 2.1. The relative scale of these nested catchments and their river systems can be measured using an ordering system such as that proposed by Horton (1945) and Strahler (1957). Source streams and their catchments are designated as order 1, as low order streams come together the order increases as indicated in Figure 2.1. The magnitude of a river system at any point within the larger river system can thus be described and compared to other systems.

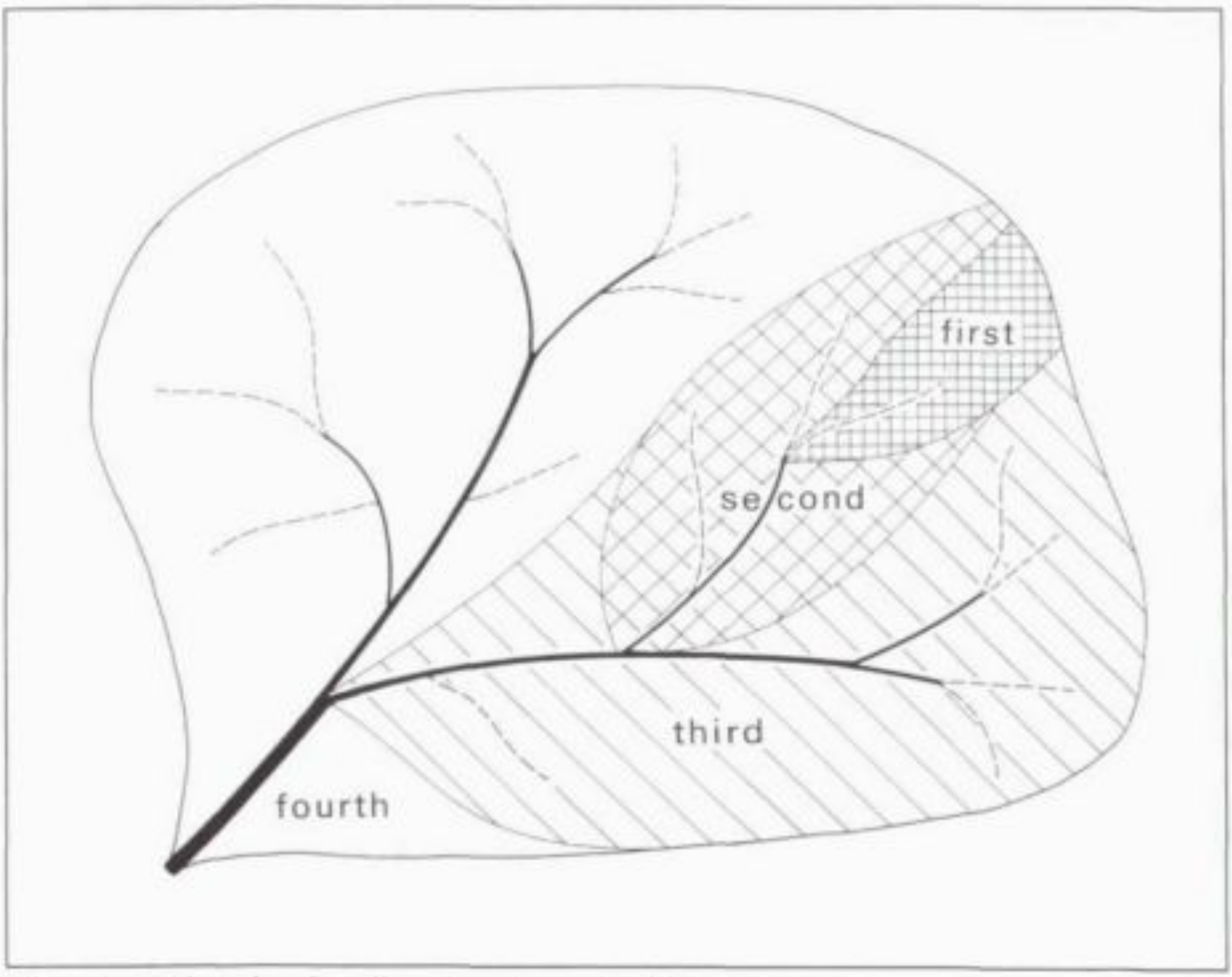


Figure 2.1 A hierarchy of small catchments nested within a larger one

Topographic indices are also available to describe and compare the relief and shape of catchments which can be applied to any order. They include indices such as basin relief, relief ratio, basin shape and the hypsometric curve. These are detailed in section 3. 8 (Chapter 3) . Indices are also available to describe the drainage network, such as drainage density and the bifurcation ratio (sections 3.7 and 3.8). These indices can be applied at any order, from first order catchments to the entire river system.

Other whole system classifications make reference to regional variables which control catchment processes such as climate, geology, natural vegetation and so on. Bull *et al.* (1988) used a multivariate approach to classify 72 catchments into 8 classes based on their physical characteristics. They came up with broad grouping which they were able to relate to biological and chemical data. This approach may work well for relatively low order catchments, but for larger catchments it may be that the degree of uniqueness would defy classification. Large catchments cut across climate, geology and vegetation zones so that classification would have to be in terms of the mix of variables.

South African ecologists have made a number of attempts to define homogenous regions within which rivers are expected to show a similar physical or biotic response. These include the eco-region map of Roux and Everett (1994), groupings of rivers based on flow variables (Joubert and Hurley, 1994) on chemical characteristics (Harrison and Agnew, 1962, Day *et al.*, 1994), or on stream biota (Eekhout, 1994). Although useful, these classifications tend to be based on the grouping of points in rivers without reference to the larger river system of which they are a part. The resulting classifications therefore cut across catchments rather than classify river systems themselves.

In general, classification of entire river systems has proved difficult whenever several variables have been taken into account. This is because rivers and their catchments are composed of a complex system of linked components situated within a particular geographical environment. Hence each system may well comprise a unique entity. Mosley (1987) proposes that it may be more useful to classify rivers in term of their parts, or homogenous stretches which can be identified and classified

2.1.2 Zonal classifications

A number of river classification systems have been based on the concept of zonation down the long profile. Probably the earliest geomorphological zonal classification was that of Davis (1890) who subdivided the channel and adjacent catchment in terms of gradient. The steep headwater zones were termed youthful, being characterised by high potential energy and active degradational processes, the foothill areas were termed mature, with more gentle slopes, less active degradation and a tendency to equilibrium between erosion and sediment deposition in the channel, a condition traditionally termed 'grade' (Makin, 1948). The lower zones of the river and catchment, characterised by low gradients and therefore low potential energy, were termed old age, and were thought to be zones dominated by low velocity flows, deposition and low rates of catchment denudation. Davis's scheme, which was linked to a model of long term landscape evolution, has largely been discredited because his ideas were not based on a good understanding of river processes. Interpreting his concept of river ages as being related to true age is unfounded as there is no reason to believe that mountain streams are in fact any younger than coastal systems which are often superimposed on recent sediments or low angle platforms related to sea level change. Nonetheless, the idea of a progressive change in river characteristics as one moves down the channel remains valid and has provided the basis of a number of more recent zonal classifications.

Schumm (1977) envisaged an idealised fluvial system as consisting of three zones: an upper zone of sediment production (source), where the major controls were climate, diastrophism and land use; a middle zone (transfer) essentially in equilibrium; a lower zone (sink or depositional area), where controls were base level and diastrophism (Figure 2.2). This idealised and simplistic description has been adopted by numerous researchers for the classification of river systems (Newson, 1992).

The simple model of Schumm (1977) was further extended by another geomorphologist, Pickup (1984), and used to explain variation in bedload characteristics and movement in the Fly and Purari Rivers of Papua New Guinea. The result of this study was the identification of five separate zones, each with their own characteristic particle size distribution. The zones were labelled as the "source", "armoured", "gravel-sand transition", "sand" and "backwater" (Figure 2.3). Pickup stresses that these zones reflect variations in the controls of gradient, bed material, stream power potential, and the ability to move different sized materials at different frequencies. The resultant segments or zones have a distinctive set of slope, sinuosity and width depth ratio values.

Zonal classifications have been widely adopted by ecologists to explain variations in biotic distributions down the long profile (Hawkes, 1975). A major contribution to ecological zonation was that of Illies (1961) and Illies and Botsaneanu (1963). They developed a system which divided streams into eight zones based on such physico-chemical variables as water temperature, water velocity, substrata and altitude (Illies and Botsaneanu, 1963). These zones correlated closely with biological zones. Their basic structure was adopted by Harrison (1965) and Noble and Hemens (1978) for the classification of South African river zones. Their zones are summarised in Table 2.1. It should be noted that although referring to geomorphological features, these zonal descriptions are based more on Davisian concepts rather than current geomorphological thinking. A number of misconceptions are apparent in the classification. For example, a wide number of geomorphological studies have shown that, as long as discharge increases downstream, so too does the average flow velocity through a section due to a marked reduction in channel roughness. In headwater areas flow velocities are highly variable, with rapid flow over waterfalls and cascades, but very slow flow within pools. In lowland areas velocities are much more uniform, but overall velocity is at least equal to that higher up the stream system. An alternative zonation scheme based on geomorphological criteria is presented in section 3.6.

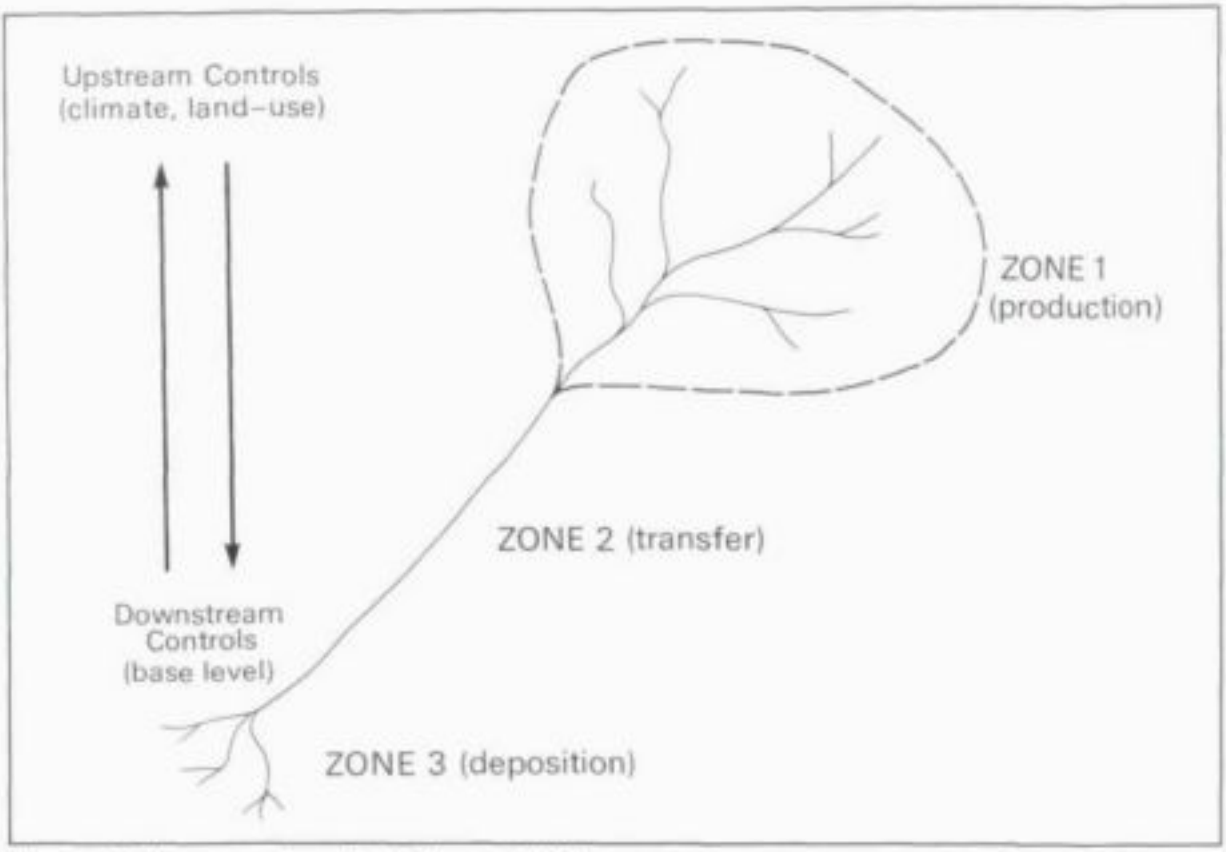


Figure 2.2 River zonation after Schumm (1977)

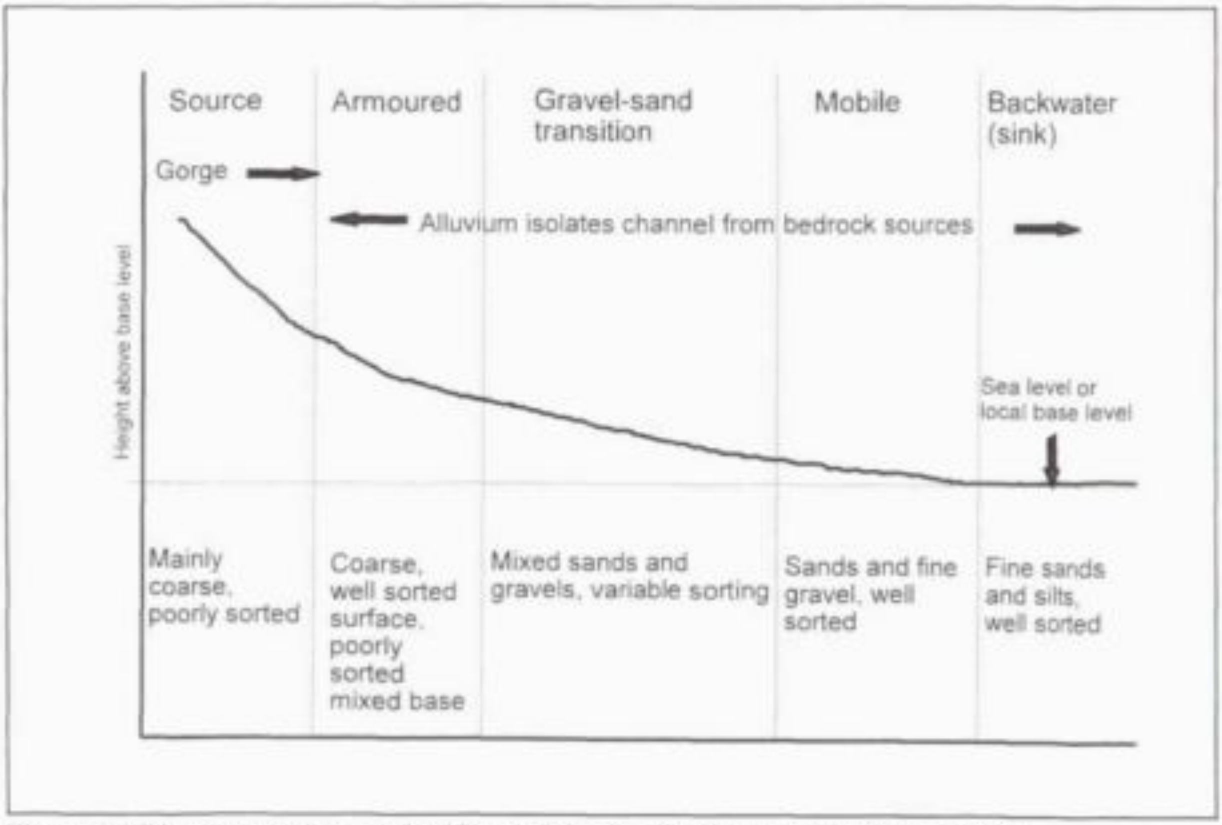


Figure 2.3 River zones characterised by particle size distribution after Pickup (1984)

Table 2.1 Ecological river zonation after Harrison (1965) and Noble and Hemens (1978)

Zone	Physical characteristics	Flow characteristics	Turbidity
High altitude source zone	Source often with sponge or spring. Substream bedrock or humic turf.	Slow flow, often seepage, but may be dispersed with waterfalls	Negligible, even during storms
Mountain stream	Mountain torrents, waterfalls and rapids; little or no true emergent vegetation. Substratum bedrock, boulders and smaller stones. Deposition negligible, stone surfaces clean.	Fast to torrential, turbulent, always oxygenated.	Negligible, even during storms
Foothill: rocky bed	Gradient moderate but still noticeable. Substrate dominated by bedrock, boulders and smaller stones, but with occasional patches of gravel and coarse sand. Some epilithic growth. Sparsely distributed emergent vegetation. May or may not be interspersed with occasional waterfalls	Fast, but with slow flowing pools	Generally low, turbid during floods
Foothill: sandy bed	Stony runs alternate with sand or sediment. Marginal riverine vegetation becomes noticeable and islands may form within river channel.	Lower flow velocity but fast in rapids and during floods.	Extremely variable, turbid at least during floods
Midland river	Further reduction in gradient. Deposition increases. Substratum predominantly sand and finer sediments, but with occasional stony runs. Emergents can become extensive.	Generally slow.	Variable but usually turbid.
Lowland river	Substratum changing to fine silts. Flood plains and meanders can occur or channels may be braided. Islands often present. Emergents usually prominent in channel and on margins.	Flow relatively slow	Usually turbid
Swamp	Area of wet spongy ground with a substratum of fine clays and silts high in organic materials. Channels are braided and usually blind. Emergent macrophytes are dominant and form dense impenetrable masses.	Generally slow	Negligible to low turbidity except during floods.

2.1.3. Morphological classifications

Many authors have pointed to the difficulties in classifying rivers systems above the level of single reaches. Kellerhals and Church (1989) stress that the basis of any classification system should be the river reach, a homogenous reach being a stretch of river of variable length within which controls of channel form such as hydrology, geology, and adjacent catchment conditions are sufficiently uniform to result in a relatively uniform channel morphology. Supporters of this viewpoint include Mosely (1987), Brierly (1994) and van Niekerk *et al.* (1995). Brierly (1994) and van Niekerk *et al.*, (1995) view reaches as assemblages of geomorphological units which form the building blocks of any system for classifying channel geomorphology.

There have been few structured attempts to draw up a comprehensive or definitive classification of morphological units. Bisson *et al.* (1982) provides one of the earliest attempts to relate channel morphology at the scale of the morphological unit to stream habitat and presents a number of useful examples and definitions. Although Brussock *et al.* (1985), Church (1992) and Brierly (1994) all list or refer to a number of units, these references are far from comprehensive and do not give clear definitions. Van Niekerk *et al.*'s (1995) classification provides a useful starting point for South African rivers. Their scheme has been developed further and integrated into a classification system presented in this report.

More comprehensive classifications have been developed at the reach scale, generally based on channel pattern. One of the earliest classifications was that of Leopold and Wolman (1957) who differentiated between straight, meandering, and braided channel patterns based on relationships between slope and discharge; Brice (1984) later proposed the use of channel pattern to classify streams. Other classification systems based on similar premises have been developed subsequently by Kellerhals and Church (1989), Church (1992) and Nanson and Knighton (1996). These will be discussed further in section 3.5.3 (Chapter 3).

It is at the level of the reach or morphological unit that the strongest links are thought to exist between geomorphology and ecological function in that the channel morphology provides the physical structure determining habitat conditions. These are best described in terms of the amount of cover available to organisms, determined by substratum on the channel bed and features such as bank overhang along the channel margins, and by flow characteristics which include mean depth and velocity and the near bed flow hydraulics. Flow characteristics are strongly determined by the channel cross-section shape, bed roughness, bed slope and the distribution of hydraulic controls which determine the upstream water surface slope. These are all a function of channel morphology, a relationship recognised by Bisson *et al.* (1982). As explored further in this report (Chapter 4) there is a definite need to provide a habitat classification which is based on a clear understanding of the relationship between channel morphology and instream habitat.

2.1.4 Hierarchical classifications

A pervasive theme in recently developed stream classification systems in North America has been a hierarchical perspective that links large regional scales (ecoregions) with small microhabitat scales (Naiman *et al.*, 1992). A number of such schemes, which incorporate geomorphological concepts, have been developed as tools for effective water management, the most common ones in use include Lotspeich (1980); Bailey (1978); Cupp (1989); Brussock *et al.* (1985); Rosgen (1985; 1994) and Kellerhals and Church (1989). The most comprehensive hierarchical classification is that of Frissell *et al.* (1986), who extended an earlier approach of Warren (1979) by incorporating spatially nested levels of resolution, and produced a system which addresses form and pattern within a number of hierarchical levels, as well as origins and processes of development.

The basic assumption for the development of the hierarchical stream classification is the geomorphological premise that the structure and dynamics of the stream are determined by the surrounding catchment (Figure 2.4.) Channel morphology at the reach scale is a function of wider regional scale processes acting at the catchment scale. Many ecological researchers have embraced this view: Van Deusen (1954); Slack (1955); Platts (1974), (1979b); Hynes (1975); Morisawa and Vemuri (1975); Lotspeich and Platts (1982) and Frissell *et al.* (1986).

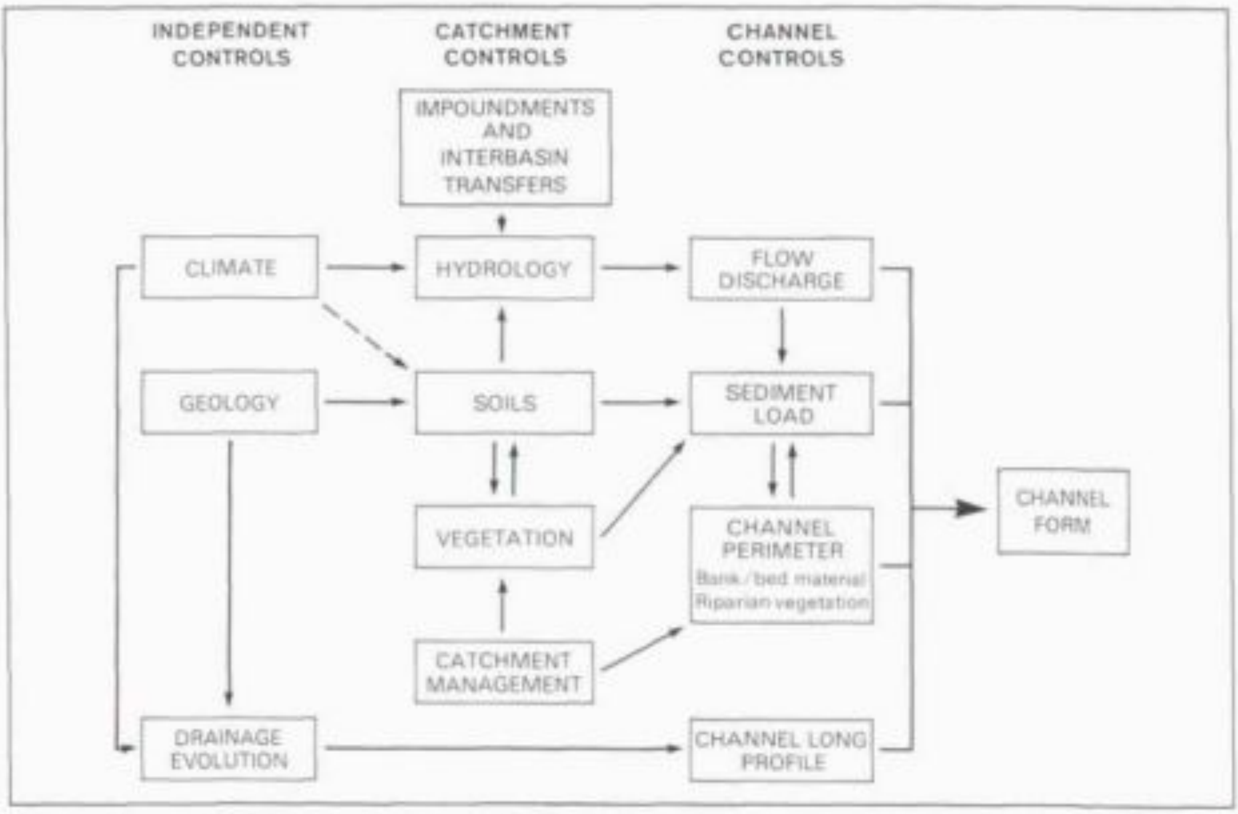


Figure 2.4. Variables in a catchment affecting the dynamics and morphology of a fluvial system, from Rowntree and Dollar (1996a).

Frissell *et al.* (1986) recognise two important problems which need to be considered when developing a stream classification.

Firstly, different processes control the form and development of landscapes, catchments and streams (Wolman and Gerson, 1978; Minshall *et al.*, 1983). Therefore it is likely that different catchment variables will be important in different locations. This means it is imperative that any stream classification be placed in a geographic spatial hierarchy (Frissell *et al.*, 1986). Catchments can be related to the regional scale classifications such as the terrestrial ecoregions of Bailey (1983) and Omernik (1987); the physiographic classification of Godfrey (1977) and Lotspeich and Platts (1982); for South Africa, the biogeoclimatic classifications of Rutherford and Westfall (1988). Each of these approaches allows an individual study site to be kept within a geographical reference of large-scale, regional variation in geology, climate, geomorphology, soils and vegetation (Frissell *et al.*, 1986).

Secondly, Frissel recognised that the time frame in which the system is viewed will largely determine the importance of particular variables. The most useful classification must account for factors that determine both the long and short term changes. Frissell *et al.* (1986) explain that the smaller scale system will develop within the constraints of the larger scale system; this follows the reasoning of Schumm and Lichty (1965) who show for example how the potential pool/riffle morphology of a stream section is determined by the slope, sediment inputs and discharge. In turn, the slope, pattern of sediment and water discharge are determined by the climate, lithology, basin topography, area, and paleohydrologic history. Thus persistence of a particular pool or riffle may be largely dependent on the land management activities occurring in the watershed (Swanson and Dyrness, 1975; Gorman and Karr, 1978; Bryant, 1980; Triska *et al.*, 1982). This suggests that a useful framework for classification is a hierarchical one in which the higher levels of a system either wholly or partly determine the characteristics of the lower levels of the system of which they are a part.

Godfrey (1977) recognises three major benefits from a hierarchical structure:

a. Classification at higher levels narrows the set of variables needed at lower levels.
b. It provides for integration of data from diverse sources and at different levels of resolution.
c. The researcher can set the most appropriate level of resolution.

Many researchers have adopted an implicitly hierarchical approach, though often focussing on one level within a broader framework. These include the classification frameworks of Brussock *et al.* (1985), Rosgen (1985) and Cupp (1989). Naiman *et al.* (1992) describes these three systems in some detail.

Brussock *et al.* (1985) proposed a system to classify running water habitats based on their channel form which can be considered in three different sedimentological settings: a cobble and boulder bed channel, a gravel bed channel, or a sand bed channel. Three physical factors (relief, lithology and runoff) were selected as state factors that control all other interacting parameters associated with channel form such as temperature, depth, velocity and substrate. Brussock *et al*. (1985) examined streams throughout the United States and described seven regions based on differences in state factors. They related channel form to community structure, and confirmed much of the earlier work of Leopold *et al*. (1964) that stream channel-form can be predicted along the length of the river within geographic regions.

Cupp (1989) applied a hierarchical model to small forested streams in Washington State, using eight hierarchical levels ranging from ecoregion to microhabitat. He focussed on the valley segment which was defined in terms of average channel gradient and valley form as indicated in Figure 2.5. Beechie and Sibley (1990) have shown in their initial field tests of this model that stream segment types are correlated with habitat units. Although Cupp's system claims to be based on a hierarchical framework, it only enables the reach to be placed within the local valley topography; there is no means of relating the reach to the catchment.

Rosgen (1985, 1994) developed a classification based on geomorphic and in-channel characteristics on a spatial scale of 10 - 1000 m^2. The system is characterised by features that include channel gradient, sinousity, width/depth ratio, bed material, entrenchment, channel confinement, soil erodibility and stability. It also includes sub-types that are characterised by riparian vegetation, channel width, organic debris, flow regime, meander patterns, depositional features, and sediment supply. Rosgen's stream-type classification system has been used widely in the Western United States for more than ten years for site specific riparian forest and fisheries management, and for predicting geomorphic and hydrologic processes.

Rosgen's initial efforts to develop a classification procedure began in 1973; the preliminary version of this classification was presented to the scientific community in 1985 (Rosgen, 1985). The classification procedure has evolved futher as a result of hundreds of field observations of rivers in all the climatic regions of North America (Rosgen, 1994). This most recent work describes morphologically similar reaches that can be divided into seven major stream type categories based on degree of entrenchment, gradient, width/depth ratio and sinuosity. Within each major category an additional six different stream types may be delineated according to dominant channel material together with gradient. Further details are given in section 3.5.4 (Chapter 3). Rosgen's (1985, 1994) stream classifications provide detailed descriptions of the reach within the context of the stream network, but the systems are not linked to hillslope processes and the boundaries are relatively indistinct.

The classification system presented by Frissell *et al*. (1986) presents an example of a comprehensive hierarchical model which embraces all scales from the catchment to the micro-habitat. This system provided the model on which the development of a geomorphological classification system for South African rivers was based. It will be described in some detail in the next section.

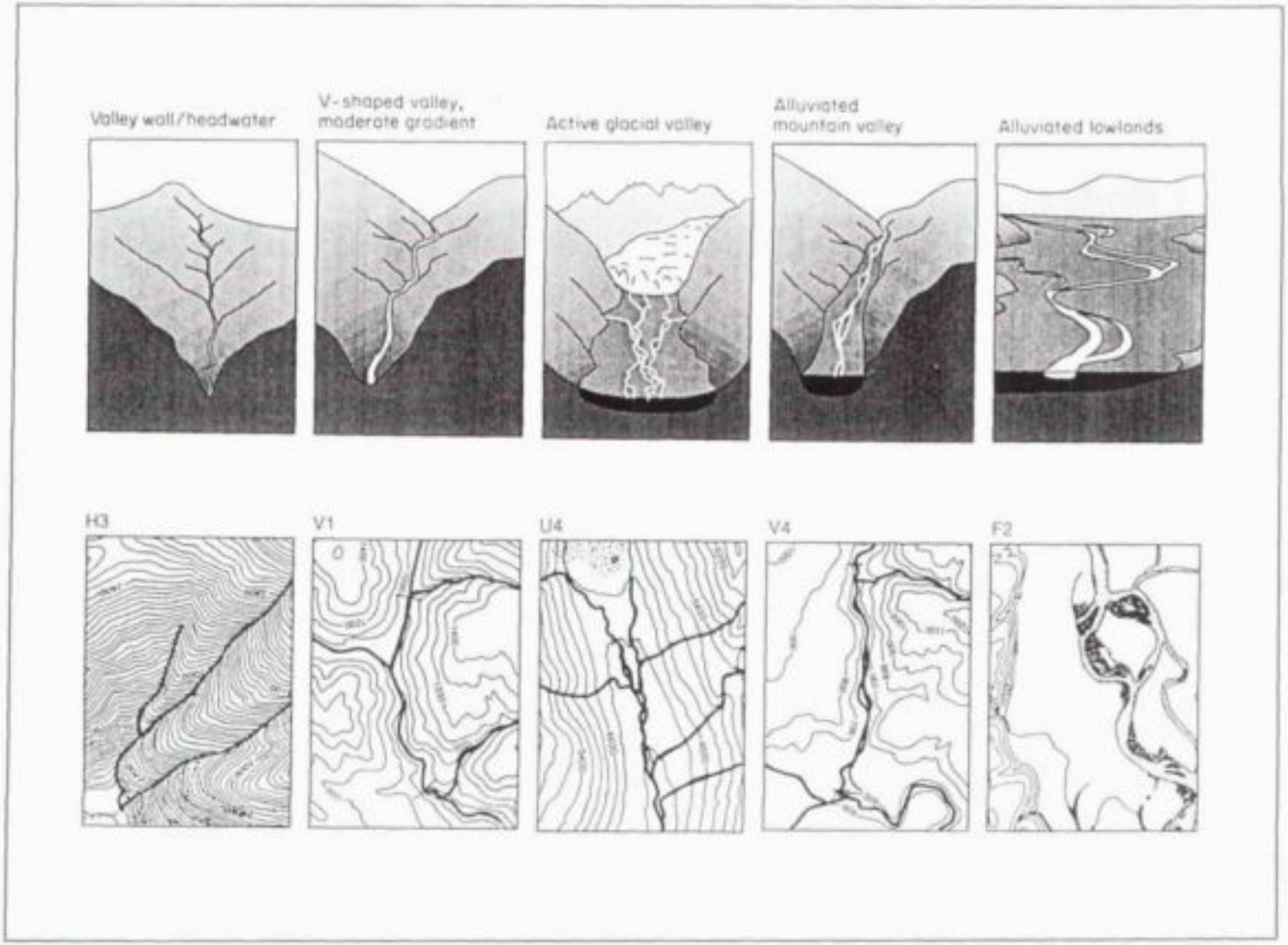


Figure 2.5 Elements of the Cupp classification as used by the State of Washington, USA. Three-dimensional projections are made from topographic maps to assist in determining segment type.

2.2 THE HIERARCHICAL MODEL OF FRISSELL *et al.* (1986)

Frissell *et al.* (1986) recognise the *'stream system'* as a hierarchical system which consists of *'stream'*, *'segments'*, *'reach'*, *'habitat'* and *'microhabitat'* subsystems (Figure 2.6). Because the hierarchy is spatially nested, a system at one level will determine the characteristics of the lower levels. They believed that this framework would provide "a tool that can guide researchers and managers in conceiving and executing studies, perhaps affording new ways of dealing with old problems" (Frissell *et al.*, 1986 p.212). The different levels of Frissell *et al.'s* (1986) hierarchy are described below.

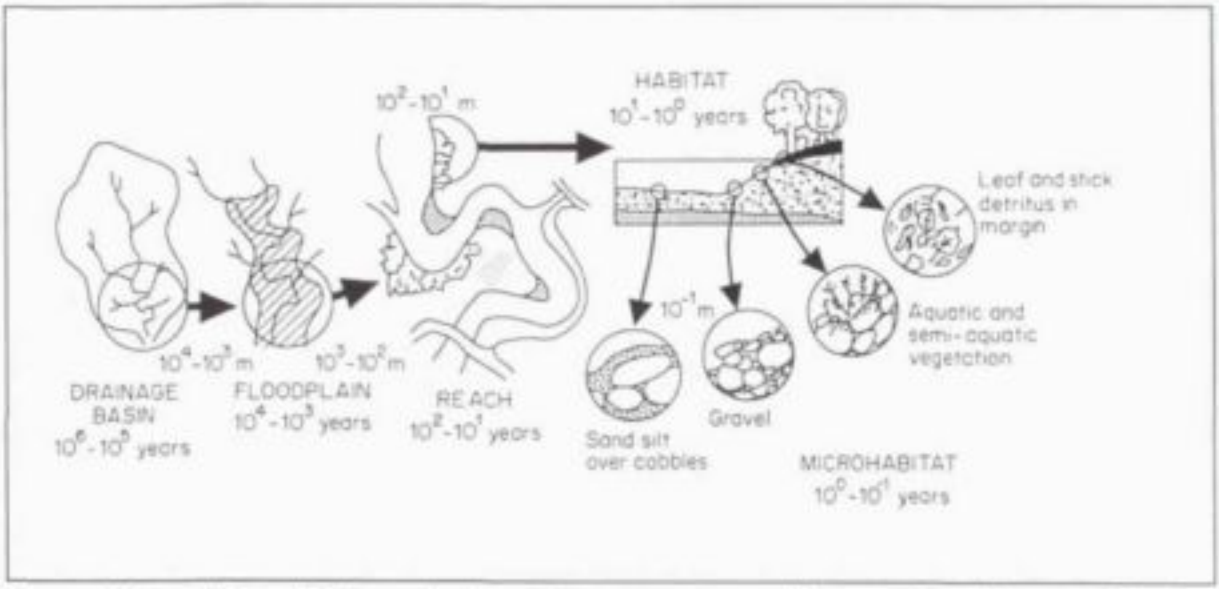


Figure 2.6 Hierarchical organisation of a stream system with approximate linear spatial scales, from Frissell *et al.* (1986).

Stream Systems

The development and physical characteristics of a stream system are dependent upon the geological history and climate of its drainage basin (Hack, 1957; Schumm and Lichty, 1965; Douglas, 1977). Thus, stream systems might be classified on the basis of the biogeoclimatic region in which they reside (Warren, 1979; Bailey, 1983), the slope and shape of the longitudinal profiles (Hack, 1957), and some index of drainage network structure (Strahler, 1964). It should be noted that Frissell *et al.* focussed on second and third order streams so that it could be assumed that the entire stream system would fall within one biogeoclimatic region.

Segment Systems

A segment is a component of the steam network which is bounded by tributary junctions or major waterfalls and may flow through one bedrock type. Classification criteria include: the class of stream system in which it resides, the lithology and structure of underlying and adjacent bedrock, slope, position in the drainage network by order (Strahler, 1957) or by link number (Shreve, 1967), and valley side slopes. Segments can be further discriminated on the basis of soil associations, land types (Lotspeich and Platts, 1982), or potential natural vegetation (Daubenmir, 1968). In most cases this segment can be classified using existing topographic, geologic, and vegetation and soil maps. Aerial photo interpretation is also useful.

Reach Systems

A reach system is defined by Frissell *et al.* (1986 p.205) in terms of "breaks in channel slope, local side slopes, valley floor width, riparian vegetation and bank material." The reach typically possesses a characteristic range of channel bed materials. Its length can be measured in metres to tens of metres in small, steep streams, or perhaps hundreds of metres or more in fifth order and larger streams. Reach associated features are visible in the field and sometimes on low-level aerial photographs.

Habitat (pool/riffle systems)

A pool/riffle system is a sub-system of a reach having characteristic bed topography, water surface slope, depth, and velocity patterns. Frissell *et al.* (1986) recognise that in many streams, habitats at this level are complex, and include not simply pools and riffles, but rapids, runs or glides, falls, side channels, and other forms. Frissell *et al.* (1986) have developed a classification which begins with the definition of pool/riffle "forms" based predominantly on Bisson *et al.* (1982); these reflect bed topography, low water surface slope, hydrodynamic pattern and relative position to the main channel. Frissell *et al.* (1986) recognise that flow velocities, depths and sediment dynamics may be of prime importance in determining the bedform's suitability as habitat for different organisms.

Microhabitat Subsystems

Frissell *et al.* (1986 p.208) define microhabitat subsystems as "patches within the pool/riffle system that have relatively homogenous substrata type, water depth, and velocity." In the view of Frissell *et al.* (1986), the classification of microhabitats should account for their origins and development, as well as their characteristics at any single time. The relationship of a patch of bed material to its larger-scale (pool/riffle or reach) environment is also important in understanding its dynamics (Laronne and Carson, 1976; Jackson and Beschta, 1982). Bed particle size, shape, and transport dynamics are dependent on the drainage basin, as well as on the general drainage network position and slope of the stream segment under consideration (Hack, 1957; Miller, 1958; Knighton, 1982; Douglas, 1977).

2.3 A HIERARCHICAL GEOMORPHOLOGICAL MODEL FOR SOUTH AFRICA

2.3.1 Introduction

Frissell *et al.*'s (1986) model has been adapted as the basis of a classification of South African river systems and a tool for river basin management. The South African model has six nested levels: the catchment, the zone, the stream segment, the reach, the morphological unit and the hydraulic biotope. This is a cascading system in which each level provides the input into the lower one. This framework provides a scale based link between the channel and the catchment so as to account for catchment dynamics and allows a structured description of spatial variation in stream habitat. The hierarchical model thus provides the spatial framework of physical features upon which process models of catchment hydrology, flow hydraulics and sediment transport can be based. For a classification system to be successful it must be based on valid process-form relationships, objectively defined units, clear identification procedures and readily accessible data. These features of the model are developed in this report.

In developing the South African system a number of modifications were made to Frissell *et al.*'s original framework, and attempts were made to come up with rigorous working definitions of geomorphological components at each classification level so that the system would be readily transferable between different geographical regions as well as between different researchers. One important difference between the classification of Frissell *et al.* (1986) and the model to be proposed here is the size of the streams and catchment. Frissell *et al.* (1986) oriented their classification primarily towards third order and smaller streams. We feel that some modifications need to be made to the hierarchical framework if it is to be applied to the larger river systems which are often the subject of management decisions in South Africa. Frissell *et al.* (1986) suggest that the uppermost level of the classification hierarchy should be based on the biogeoclimatic region in which the stream resides. It is felt that this may indeed work with smaller streams on a local scale, but looking at large streams on a national scale it is unlikely, if not impossible, for whole stream systems to flow within a single biogeoclimatic region. It will therefore be necessary to zone the catchment into sub catchments which can be considered to be homogenous in terms of their hydrological and erosional response. The South African Hierarchical System consists of two classes of attribute, the aerial features related to the catchment surface and the channel features themselves which constitute the drainage network. The system has six nested levels: the catchment, zone, segment, reach, morphological unit and hydraulic biotope (Figure 2.7). These will be defined in turn below. A comparison between the South African system and that of Frissell *et al.'s* (1986) is given in Table 2.2.

Table 2.2 The classification hierarchy together with general variables proposed by Frissel *et al.* (1986)(a), and its proposed modification for a South African classification (b).

a) Frissell *et al.*(1986).

WATERSHED	STREAM SYSTEM	SEGMENT	REACH	POOL/RIFFLE	MICROHABITAT
Biogeoclimatic region	Watershed class	Stream class	Segment class	Reach class	Pool/riffle class
Geology	Long profile shape	Channel floor lithology	Bedrock relief slope	Bed topography	Underlying substrate
Topography	Network structure	Channel floor slope	Morphogenetic structure or process	Water surface slope	Overlying substrate
Soils		Position in drainage network	Channel pattern	Morphogenetic structure or process	Water depth, velocity
Climate		Valley side slope	Local side slopes, floodplain	Substrates moveable in 10-year flood	Overhanging cover
Biota		Potential climax vegetation	Bank composition	Bank configuration	
Culture		Soil association	Riparian vegetation		

b) RSA

CATCHMENT	ZONES (sub-catchment)	SEGMENT	REACH	MORPHOLOGICAL UNIT	BIOTOPE
Shape	Climate	Zone class	Segment class	Reach class	Morphological unit class
Relief	Soils	Channel gradient	Flood plain width	Channel width	Velocity
Hypsometric integral	Geology	Position in drainage network	Local geology	Channel depth	Depth
Climatic integral	Vegetation	Valley slope gradient	Valley gradient	Form ratio	Substrate
	Drainage density	Impoundments	Bank material	Bed material	
	Land use	Abstractions	Riparian vegetation	Surface water gradient	
			Channel pattern		
			Channel bed material		

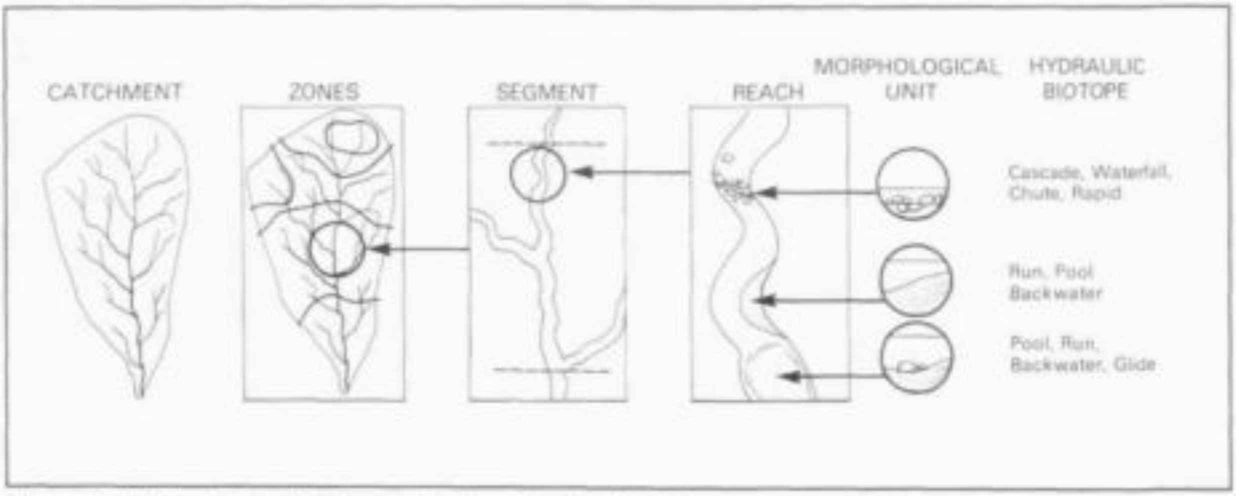


Figure 2.7 The hierarchical organisation of a South African stream system.

2.3.2 Aerial features

The catchment

The catchment is the land surface which contributes water and sediment to any given stream network. This can be applied to the whole river system, from source to mouth, or to a lower order catchment within the larger system. Classification of whole catchments allows comparison between systems and an assessment of the extent to which relationships established for one catchment can be extrapolated to another. Simple classification indices include topographic descriptors such as the hypsometric integral, relief ratio, catchment shape and bifurcation ratio (channel network shape). Catchments can also be described (but not classified) in terms of their regional characteristics such as climate, geology, vegetation, hydrological measures such as mean annual runoff, regional flood indices and sediment yield region.

Data requirements for classifying at this level should be based on nationally available data networks at a manageable scale, say 1:250,000 or smaller. The compilation and use of a national geographical information system (GIS) data bases is especially relevant here.

The zone

Within higher order catchments there is much heterogeneity with respect to topography, climate, geology, vegetation cover, soils and land use so that subdivision into zones is necessary for classification purposes. Zones are defined as areas within a catchment which can be considered as homogenous with respect to flood runoff and sediment production. The geomorphological response of these zones should be manifested through drainage network characteristics such as drainage density.

For the large catchments commonly considered for water resource development purposes, it is necessary that data inputs into the model at the zone level are readily accessible from published sources, can be uniformly applied throughout the country and do not require detailed field mapping. A GIS is well suited to manipulating separate covers to produce zones. Data inputs at this level include rainfall and/or runoff, slope gradient, geology, soils, natural vegetation cover and land use. The availability of these data vary, most data is available in hard copy map form, more limited data has been captured on to national GIS data bases, whilst certain data may have to be derived from primary surveys.

Once zones have been identified and their characteristics described, they can be used as the basis of suitable hydrological and sediment models in order to estimate flood runoff and sediment yield to the stream network. These quantities become input to the next level of the hierarchy, the stream segment.

2.3.3 Channel features

The catchment zones are the source areas for runoff and sediment whereas the channels provide the network through which flows of water and sediment are routed. The channel network can be subdivided into segments and reaches. Reaches in turn are described in terms of morphological units and associated hydraulic biotopes.

The segment

A segment is a length of channel along which there is no significant change in the imposed flow discharge or sediment load. Segments can be delineated by overlaying the zone maps with the channel network so as to identify major changes in runoff and/or sediment along the length of the channel. Segment boundaries will tend to be co-incident with major tributary junctions and/or a change in stream order.

Discharges of water and sediment through a segment should change slowly so that these control variables remain uniform along the length of a segment. There should therefore be a recognisable similarity in channel type throughout the segment, particularly with respect to overall valley form, channel dimensions and bed material (alluvial or bedrock; boulder, gravel or sand). Segments can be further described in terms of their average gradient and can thus be related broadly to the channel zonation classifications often used by ecologists.

Local variations in channel morphology may occur within a segment due to changes in perimeter conditions which determine the next level of the hierarchy, the reach.

The reach

The reach is a length of channel within which the local constraints on channel form are uniform, which has a characteristic channel pattern (straight or sinuous) and degree of incision and within which a characteristic assemblage of channel morphologies occur. Reach control variables such as channel gradient, geological heterogeneity, bank and bed material and riparian vegetation determine the possible direction of the response to changes in flow and/or sediment load, in particular whether the reach acts as a source, transfer zone or sink for sediment. Characteristic channel forms are the result of these dynamic processes. Reach control variables and associated channel forms can be determined from large scale topographic maps, aerial photography and from field surveys. A method to identify reaches from 1:50 000 maps based on an analysis of the rate of gradient change has been developed. This allows an efficient desk procedure for subdividing channels prior to field surveys and confirmation of reach breaks.

This definition of reaches closely follows that of Frissell *et al.* (1986) and adaptations of their ideas (Cupp, 1989). The identification of uniform 'reaches' within the 'segments' requires a modification of the 'valley segment type' described by Frissell and Liss (1986) and the channel types identified by Rosgen (1985, 1994).

Van Niekerk *et al.* (1995), working in the Sabie River in the low veld, distinguished two further levels within the reach category: channel type and the macro reach. They considered that reaches may be composed of one or more channel types which have a characteristic channel plan (single thread, braided, anastomosing) composed of a characteristic assemblage of morphological units. Channel types may be distinguished from large scale aerial photography (1:12 000 or greater), but field verification will be required. In the South African Hierarchical Classification System channel type is subsumed under reach. According to Van Niekerk *et al.* (1995) the macro reach describes the valley form characteristics, including valley floor slope, valley sinuosity, and valley floor width, characteristics which are closely related to the coarse long profile gradient and to macro-scale geology. This scale of feature is probably more closely related to the segment than to the reach, but may represent a useful transition between the two scales in some river systems.

The morphological unit

The next level of the hierarchy involves the identification of individual morphological units within the reach and is equivalent to Frissel *et al.*'s (1986) pool-riffle level. The morphological units are the basic structures recognised by fluvial geomorphologists as comprising the channel morphology and may be either erosional or depositional features. Although in the long term their characteristics are dependent on the imposed flow regime which determines erosion and sediment transport processes, in the short term they can be considered to be constant features.

Morphological units occur at a scale of an order similar to that of channel width and commonly span the channel bed. Brierly (1994) distinguishes three classes of morphological unit depending on their location relative to the active channel: within-channel units, channel margin units and flood plain units. This subdivision has been adopted in the present system. The in-channel units can be further subdivided into two groups: pools and hydraulic controls. Pools are scour or erosional features with relatively high depths relative to width and within which the macro-scale flow hydraulics are controlled by a downstream hydraulic control. The hydraulic controls are usually aggradational (such as riffles) or erosionally resistant features (such as rapids associated with bedrock bars) with relatively low depth relative to width and within which the macro-scale flow hydraulics are not controlled by downstream hydraulic features. Shallow flows and large bed material calibre leads to micro-scale hydraulic controls at low flows so that these features tend to be hydraulically complex. Morphological units are described further in section 3.4 (Chapter 3).

The description and mapping of morphological units requires intensive field survey of channel width and depth, bed material, channel roughness and bed slope. It is not practical to include every part of the channel network in any survey. Rather, the hierarchical approach can be used to subdivide the channel network into sample segments and reaches and to sub-sample within these.

The hydraulic biotope

Hydraulic biotopes are the habitat assemblages which can be equated to these morphological units; their recognition is determined by the associated temporally variable hydraulic and substrate characteristics. Wadeson (1994) has defined the hydraulic biotope as a spatially distinct instream flow environment with characteristic hydraulic attributes. They occur at a spatial scale of the order of 1 m^2 and although they can be related to morphological features they are temporally unstable.

Hydraulic biotopes can often be related directly to morphological units and are therefore commonly given the same terminology, but being flow units rather than sedimentological units, they vary with discharge. Thus riffle hydraulic biotopes are associated with riffle morphological units, but, as will be demonstrated in this report, a riffle morphological unit contains an assemblage of hydraulic biotopes which changes as flow discharge changes.

2.3.4 The hierarchical stream modelling strategy

For the hierarchical model to be both useful and manageable within the time constraints of any project, there needs to be selective sampling and data analysis. The first four levels of the hierarchy, namely 'catchment', 'zones', and 'segments' and identification of 'reaches', all entail comprehensive desk studies, GIS data capture and limited field verification. These levels of the hierarchy can be dealt with adequately for all selected catchments. The classification at the 'reach' level of the hierarchy and below requires extensive field work and therefore is likely to be the most time intensive. It is proposed that the selection of reaches should relate to particular areas of concern, for example those reaches immediately downstream from proposed dam sites rather than to the whole catchment. This means that the sampling programme is likely to be focussed on the main channel rather than on low order tributaries. Within selected reaches all morphological units and hydraulic biotopes can be identified and classified.

2.3.5 Anticipated benefits and possible limitations

The most obvious benefit from a hierarchical model is that it provides a common system for the description of streams at various scales. In this way it facilitates the comparison of numerous variables within and/or between similar systems; for example, the biotic potential of similar hydraulic biotopes may be compared in similar reaches and zones either within or between regions. Emphasis can be placed on disturbed or undisturbed systems. Likewise it may provide a methodology for the subdivision of river systems into characteristic reaches for application of instream flow models such as PHABSIM or for South African procedures as developed in the Building Block Methodology (King, *et al.*, 1993).

The geomorphological bias may allow the assessment of the flow requirements necessary to maintain the present channel form and provide an objective definition of biotopes, which relates them to recognisable morphological and hydraulic conditions.

A possible limitation of the model is that the stream morphology is assumed to be the result of the current climatic and geomorphic regime. The classification does not take into account the possibility that the present physical characteristics to a greater or lesser extent reflect historical events. It is therefore necessary to be aware of the historical perspective when interpreting geomorphological data.

It is hoped that the model will provide a framework for the prediction of potential for change under altered flow conditions. This may be the most difficult because, although we do have a broad understanding of what determines river morphology, predicting morphological changes due to interference with the controlling factors remains extremely complex, mainly because of the many interacting processes (Kellerhals and Church, 1989). It is perhaps sufficient to refer here to Table 2.3 from Kellerhals and Church (1989), and state that this technique may be incorporated to form a basis for the prediction of morphological change within South African rivers.

Finally, and perhaps most importantly, the hierarchical model should provide a sound basis for the future classification of rivers.

2.4 CONCLUSIONS

Closely following recent research trends in stream classification (Bailey, 1978; Lotspeich, 1980; Brussock *et al*., 1985; Rosgen, 1985; 1994; Frissell *et al*., 1986; Cupp, 1989 and Kellerhals and Church, 1989), this outline presents a system whereby the characteristics of the stream are defined on several spatial and temporal scales according to the geomorphic processes operating within the catchment.

An outcome of the review of the river classification literature is the need to clarify the use of the term 'classification' as it applies to this project. It is impractical to produce a comprehensive classification of whole river systems in the traditional sense as the complexity of each drainage basin makes it a unique entity. Because this project attempts to link the most important physical variables within the catchment, at a number of different scales, it is felt that it may cause confusion to talk of a hierarchical classification in the present context. In the traditional ecological literature, hierarchical classification refers to the development of a technique for ordering or arranging features measured at the same spatial scale into various levels of similarity or dissimilarity. This would require a radically different approach to that proposed. In contrast the aim of this project is to apply extant geomorphological classifications to the different levels of a hierarchical geomorphological model which describes the linkages between the channel morphology at the reach scale, the drainage network through which the sediment and water are rooted, and the catchment which supplies sediment and water to the channel network. Closely related to this is the development of a hydraulic-ecological model which relates hydraulic biotopes to the morphological units which comprise a given reach. This approach closely follows the conceptual model proposed by Frissel *et al.* (1986) and Naiman *et al.* (1992) as a basis for river classification.

In broad terms we are developing an objective technique for the description of a single river system or the comparison of two or more systems, together with a method for the definition of hydraulic biotopes. At a later stage, this geomorphological model may constitute the basis for a future river classification. From discussions with potential users of the system it would seem that the proposed methodology would meet the requirements of many ecologists and river managers.

Three catchments were selected for initial model development, the Sabie river in the eastern Transvaal, the Buffalo river in the eastern Cape and the Olifants river in the western Cape. These river systems encompass a wide range of environmental variables and spatial scales. They are also systems which are the focus of ecological studies and for which a significant amount of ecological and channel morphology data is already available.

Table 2.3 Qualitative changes in major morphologic parameters for selected imposed changes from Kellerhals & Church (1989).

Case	Imposed Changes			Probable direction of resulting change								
No	Q	q_{bm}	q_w	w	d	S	D_{50}	F	λ	P	M	Remarks
1	+	–	–	+	+	–	+	–/±	+	+	–	Assuming no changes in q_{bm} and q_w
2	–	+	+	–	–	+	–	–/+	–	–	+	
3		+		+	–	+	±	+	?	–	–	Changes in D_{50} depends on type of material supplied from upstream
4		–		–	+	?	+	–	?	+	+	
5			+	–	+	?	–	–	?	+	+	
6			–	+	–	?	+	+	?	–	–	
7	–	–	–	–	±	–	±	±	–	+	–	Depends upon balance in Q, q_{bm}
8	–	–	+	–	–	–/+	–	±	–	?	+	
9	+	+	+	+	+	±	±	±	+	?	±	
10	+	+	–	+	+	±	±	+	+	–	–	

Legend:
- Q - Channel forming discharge, approximately 2-10 yr flood
- Q_w - Wash load
- Q_{bm} - Bedmaterial load
- q_{bm} - Relative bed material load. Q_{bm}/Q
- q_w - Relative washload. Q_w/Q
- w - Channel width
- d - Channel depth
- S - Channel slope
- D_{50} - Median bed material size
- F - Width/depth ratio
- λ - Meander wavelength
- P - Sinuosity
- M - Percent silt and clay in channel perimeter materials

NOTE:

All parameters are associated with discharge Q.

If initial changes are thought to be different from long-term changes they are separated by /. If changes can occur in either direction it is shown as ±.

Imposed changes are assumed to be relatively large, but not large enough to change the order of magnitude of the affected parameter.

CHAPTER THREE

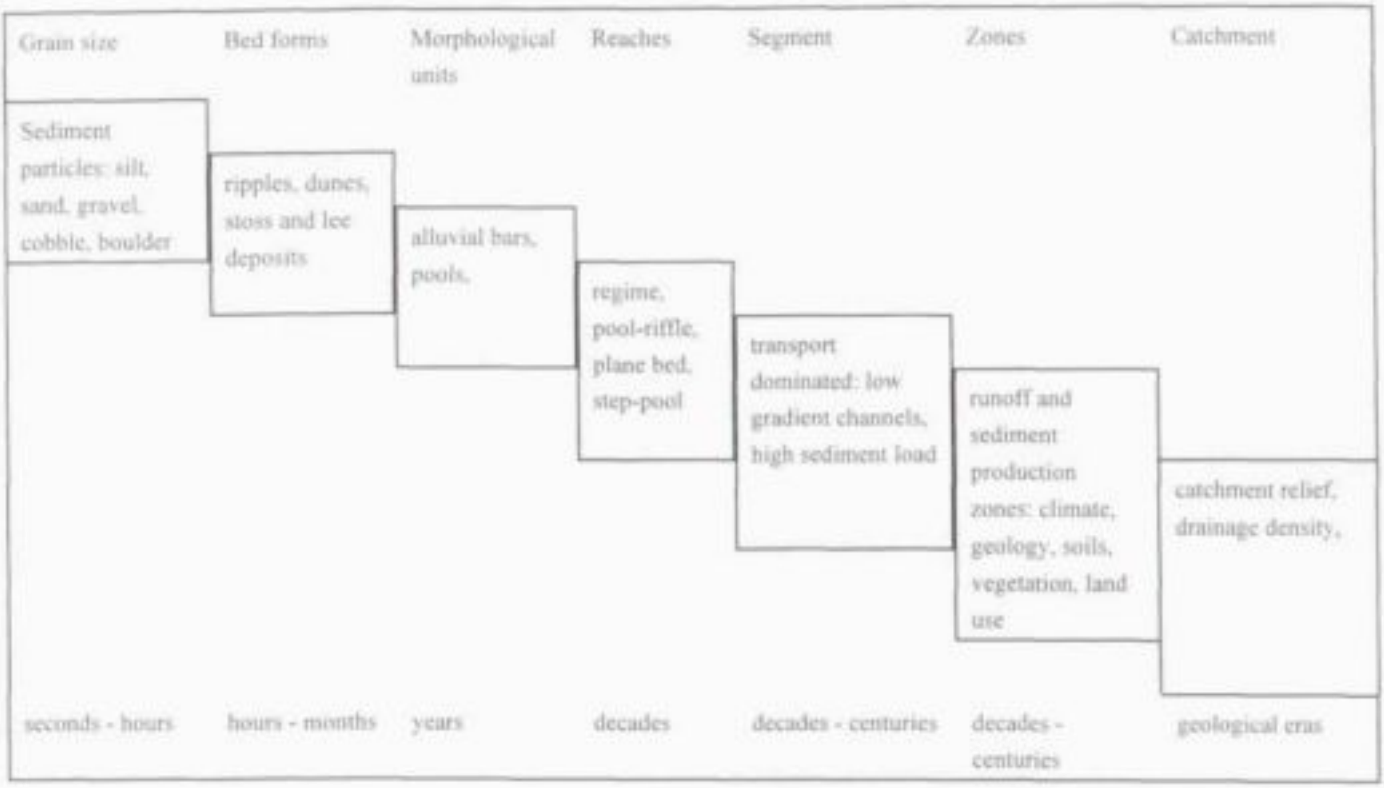
LITERATURE REVIEW: GEOMORPHOLOGICAL PROCESSES AND CLASSIFICATION

3.1 INTRODUCTION

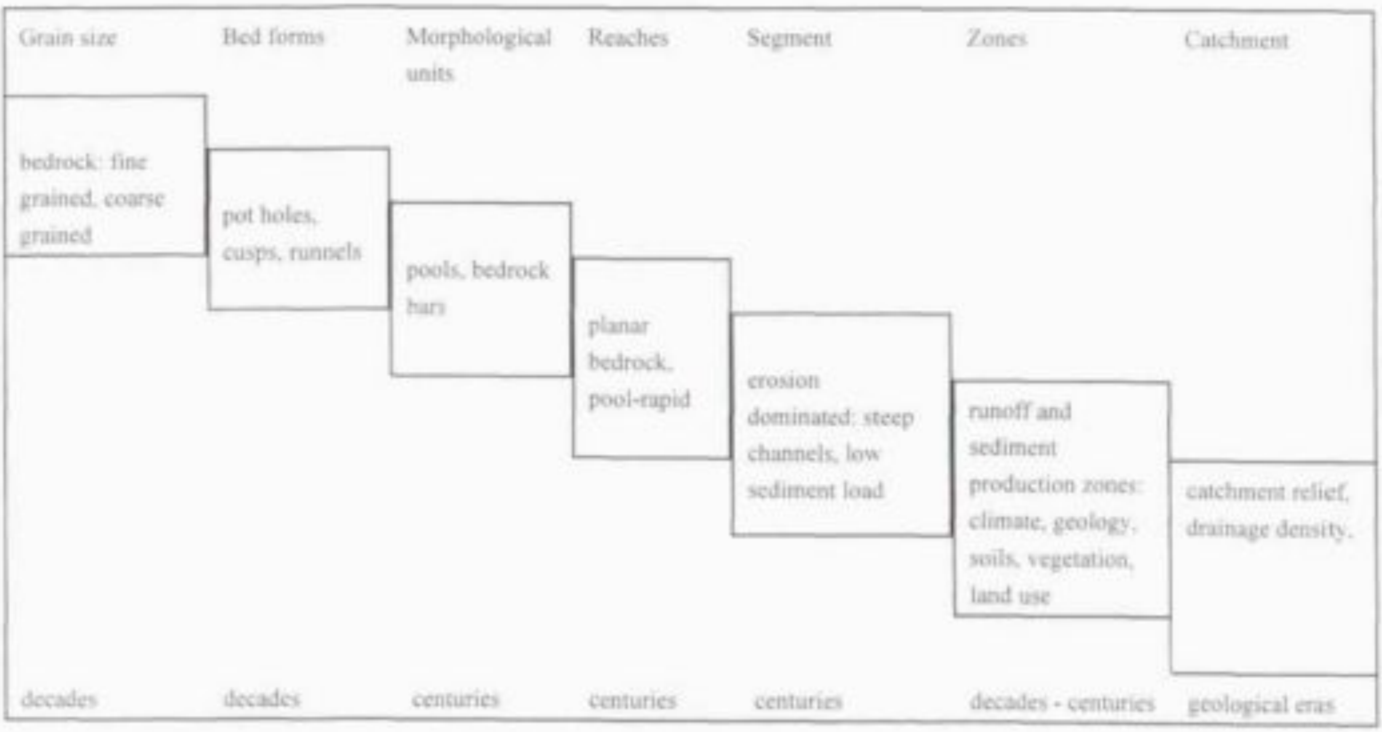
Fluvial geomorphology is the branch of science that attempts to find systematic order in the wide array of landforms shaped by rivers and to understand the processes responsible for their development (Kellerhals & Church, 1989). This chapter presents a review of channel forms and the processes which shape them. The review is structured around the hierarchical framework introduced in Chapter 2.

Geomorphological processes take place at a range of temporal and spatial scales; the resulting geomorphological features can likewise be classified according to a hierarchy of these scales. The driving forces for fluvial process are ultimately related to catchment scale processes. These take place over time scales ranging from decades to geological era at one end of the scale to the movement of individual grains of sediment which can be measured in terms of seconds or hours at the other end of the scale. The relationships between temporal and spatial scales are illustrated in Figure 3.1 for both alluvial and bedrock systems.

Fluvial processes are driven by two main groups of factors: those determining the supply of sediment to the channel and those determining the capacity for sediment transport or erosion of the channel bed. The sediment supply is largely determined by catchment factors which control rates of hillslope erosion, and the potential for sediment storage at different points in the system. Sediment entrainment and transport is directly related to stream power, the product of discharge and channel gradient. Channel gradient is determined by the long term development of the river profile, discharge is a function of climate and catchment characteristics. It is thus apparent that a consideration of process logically starts with macro-scale components of the system, the catchment and its zones. In contrast, the resulting channel forms are composed of the agglomeration of micro-scale units (sand, gravel etc.) through a hierarchy of forms as indicated in Figure 3.1. A classification of channel form therefore more logically takes an agglomerative approach. This chapter will open with a consideration of some of the basics of channel processes before examining in more detail the channel forms.



a) Time-Space relationships in alluvial systems



b) Time - Space relationships in bedrock systems

Figure 3.1 Time space relationships in, a) alluvial systems and b) bedrock systems

3.2 DRIVING FORCES FOR FLUVIAL PROCESSES

3.2.1 Sediment load

The sediment load is defined as the total mass of sediment which is transported through a channel cross-section over a given time period, measured in units ranging from grams per sec to tonnes per year. It is related to the catchment sediment yield which is the total mass of sediment which is lost from the upstream catchment area and channel network, usually measured in tonnes per square kilometre or per hectare per annum. The sediment load can be conveniently subdivided into bedmaterial load, wash load and dissolved load. Each has a separate effect on channel form.

The bedmaterial load

The bedmaterial load is the coarse sediment which makes up the bed of the channel and is transported at or close to the bed. It includes particles ranging in size from sand grains to boulders. Movement may be by rolling, sliding or by saltation. Transport of bedload is episodic, particularly so for the largest particles, material often being moved through the channel system in a series of pulses. Between events bedmaterial is stored within the bed as sedimentary bars which are major components of the channel form. This same class of material is also found stored in the channel banks.

The immediate source of bedmaterial transported through a channel section is alluvium in the upstream channel network and channel banks. The ultimate source is the hillslopes or erosion of bedrock in the channel bed. Coarse material is derived by mass erosion of steep hillslopes which abut on to low order headwater channels or in gorge sections of high order channels. Gully erosion is another significant source of bedmaterial in South African river systems.

The material which is input into the channel in the steep headwater areas may be of mixed calibre, but further downstream the material tends to become finer due to sorting and to breakdown of the particles as they are transported through the system. There is a close relationship between the size of the material resident in the bed and the slope gradient, with steep headwater areas being characterised by boulder and coarse cobbles, grading into gravels and sands as the gradient decreases downstream. Local channel steepening in downstream areas may be associated with increased bedmaterial size. Generally bed load transport is dominant in headwater areas, with the transition of a gravel to sand-bed stream occurring around a median particle size (D_{50}) of 10mm (Howard, 1980; Kellerhals, 1982). This discontinuity has important implications for channel form and pattern adjustment.

Rates of bedmaterial transport are closely related to stream power and therefore to discharge. For any given particle size there is a threshold level required for movement to take place, after which the transport rate is directly proportional to stream power. The relationship is not a simple one, being compounded by factors such as the heterogeneity of the bedmaterial, its packing and arrangement on the bed (Bathurst, 1987). Fine particles are often protected by the coarser ones so that entrainment of particles across the whole size range is determined by the thresholds for the larger particles. The median particle diameter appears to be a reasonable indicator of the bed mobility.

An understanding of the spatial and temporal movement of sediment in channels is important because of its implications for channel form and pattern, but is made difficult due to sediment movement patterns being complicated by storage and transport rates which can vary markedly over very short distances (<1km). Simons and Simons (1987) indicate that sediment supply events tend to be episodic in upland streams and non-uniform in their spatial distribution. These changes may be in response to climatic change, major floods or land use (Ferguson, 1987). Because of this, sediment slugs or pulses may move through the system, producing sedimentation zones in which changes in channel form and pattern are commonly observed (Church and Jones, 1982; Church, 1983).

The wash load

The wash load is composed of fine sediments (silts and clays) which are able to remain suspended in the water column at all but the lowest velocities and therefore tend not to settle out onto the bed of the active channel. The wash load is derived from the hillslopes by surface wash erosion or from the river banks following mass failure. Because of the slow settling rates the wash load only contributes to the channel bed material in backwater areas and to channel banks following overtopping. Fines may settle out in pools to form a temporary surface layer which is re-transported during the next flood event. The wash load therefore represents a major proportion of the total sediment load and has serious implications for water quality, reservoir sedimentation and so forth, but it has less direct impact on channel form than does the bedmaterial load. It does however impact on the composition of channel banks, which in turn can effect the form of the channel.

Rates of wash load transport are primarily determined by slope erosion processes which are responsible for introducing fine sediment into the channel. Wash load is therefore determined by the extent of surface runoff over the catchment and the availability of fine sediment over the hillslope surfaces. Washload tends to increase with flow discharge, but the relationship is a complex one, depending as it does on hillslope process rather than channel processes themselves.

The dissolved load

The dissolved load is that part of the load carried in solution. It is a critical component with respect to water quality and provides a good measure of overall denudation rates in the river basin and therefore of long term geomorphic change, but the dissolved load has little known direct impact on the channel morphology itself. It will not be discussed further in this report.

Estimating sediment load

Estimates for sediment load are derived from two main types of measurement. The first is through sampling the concentration of suspended sediment in the water column at a given discharge at a particular cross-section, the second is through surveying sediment deposits in accumulation zones such as reservoirs. The first method grossly underestimates the bed material load whereas the second method includes all but the finest sediment which may be lost over the dam wall. Sampling the water column allows a finer time-scale resolution and measures the sediment load at one point in time, whereas reservoir surveys take place at a much coarser time scale and integrate the sediment load over a longer time span. In general, estimating sediment load is fraught with problems so that available data must be treated with a fair degree of circumspection.

Available data on sediment yields for South Africa has been reviewed by Rooseboom *et al.* (1992). Limited data is available relating to recorded suspended sediment load records, the most important source of data is from reservoir surveys. Rooseboom's report gives sediment yield data for 124 reservoirs located throughout the eastern and southern regions of the country.

3.2.2 Flow discharge

Streamflow is variable in both time and space as the channel responds to rainfall events over the upstream catchment. The downstream increase in flow discharge depends on the distribution of rainfall over the catchment and on physical characteristics of the catchment such as soils, vegetation and landuse. In humid areas such as the British Isles discharge tends to increase as the 0.7 power of catchment area; in many South African catchments most of the runoff is produced in the headwater areas so that discharge will increase much more slowly with catchment area, and may even decrease due to transmission losses in semi-arid areas. Pitman (*pers.comm.*) recommends that the mean annual flood is proportional to the square of the catchment area for South African rivers.

Temporal variations in discharge are related to storm events over the catchment. Floods are the direct response to storm runoff, whilst baseflow is the water which drains more slowly from soil and ground water storage. Flood runoff is the most important in determining geomorphological processes as high discharges are required for significant sediment entrainment and transport. There is considerable debate, however, concerning the efficacy of different discharges related to their magnitude and frequency. This debate is encapsulated by considerations of what has become known as the dominant discharge concept. This will be reviewed below.

Dominant or channel forming discharge

Because of the range of discharge to which most natural channels are subjected, it is logical to assume that the channel shape is affected by a range of flows rather than by a single discharge. Research has shown that events of moderate magnitude and relatively frequent occurrence control the erosional form of the channel, including its size and shape.

In 1960 Wolman and Miller, studying rivers in humid areas, observed that many rivers are competent to erode both bed and banks during moderate flows. Observations of natural channels suggested that the channel shape as well as the dimensions of meandering rivers appeared to be associated with flows at or near the bankfull stage. The fact that the bankfull stage recurs on average once every year or two years indicated that these features of many alluvial rivers are controlled by those more frequent flows rather than by the rarer events of catastrophic magnitude (Wolman and Miller, 1960).

Dominant discharge has been defined in various ways: as the flow which determines particular channel parameters, such as meander wavelengths (Ackers and Charlton, 1970), or as the flow which performs most work, where work is defined in terms of sediment transport (Wolman and Miller, 1960). Since it seems reasonable to suppose that river channels are adjusted on average to a flow which just fills the available cross section, dominant discharge has been equated with bankfull flow, thereby giving it additional morphogenetic significance. This assertion was based on an apparent consistency in the frequency with which bankfull occurs along streams (Wolman and Leopold, 1957), and an approximate correspondence between the frequency of bankfull discharge and the frequency of that flow which cumulatively transports most sediment (Wolman and Miller, 1960). A link is thus established between dominant discharge, most effective discharge and bankfull discharge with an approximate recurrence interval of 1.5 years on the annual series, or 0.9 years on the partial duration series (Carling, 1988b).

There is a growing body of evidence to indicate that bankfull discharge does not have a constant return period and may be a function of flow regime, slope and sediment load. Harvey (1969); Pickup and Warner (1976); Baker (1977); Williams (1978); Wolman and Gerson (1978) and Osterkamp (1980) all argue for, or demonstrate that, rivers with a more variable or flashy regime tend to have a greater channel capacity than those with low variability. Kilpatrick and Barnes (1964) and Williams (1978) found that rivers with high slopes had greater bankfull return periods than those with low slopes.

Bankfull studies carried out in New South Wales by Woodyer *et al*. (1972), Gregory (1976) and Pickup and Warner (1976) indicate that the recurrence intervals of the bankfull flows are likely to be greater than one year (partial series) generally quoted for humid areas. McDermott and Pilgrim (1982) estimated bankfull discharge using the Manning formula at 75 locations in New South Wales in an attempt to provide the basis for a method of flood estimation. The authors suggest an approximate value for the average recurrence interval of bankfull discharge as 2.5 years from the partial duration series. Similar values have been reported for the Cumberland Plain, south west of Sydney (Pickup and Warner, 1976).

If dominant discharge is defined in terms of sediment transport rather than channel capacity, the picture becomes complicated further. Pickup and Warner (1976) recognised two groups of events as being responsible for creating the channel form: a more extreme group which defines channel capacity (bankfull discharge), and more frequent events which control bedload movement and bedform construction. This they termed the 'effective discharge'. These authors found that the return period of the effective discharge ranged from 1.1 to 1.4 years, less than the most probable annual flood and the bankfull discharge. Similarly, although Wolman and Miller (1960) equated maximum sediment transport to bankfull discharge, Benson and Thomas (1966) combined flow duration curves and sediment rating curves to show that maximum suspended sediment transport is distributed across a range of discharges; these discharges are well below bankfull stage.

The mode of sediment transport also affects the role of discharges of varying frequency. Bedload transport demands the exceedence of a threshold stream power, so the most effective discharge should be more extreme. The effective, or dominant, event is lower in magnitude therefore if the stream carries suspended sediment than if bedload is transported (Hey, 1975).

The relative importance of extreme events appears to be dependent on the hydrological regime. In semi-arid environments with variable flow regimes, about 40% of sediment transport is by events of less than a 10 year return period, whereas in humid environments with more consistent flow and lower sediment yield from slopes during extreme events because of the protective effects of vegetation, more than 90% of sediment transport is by frequent events (Neff, 1967).

It is important to recognise that the dominant discharge may change over time, either due to natural climatic cycles or to man imposed disturbances. Erskine and Warner (1988) have identified drought and flood cycles in eastern Australia, with associated cyclical adjustment of channel form. Impoundments have an immediate effect on the dominant discharge which is accompanied by long term morphological change (Petts, 1980).

Measurement of discharge magnitude

As discharge is one of the most important variables determining channel response it is appropriate to outline the methods available for estimating discharge within a channel segment and for analysing the discharge records obtained.

Discharge measurement techniques

The Department of Water Affairs and Forestry has set up a gauging network to cover many river systems in the country using gauging stations as described in any standard hydrological text book. Although valuable in providing historic data series for certain river sections, the data records are limited in terms of their application to geomorphology. Firstly, the network has been set up with the needs of water resource managers in mind rather than research geomorphologists so that gauges may not be present on the river in question. Secondly, gauges are designed to monitor base flows rather than the geomorphologically effective flood flows so that the most relevant section of the data is often missing. It is often necessary therefore to augment the national data set with more appropriate data.

To relate hydrological events to river channel form it is convenient to gauge discharge at a stable natural river section. This can be done by defining a stage-discharge relationship and recording variations of stage. A range of systems can be used to automatically record water-level variations either in analogue form as a pen trace on a calibrated chart, or in digital form on paper or magnetic tape. The initial establishment of a stage-discharge curve requires direct field gauging over a range of discharges, including flood flows, in order that reliance on unsubstantiated extrapolation does not occur.

A number of methods are available for estimating discharge at a section; the choice of method depends on the channel form and the flow magnitude. The commonest technique is the velocity-area method. The average velocity through the river cross section, normally estimated using a current meter, is multiplied by the cross-section area. This method is best suited to relatively uniform cross-sections with a smooth bed without cobbles or boulders protruding into the flow.

Another useful technique is the dilution gauging method. This measures the dilution effect when a tracer such as a solution of common salt is injected into the flow. No cross-section measurements are required and no point measurements of velocity are taken so that this method is useful in conditions where a high channel roughness hinders the application of the velocity area method. This method is outlined by Gordon (1992) and is detailed by Church (1975).

The estimation of representative flood magnitude statistics requires a complete record of the peak flows experienced at a river section. Crest stage gauges provide a simple means of generating this data. Simple poles painted with poster paint provided effective crest gauges in the Sabie geomorphological study (Heritage *et al.*, 1997). In the absence of crest gauges, the presence of flood debris can be used to indicate the maximum flood height as well as the water surface slope.

If the water level and water surface slope are known, peak discharge (Q_p) can be estimated from the Manning equation (Gordon *et al.* 1992).

$$Q_p = C\, d^{2/3}\, S_w^{1/2}\, n^{-1}$$ *Equation 3.1*

C = channel capacity, d = mean water depth, n = estimated roughness coefficient, S_w = water surface slope

Mannings roughness is an empirical measure of the frictional resistance of the channel perimeter and is related to the size of the bed material, bed forms, bank vegetation, bed uniformity in both cross-section and long profile and channel sinuosity. Values commonly vary from between 0.02 for a smooth, sand bed channel to over 0.07 for a boulder bed channel with many obstructions to the flow. Values exceeding 0.1 are uncommon but may occur in highly vegetated sections. A fuller consideration of channel roughness is given in Broadhurst *et. al.*, (1995).

Estimation of discharge frequency

The long term flow regime of a river can be described by the use of a flow duration curve. This incorporates all flows in a river, the 'duration' curve representing a cumulative percentage curve of the time each discharge is equalled or exceeded (Richards, 1982). Log-normal discharge distributions are indicated by linear duration curves on log probability paper. Their slope reflects flow variability, measured by a 'variability index' which is the standard deviation of logarithms of discharges at intervals of 10% duration between 5% and 95%. Flow duration curves are usually applied to average monthly or daily flow data rather than to instantaneous values and tend to obscure the infrequent high flow data related to flood events.

Flood frequency analysis

A flood frequency analysis is the most common technique used to analyse the geomorphologically relevant flood events. It is based on an analysis of the flood peaks which may be the instantaneous flood peak or, if this data is not available, the daily average at the time of peak. A flood frequency analysis estimates the magnitude of events of various return periods (T), or probabilities of occurrence.

If the annual maximum discharges of N years of record are ranked from highest (rank, m=1) to lowest (M=N), the resulting 'annual series' forms N + 1 rank classes. The probability of a random event of magnitude x being equal to or greater than an event ranked M is

$$P(x) = M/(N + 1) \qquad \textit{Equation 3.2}$$

and the mean return period of this event is

$$T = 1/P\,(x) = (N + 1)\,/\,M \qquad \textit{Equation 3.3}$$

Benson (1960) showed that a forty-year record is required to estimate mean annual flood within about 10% of the true value with 95% confidence.

An alternative approach is to use the 'partial duration series' consisting of all independent flood peaks above a threshold discharge. The theoretical basis of the model is questionable in that it requires that events are randomly distributed through time with magnitudes described by an exponential probability distribution. Richards (1982) suggests that the partial duration series may be used with confidence to estimate the mean annual flood, and other events with $T < 10$ years. As long as at least 1.65 events are included per year, the partial duration series may yield estimates of discharge with lower variance than the annual series (Cunnane, 1973). Although the use of the partial duration series for extrapolation to higher magnitude events is not recommended, this is probably the most suitable series for analysing the frequency of events within the period of record. Unlike the annual series, the partial series allows the occurrence frequency to be calculated for events occurring more frequently than one year.

Flood estimation in ungauged catchments

In ungauged catchments, graphical correlation or multiple regression is used to estimate discharges of selected frequency from catchment characteristics and network morphometry. These include climate, land use and basin morphology, and particularly the size, slope and network density aspects isolated by principle components analysis (Rodda, 1969; Newson, 1975).

3.2.3 The channel long profile

Channel gradient is essentially an inherited feature, determined by the shape of the channel long profile. The long profile is itself the product of regional geological events and long-term fluvial action. Uplift, tectonic warping and volcanic activity provide the template upon which the profile develops. Over geological time the profile becomes adjusted to transport the sediment that becomes available to the river channel. Such a profile is said to be graded. A typical graded profile developed on bedrock of a homogenous resistance is concave in shape. The steep headwaters are in equilibrium with coarse materials being transported by relatively low flows in low order streams, whereas the lower gradient lowland areas are in equilibrium with the transport of finer materials by increasing flows in high order streams.

This classic long profile may be disrupted by a number of features including local outcrops of more resistant rock and rejuvenation due to tectonic uplift or a fall in sea-level. In South Africa widespread rejuvenation occurred during both the Miocene and Pliocene (Partridge and Maude, 1987). The axis of uplift runs more or less parallel to the east and south coast and reached a maximum of 800m in the Natal midlands in the Pliocene (Figure 3.2). This has resulted in east coast rivers in the Eastern Cape Province, Kwa-Zulu Natal and Mpumalanga having steepened long profiles with typically a concave upper section above a steeper engorged lower section. This has disrupted the classical bed material sequence so that sand bed channels in the lower reaches are replaced by bedrock, boulder and cobble.

A distinction should be made between the valley gradient and the channel gradient. Valley gradient depends on the regional topography and adjusts over geological time. The channel is imposed on the valley floor and may achieve a lower gradient through meandering. Occasionally the channel gradient may be steepened through incision. Adjustment of the channel gradient can take place within a much shorter time span, measured in years or decades.

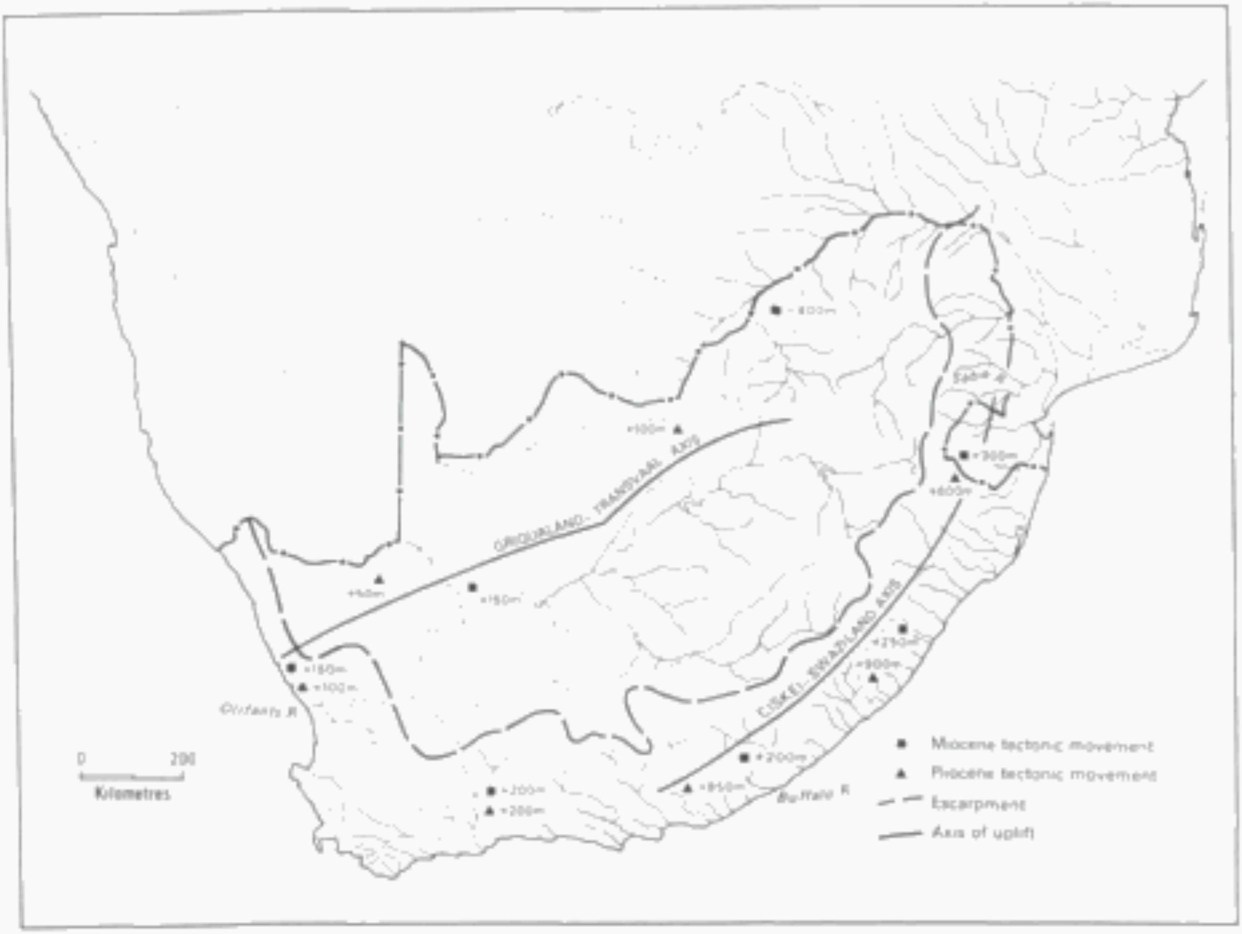


Figure 3.2 Axis of uplift in South Africa

3.2.4 Stream power

Stream power is defined as the ability of the water to perform work and is a good measure of its capacity to erode and transport material. One measure of stream power is based on the product of discharge and slope, this gives the total stream power per unit of stream length and is given as:

$$\bar{\omega}_t = \rho g Q S \qquad \textit{Equation 3.4}$$

where $\bar{\omega}_t$ is stream power per unit of stream length in units of kg-m/s³, ρ is water density, g is acceleration due to gravity, Q is flow discharge and S is the energy slope of the reach.

It can be seen from Equation 3.4 that variations in stream power down the stream network will depend on the relative increase or decrease in gradient and flow discharge. In rivers possessing a classic convex long profile the increased discharge tends to be cancelled out by the concomitant reduction in gradient so that stream power as defined in Equation 3.4 is relatively uniform. If, however, channel gradient increases downstream due to rejuvenation, stream power will also increase significantly. Channel forms developed under such conditions will vary significantly from those expected for a classical convex profile. This is an important consideration when classifying South African rivers, many of which have rejuvenated lower courses.

3.3 CHANNEL TYPE

River channels can be classified into two broad types: *bedrock channels* and *alluvial channels*. In bedrock channels the energy of the stream during flood events is sufficient to transport all available loose material, whether it is coming in from the side slopes, the banks or the bed of the stream itself. Such conditions occur where channel slopes are steep, the bedrock underlying the channel is resistant to weathering and/or there is a limited input of sediment from the valley side slopes. In bedrock channels the geology of the channel bed and its resistance to erosion is the main determinant of channel form. In contrast alluvial channels are formed within the sediment which is being transported by the river. Both the bed and the banks of the river are composed of sediment which is in temporary storage within the system. The channel form is now the result of the balance between the available sediment and the transport capacity of the flow. Fluvial research commonly emphasises these systems, largely because of their relative ease of study in comparison to bedrock systems and a generally rapid morphological response to changes in discharge.

Bedrock channels and alluvial channels with either fine (sand) or coarse (gravel) beds commonly coexist in many drainage basins of the world. Such channels are known as *bedrock controlled* or *mixed channels* Short sections of bedrock channel with steep gradients may occur in predominantly alluvial channels where resistant rocks outcrop, these are particularly prominent throughout South Africa and include reaches within the Sabie River (Mpumalanga); the Tugela River (Kwa-Zulu Natal) and the Olifants River (Western Cape). A more resistant bedrock section may also act as a local base level and a zone with a low rate of erosion, and correspondingly low gradients, commonly occurs above such resistant outcrops (Howard, 1980); these low gradient sections are generally alluvial, even if the majority of the channel system is bedrock. These are common features within parts of the Buffalo River (E. Cape) and the Sabie River (Mpumalanga).

Alluvial channels tend to dominate lowland areas in many parts of the world whilst bedrock channels dominate many of the highland areas. South Africa finds itself in a situation with a complex mix of both alluvial and bedrock morphology, particularly in the lowland areas.

Alluvial rivers can be further subdivided depending on the size of their bed material. Three general classes of alluvial channels are recognised - sand bed, gravel bed and boulder bed channels. A classification of grain size is given in Table 4.4 (Chapter 4).

Sand beds:

Sandy or fine-bed alluvial channels have beds dominated by sand with small percentages of gravel. These beds are highly mobile, exhibiting motion at even moderate to low discharges, and are characterised by moderate to high rates of sand transport. The micro scale alluvial features associated with sand beds (ripples, dunes, plane beds and antidunes) adjust their form rapidly to flow conditions (Simons & Richardson, 1966).

Gravel beds:

Gravel or coarse-bed alluvial channels have beds dominated by gravel with small percentages of sand. These channels usually experience bed sediment transport only during high-flow stages with slow rates of gravel transport. Gravel bed channels are favoured by low sediment loads and relatively large proportions of coarse detritus. International literature suggests that, in many natural channel systems, a common spatial transition is the threshold change from headwater gravel-bed channels to downstream sand-bed channels (Howard, 1980). South African experience would suggest that this is the exception rather than the norm in this country. Many rivers visited during the course of this research exhibited complex transitions involving the deposition of coarse substratum, associated with upper reaches (cobbles and boulders), over and behind bedrock controls in the lowland reaches (Tugela River, Buffalo River, Great Fish River and the Sabie River).

Cobble and boulder beds:

Cobble and boulder channels are dominated by large clasts which require high thresholds of stream power before movement takes place. The larger cobbles and boulders provide relatively immobile channel structures through which finer material is transported. Cobble and boulder channels therefore frequently have a wide particle size range and are poorly sorted.

3.4 MORPHOLOGICAL UNITS

As can be seen from Figure 3.1 bedrock and alluvial systems can be separated at scales ranging from grains to segment, but at the zone and catchment scale they can be considered together. The following discussion will therefore follow this same structure.

3.4.1 Morphological units in alluvial channels

Morphological units in alluvial systems can be divided simply into pool and bars. Pools are scour features which form behind a hydraulic control and which, at low flow, have relatively slow flow and deep water. Bars are depositional features which can be classified according to the nature of the material of which they are composed and by their location within the channel. A summary of bar types and other alluvial morphological units is given in Table 3.1 and Figure 3.3. Classification in the field may be more difficult due to transition types. The distinction between mid-channel bars and braiding is a case in point.

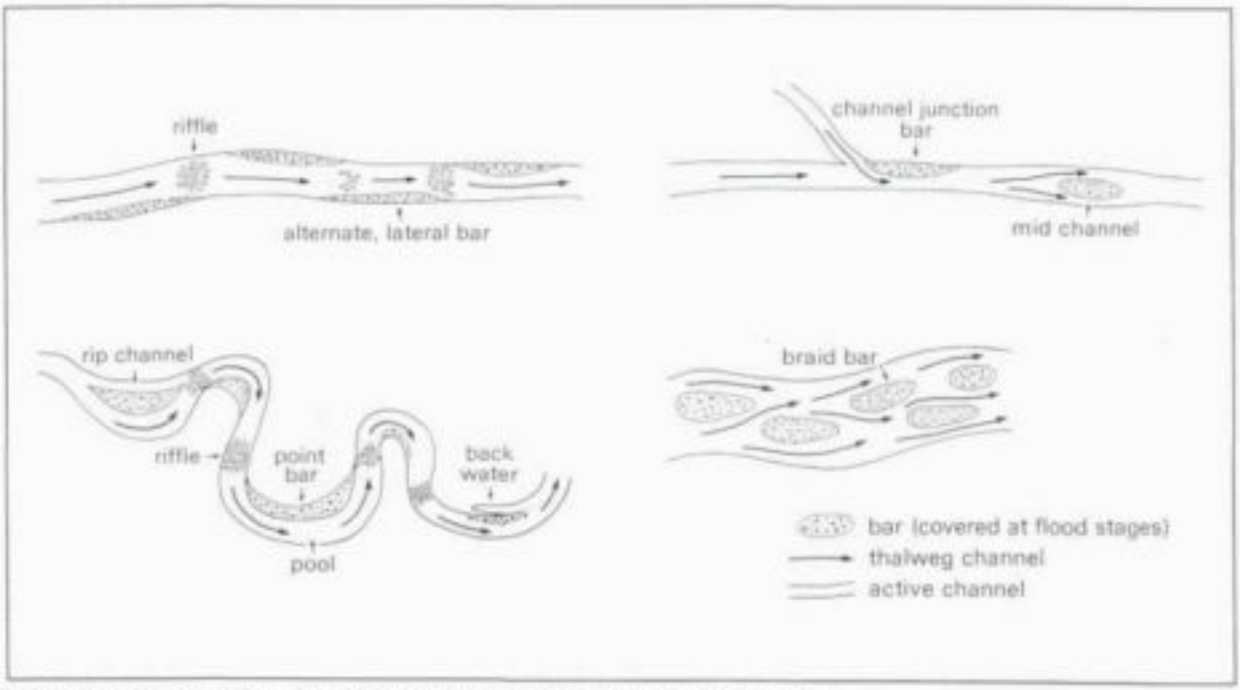


Figure 3.3 Classification of bar types and morphological units

Table 3.1: Classification of alluvial morphological units (modified from Kellerhals and Church, 1989; van Niekerk *et al.* 1995 and Wadeson, 1996).

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

3.4.2 Morphological units in bedrock channels

Morphological units in bedrock channels are less predictable than their alluvial equivalent because their formation and morphology depend on the nature of the bedrock in which they occur, as well as the hydraulic forces of the water. Resistance to erosion depends on many factors including the mineralogy and grain size of the intact rock, degree of jointing, direction of fracture zones and direction of dip in sedimentary rocks. This combination of factors tends to produce unique assemblages of features in different river systems. It is possible, however, to develop a general classification which will encompass most bedrock forms. Van Niekerk *et al.* (1995) have produced a useful starting point for such a classification based on features observed in the Sabie River in the lowveld. Table 3.2 incorporates their classification.

Table 3.2: Morphological units in bedrock channels

Morphological unit	Description
Bedrock pool	Area of deeper flow forming behind resistant strata lying across the channel.
Plunge pool	Erosional feature below a waterfall
Bedrock backwater	Morphologically detached side channel which is connected at lower end to the main flow
Waterfall	Abrupt continuity in channel slope; water falls vertically; never drowned out at high flows. Height of fall significantly greater than the channel depth.
Cataract	Step like succession of small waterfalls drowned out at bankfull flows, height of fall less than channel depth.
Rapid	Local steepening of the channel long profile over bedrock, local roughness elements drowned out at intermediate to high flows.
Bedrock pavement	Horizontal or near horizontal area of exposed bedrock.
Bedrock core bar	Accumulation of finer sediment on top of bedrock.

3.5 REACH CLASSIFICATION

Reaches are defined in the hierarchical model as a length of channel within which the local constraints on channel form are uniform resulting in a characteristic channel pattern, degree of incision and cross-section form and within which a characteristic assemblage of channel morphologies occur.

Reach types have been classified by Wadeson (1996) in terms of their assemblage of morphological units (Tables 3.3 and 3.4). They can be described further in terms of their characteristic channel cross-section and the channel pattern. Each of these will be considered in turn for alluvial and bedrock systems.

3.5.1 Reach types

Reach Types in alluvial systems

Step-pool

The predominant morphological unit associated with low order cobble / boulder channels is the step-pool or cascade of Grant *et al* (1990) and Church (1992). This is characterised by large clasts (detrital material consisting of fragments of broken rocks, which have been eroded, transported and redeposited at a different site) organized into discrete channel spanning accumulations that form a series of steps separating scour pools containing finer material (Grant *et al.*, 1990). Channel diameter is of the same order of magnitude as that of the clasts themselves. There is a strong vertical component to the flow in step-pool channels, contrasting to the more lateral flow in lower gradient pool-riffle channels.

Step-pool channels tend to exhibit a pool spacing of roughly one to four channel widths, the spacing decreasing with increasing channel slope (Grant *et al.* 1990). Warburton (1992) suggests that there are three phases of step-pool sediment transport, characterised by a low-flow flushing of fines, a bankfull-equivalent breaking up of gravel pavement (with transport characteristics similar to pool-riffle threshold channels), and a less frequent higher discharge event capable of mobilizing larger bed forming clasts. The largest volume of bed load transported through the channel is in the sand size (Leopold, 1992), while the boulder and cobble fractions make up the major features of channel morphology which remain stable except in rare flood events.

Plane-bed

The term plane-bed has been adopted to describe channels developed in coarse bed material (cobbles and boulder) with little or no influence of bedrock, which lack any clear organisation into erosional or depositional morphological units, and hence have a uniform gradient (Montgomery and Buffington, 1993). Channel width is of an order of magnitude greater than the clast diameter. The larger clasts are generally scattered over the channel bed and at low to moderate flows project out of the water. Newson and Harrison (1978) describe similar channel forms from rivers in the United Kingdom. These features are quite distinct from both step-pool and pool-riffle morphologies in that they lack rhythmic bedforms. They appear to occur at gradients and relative roughnesses intermediate between these other two reach types.

Montgomery and Buffington (1993) suggest that plane bed morphology reflects a channel that is capable of mobilising bed material at bankfull thresholds, but does not possess sufficient lateral flow convergence to cause pool development. The flashy flow regime associated with many rivers in South Africa may in part account for the widespread occurrence of this morphology in many headwater and rejuvenated sections of rivers.

Table 3.3 Summary of the reach types found in alluvial systems. (Adapted from Grant *et al.*, 1990; Montgomery & Buffington, 1993 and van Niekerk *et al.* 1995).

Reach Type	**Description**
Step-Pool	Characterised by large clasts which are organised into discrete channel spanning accumulations that form a series of steps separating pools containing finer material.
Plane-Bed	Characterised by plane bed morphologies in cobble or small boulder channels lacking well defined scour or depositional morphological units.
Pool-Riffle	Characterised by an undulating bed that defines a sequence of bars (riffles) and pools.
Regime	Occur in either sand or gravel. The channel exhibits a succession of bedforms with increasing flow velocity. The channel is characterised by low relative roughness. Plane bed morphology, sand waves, mid channel bars or braid bars may all be characteristic.

Pool-riffle

Pool-riffle reaches are most commonly associated with gravel bed rivers, though they have been identified as also occurring in coarser materials in South Africa. The longitudinal profile of the river bed is broken into a series of irregular steps of alternating steep and gentle reaches, the riffles and pools. Generally speaking pools are topographic lows which are scour features located between riffles. Their position is often coincident with point bars situated on meander bends. Riffles are topographic highs and are formed by the accumulation of coarse material to form a transverse bar with a steeper gradient (Selby, 1985). At low discharges flow through pools is deep relative to that over riffles, the surface water gradient is low as is flow velocity. Pools are therefore areas of deposition of fine material during low flow periods. At this time riffles have shallow flow with a steep water gradient and high velocity relative to that of the pool. Fines are winnowed from the riffle areas to leave a coarse substrate. At high discharges, a velocity reversal has been observed to take place between riffles and pools (Keller & Florsheim, 1993). As discharge increases the riffles are drowned out and the surface water gradient becomes more uniform over the two features. Velocities increase faster in the pools than over riffles so that scour now takes place, with deposition in the riffle areas. At high discharges velocity in the pools may exceed that over the riffles.

Within the South African fluvial environment, the classic riffle-pool morphology of gravel bed reaches do occur (Dollar, 1992); this type of fluvial environment, however, is relatively uncommon. Riffles and pools continue to be important channel form features of many South African rivers, but are dominated by considerably larger substratum, in the size class of cobble and boulder. Moreover, riffle type features are often situated on top of bedrock controls which form topographic high points within the channel, alluvial pools are dammed behind them, eg. Dolerite dikes in Karoo systems, Free State and Transvaal highveld (Chutter, *pers. comm.*)

Riffle-pool sequences are alluvial features with characteristics related to discharge. For example, a significant feature of riffle-pool geometry in gravel beds is the more or less regular spacing of successive pools or riffles at a distance of 5 to 7 times the channel width (Knighton, 1984). Even though the bed material comprising the riffle may move, the spacing and location of riffles and pools is thought to remain the same, as long as the long term flow regime does not change (Morisawa, 1985). Changes to the flow regime will, however, tend to bring about an adjustment in riffle-pool spacing. This is in contrast to bedrock (rapid) or bedrock-controlled features (riffles) common in many South Africa rivers, whose spacing is not discharge controlled and will not be modified by a change in the flow regime.

Regime

A regime channel is defined as one which has a highly mobile bed which adjusts rapidly to changes in discharge. They are characteristic of sand or fine gravel beds which exhibit motion at even low to moderate discharges and are characterised by moderate to high rates of sand transport (Simons and Simons, 1987). The micro-scale alluvial features associated with sand beds (ripples, dunes, plane beds and anti-dunes) adjust rapidly to flow conditions.

Large scale features such as point bars found on the inside of meander bend, or mid channel bars associated with braiding, determine the channel cross section and hence flow conditions across the channel. These features are relatively dynamic, with significant reshaping and shifting of bars occurring during major flood events. Sand waves are another morphological feature associated with sand bed rivers and have been observed by the authors in the Olifants River of the Western Cape.

Regime channels associated with sand bed rivers are found at relatively low gradients; in South Africa they have been observed at gradients between 0.002 to 0.0002.

Reach types in bedrock controlled systems

Cascades

Cascades form in high gradient streams dominated by a series of waterfalls, cataracts, plunge pools and bedrock pools. This reach type may include bedrock core step-pool features. Energy dissipation in these reaches is dominated by jet and wake flow, hydraulic jumps and turbulence around large clasts.

Bedrock fall

A bedrock fall is a short channel section consisting of a waterfall and associated plunge pool.

Planar bedrock

Planar bedrock describes a channel developed in bedrock with a relatively smooth bed and lacking falls or rapids. Common morphological features include bedrock pavement and shallow bedrock pools. A contiguous alluvial bed is absent but some alluvial material may be temporarily stored in scour holes and behind flow obstructions.

Pool-rapid

Pool-rapid reaches are characterised by long pools backed up behind channel spanning bedrock intrusions which form rapids. Sediments are often deposited upstream of the local control in the form of braid and lateral bars (van Niekerk *et al.*, 1995) or downstream in the form of lee bars.

Table 3.4 Summary of the reach types found in bedrock controlled systems. (Adapted from Grant *et al.*, 1990; Montgomery & Buffington, 1993 and Van Niekerk *et al.* 1995).

Reach Type	**Description**
Cascade	High gradient streams dominated by waterfalls, cataracts, plunge pools and bedrock pools. May include bedrock core step-pool features
Planar Bedrock	Predominantly bedrock channel with a relatively smooth bed. Significant falls or rapids are absent. .
Bedrock Fall	A steep channel where water flows directly on bedrock with falls and plunge pools.
Pool-Rapid	Channels are characterised by long pools backed up behind channel spanning bedrock intrusions forming rapids.

3.5.2 Channel cross-section form.

The cross-section form of a reach should take into account the full suite of fluvial features across the valley floor as shown in Figure 3.4. Typically, in humid areas, these include the thalweg channel, the active channel, the floodplain and terraces. The extent of the features varies with the long term geomorphological history of the area and with location along the long profile. In semi-arid areas such as the Karoo a somewhat different picture emerges as indicated in Figure 3.5. The pediment takes the place of the terrace or flood plain as the dominant morphological feature comprising the valley floor.

The *active channel* is that area of the channel which is inundated at sufficiently regular intervals to maintain channel form and to keep the channel free of established terrestrial vegetation. In humid areas at least this approximates to the area inundated by the annual flood and is marked on either side by relatively well defined banks.

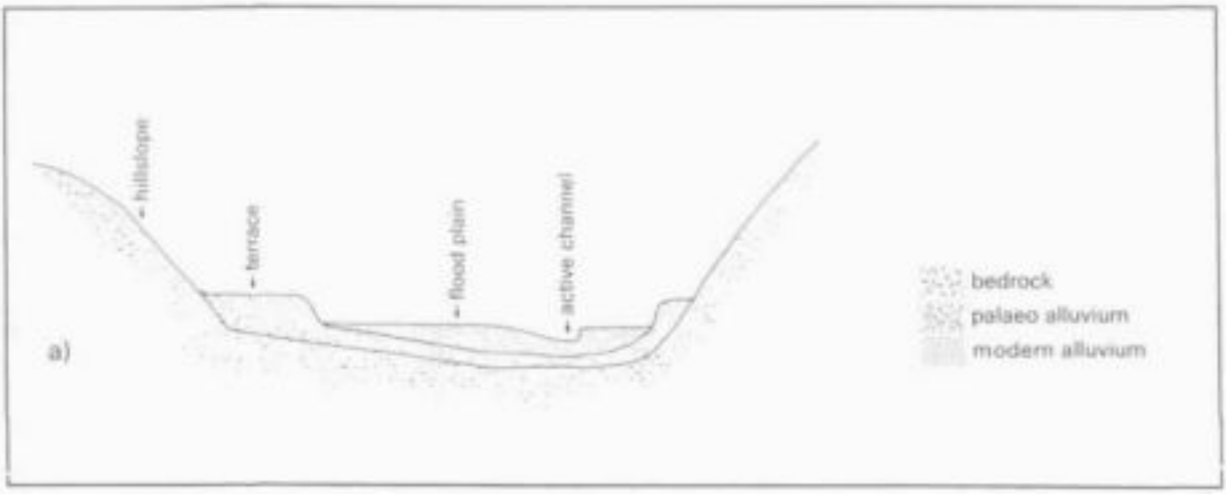


Figure 3.4 Cross sectional form of a humid river system

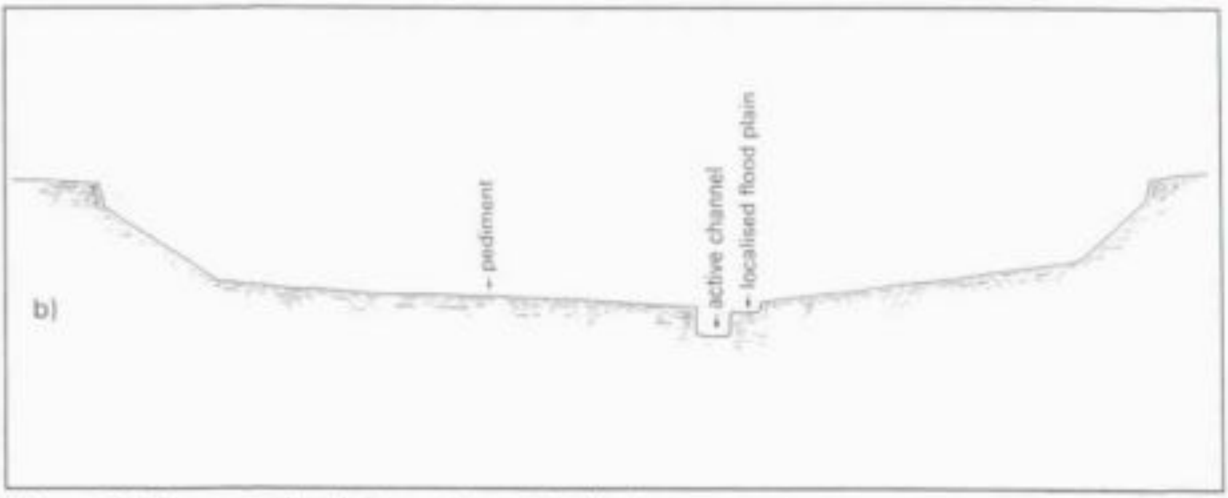


Figure 3.5 Cross sectional form of a semi arid river system

The *flood plain* is the relatively level alluvial area lying adjacent to the river channel and has been constructed by the present river in its existing regime. It therefore represents a store of sediment. The flood plain determines the area over which the present channel is free to migrate. Inundation of the flood plain, with concomitant deposition of fine sediment, occurs relatively frequently, normally once every one to two years.

An *erosional bench* may take the place of the flood plain, especially where the potential for sediment accumulation is limited as in bedrock systems. Erosional benches are described by van Niekerk *et al.* (1995) as terrace like features resulting from active down cutting within a broader macro-channel.

Terraces are relict flood plains which have been raised above the level regularly inundated by flooding due to lowering of the river channel. They are often associated with rejuvenation. Unlike the flood plain, their features are unrelated to the present river regime.

In upland areas with steep channel gradients there is limited lateral development of the valley floor so that the hillslopes may impinge directly onto the channel. In this case the flood plain and terrace may be absent or replaced by a narrow *lateral bench*. Flooding takes place directly onto the base of the hillslope.

In lowland semi-arid areas the valley floor may be dominated by a *pediment* into which the channel is incised with or without flood plain development. A pediment is a low angled hillslope which is formed by surface wash processes. It may be either erosional or depositional. Where a flood plain is absent, major flood events overtopping the channel will cause flooding of the pediment slopes close to the river but, because of the infrequent recurrence interval of flooding, slope processes predominate in determining its characteristics. Pediments dominate the fluvial environment of the upper Sundays River (Eastern Cape) where it crosses the Camdeboo Plains.

A particular feature of many South African rivers, particularly those draining the eastern seaboard, is a *macro-channel*. This has been described for the Sabie River by van Niekerk *et al*. (1995) and for the Tugela and Mvoti rivers by Rowntree and Wadeson (1995b) and Wadeson and Rowntree (1996b). Macro-channels appear to develop as the result of incision by the active channel into former terraces which mark the outer boundary of all but the most extreme flood flows. In the Sabie the macro-channel takes the form of an erosional bench which exhibits both erosional and depositional features as well as secondary high flow channels. Probably because of its confinement between terrace slopes, flood events which spill out onto the macro-channel are more effective at entraining and transporting sediment than would be the case with a true flood plain. In the case of the Tugela and the Mvoti (Figure 3.6), the erosional bench is absent. Instead the active channel is bounded by a narrow depositional bench which abuts directly onto the terrace slopes. During flood events the water is unable to spill out onto a flood plain or equivalent area, but simply rises up the terrace slopes. The geomorphological effectiveness of flood events which exceed the capacity of the active channel will therefore be considerable.

The *active channel* is the channel which by definition is inundated most frequently and is geomorphologically the most active. It has been the focus of interest of many geomorphological studies and is the main area of concern to aquatic ecologists. The following discussion will present standard methods used to describe or classify the cross-section of active channels.

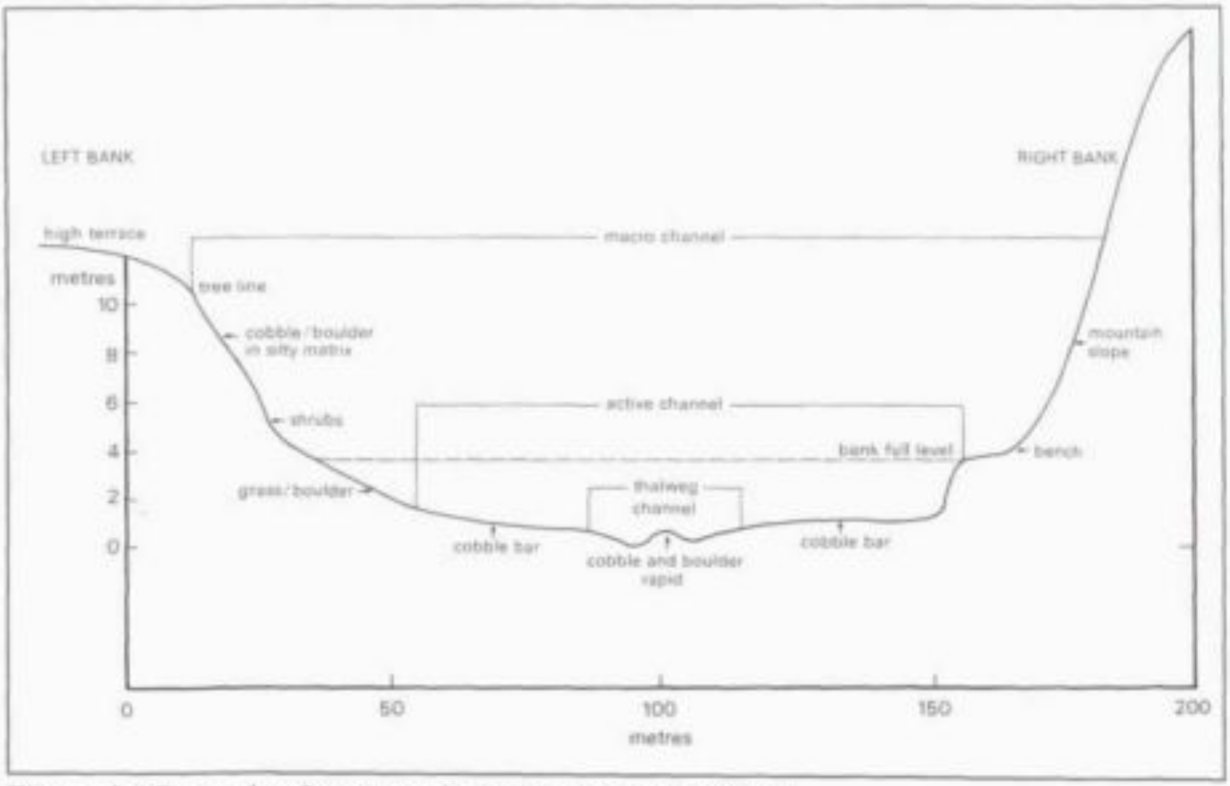


Figure 3.6 Example of a macro-channel in the Tugela River

Active channel cross section form

Figure 3.7 provides a definition diagram for cross-section form variables. The main variables are channel width, average depth, wetted perimeter or channel perimeter and hydraulic radius. These variables can be applied both to the channel morphology itself and to the water flowing through the channel. At-a-station hydraulic geometry relationships can be used to describe the relationship between the two as described below.

As noted previously, the bankfull flood is assumed to be the channel forming event and therefore has morphological significance. Standard channel form measurements are therefore taken with reference to the bankfull level, that is the morphological break between the active channel and flood plain. In many channels this is easily identified, but not so where channels lack a well developed flood plain or have compound banks. A number of methods have been proposed for identifying the boundary of the active channel; these have been summarised by Williams (1978). Wolman (1955) suggested that bankfull can be identified as the minimum point on a plot of width:depth ratio against stage. Field evidence is provided by patterns of vegetation and sediments. The distribution of woody vegetation and their age classes and of tall grasses and reeds can provide useful clues as to frequency of flow inundation and substrate disturbance. The experience of a local riparian vegetation specialist is invaluable here. The truncated distribution of lichen thalli on boulders and rock walls caused by inundation and abrasion by suspended sediment also provides evidence of a specific event frequency which may be related to maintenance of the active channel. A sedimentological criterion suggested by Nunally (1967) is the upper limit of continuous sand deposition on point bar surfaces

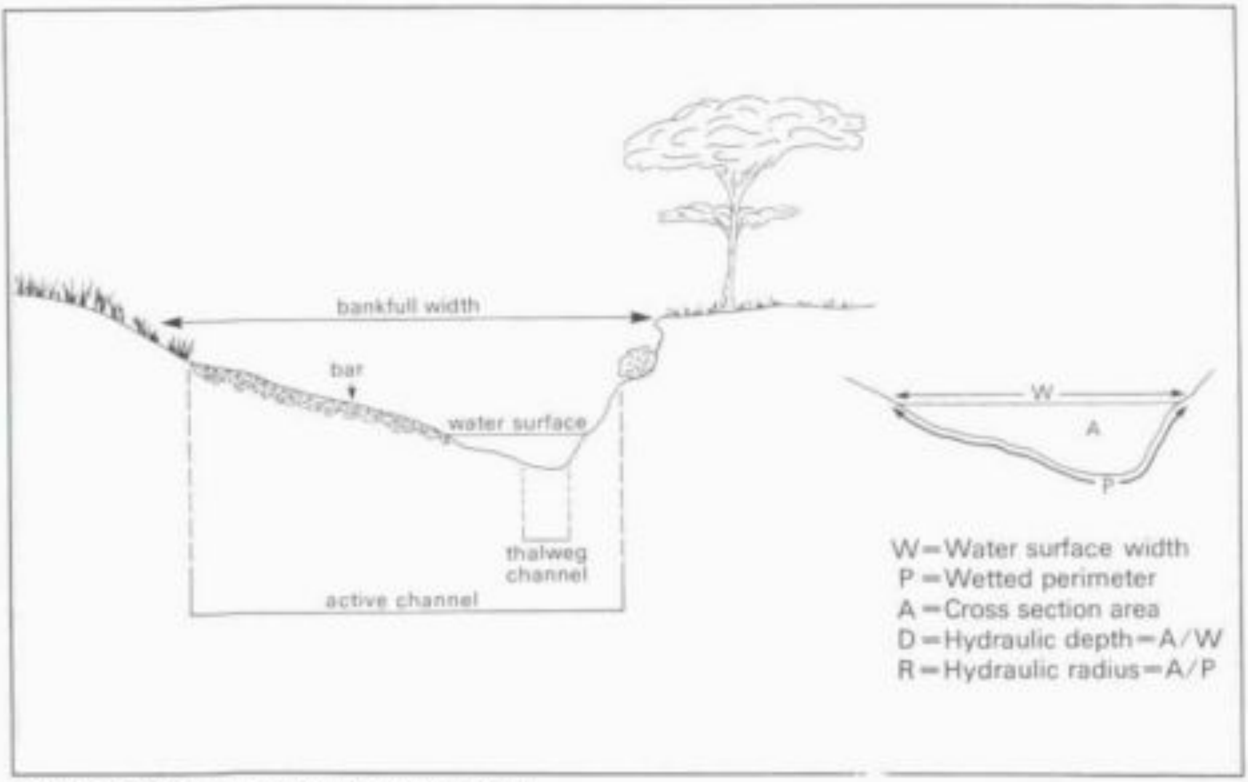


Figure 3.7 Cross section form variables

Channel width is usually taken to be the bankfull width, water surface width is measured simply as the width from one bank to the other. There is no standard convention as to whether or not to include exposed bars, boulders and so forth. The decision depends on the application of the results.

Average channel depth is estimated as the cross-section area divided by the width. Average water depth can be calculated in the same way or from the average of a number of point depth readings. The hydraulic radius is commonly used in place of depth in hydraulic equations. The hydraulic radius takes account of frictional resistance between the water column and both the bed and the banks and is defined as the cross-sectional area of flow divided by the wetted perimeter. For wide channels it is approximately equal to depth.

Channel width (w) and depth (d) do not in themselves provide a measure of channel form. They are commonly combined together in the Form Ratio (F) where:

$$F = W/d$$ *Equation 3.6*

This index gives a useful measure of channel shape which is well correlated to other reach variables such as bank and bed material composition and vegetative condition of the banks.

Although not a form variable, it is appropriate at this point to mention channel velocity as this is an important component of hydraulic geometry relationships. Velocity normally refers to the mean velocity through the channel cross section and is clearly discharge dependent. It can either be measured directly using a technique such as the standard velocity-area method (Gordon *et al.* 1992) or, if discharge is known, it can be calculated from the equation:

$$v = Q/A$$ *Equation 3.5*

where v is velocity, A is the cross-sectional area of the flow and Q is discharge.

Bank condition

Banks can be classified in term of their material composition, their shape and the degree and type of erosion. Separate descriptions may be needed to characterise the active- and macro-channels.

Knighton (1987) classifies channels into two main groups based on their boundary composition: cohesive and non-cohesive. The same classification can be applied to banks. Cohesive banks include those developed in bedrock as well as those with a high silt-clay content, giving varying degrees of cohesion. Non-cohesive banks may be composed of sand, gravel or cobble. Channel banks often exhibit a layered sedimentary structure. A cobble base overlain by finer sediments is common.

The shape of the channel bank is an indication of processes operating on them and the manner in which flow depth and width will vary with discharge. Undercut and vertical banks usually indicate active basal erosion in cohesive and semi-cohesive material respectively. Where banks are steep, flow depth will increase faster than width as discharge increase, but if banks are gentle the converse will be true. Bank shape can be classified according to the following classes:

vertical *concave* *convex* *undercut* *stepped*

Bank gradient is another variable that should be taken into account. Anderson (1993) suggests five classes:

$<10°$; $10°$-$30°$; $30°$-$60°$; $60°$-$80°$ $>80°$

Bank condition can be classified according to stability indicators:

Stable banks -	well vegetated, no sign of erosion
Active basal erosion -	vertical banks, undercutting, slumping
Subaerial erosion -	sloping bank, unvegetated or sparsely vegetated, active rilling, livestock trampling, etc.

The location of bank erosion is an additional variable that is commonly included in river inventories (Anderson,1993). Common localities for bank erosion include outer banks of meander bends, straight sections or linked to obstructions (e.g. fallen trees).

Bed condition

Bed material transport represents a continuous process of erosion and deposition, with pulses of sediment being shunted through the channel. This makes it difficult to assess whether changes in bed condition are part of the long term dynamic equilibrium of the channel or reflect a real change in status. Nontheless it is possible to make an assessment of at least the short term changes in bed condition with respect to aspects such as bed scour or siltation. Anderson (1993) suggests that "water falls in the bed" (obvious scour features) and "gravels loose and bright" can be used as indicators of eroding conditions whilst mobile point bars, extensive bar deposits, island and encroaching vegetation and steep banks decreasing in height downstream are all indicators of bed aggradation.

Controls on channel form

Channel dimensions are adjusted, through the processes of erosion and deposition, to the quantity of water moving through the cross-section so that the channel can contain all but the highest flows. The relationship between channel dimensions and discharge has been described using the concept of hydraulic geometry (Leopold and Maddock, 1953). This notion assumes that discharge (Q) is the dominant independent variable and that dependent variables are related to it in the form of simple power functions:

$$W = aQ^b \quad \text{Equation 3.7a}$$

$$d = cQ^f \quad \text{Equation 3.7b}$$

$$V = kQ^m \quad \text{Equation 3.7c}$$

W = width, d = mean depth, V = mean velocity

From the continuity equation,

$$Q = w.d.v = aQ^b.\ cQ^f.\ kQ^m \quad \text{Equation 3.8}$$

if follows that

$$a.c.k = 1. \quad \text{Equation 3.9a}$$

$$b + f + m = 1. \quad \text{Equation 3.9b}$$

The expression b+f+m should always equal unity so that a change in width (b) will be compensated by a change in depth (f) and velocity (m). Relatively consistent relationships have been found for both changes with discharge at one point (at-a-station hydraulic geometry) and changes in the downstream direction (downstream hydraulic geometry).

At-a-station-hydraulic geometry

In their early studies Leopold and Maddock (1953) found consistent hydraulic geometry relationships across a wide range of channels; their results are summarised in Table 3.5. It can be seen that on average the increase in discharge at a given cross-section is accommodated largely by an increase in depth, followed by velocity and lastly width. Hydraulic geometry relationships are clearly a reflection of the channel cross-section shape and therefore of both perimeter properties and of the occurrence of particular morphological units. Differences in exponent values have been related to channel pattern (Rhodes, 1977), with greater values for b (the width exponent) relative to f (width) being found for braided channels compared to meandering channels.

Table 3.5 At-a-station hydraulic geometry

Variable	**Exponent**	**Average values Leopold and Maddock (1953)**
Velocity	m	0.34
Depth	f	0.40
Width	b	0.26

Table 3.6 Downstream hydraulic geometry

Variable	Exponent	Average values Leopold and Maddock (1953)	Ephemeral arid rivers (Leopold and Miller 1956)
Velocity	m	0.1	0.2
Depth	f	0.4	0.3
Width	b	0.5	0.56

Downstream hydraulic geometry

The downstream hydraulic geometry reflects the manner in which the channel form changes as discharge increases in the downstream direction. Downstream hydraulic geometry must be related to a specific discharge frequency applied to all cross-sections, commonly taken to be the 1.5 year recurrence interval or mean annual flood. This should approximate to the bankfull or channel forming discharge. The hydraulic relations of Leopold and Maddock (1953) based on selected rivers in the Midwestern United States are summarised in Table 3.6. This shows that width increases faster than depth so that the width-depth ratio tends to increase downstream. Average velocity also increases slightly downstream, in contrast to entrenched conventional thinking still held by many river scientists. The increase in velocity can be explained by the greatly reduced channel roughness associated with low gradient streams. These trends are even more pronounced in ephemeral streams. Richards (1982) proposes that the resultant channel form is better suited to the transport of a sandy bedload in streams which have a less marked reduction on the downstream long-profile gradient. Channel size is not only influenced by the magnitude of discharge, but also by the hydrologic regime. A river with a flashier regime and relatively high peak flows tends to develop wider channels (Osterkamp, 1980).

Channel gradient and perimeter conditions

Knighton (1987) points out that channel form adjustment is reliant not on the quantity of water *per se*, but on the ability of the water to erode and transport the material (stream power) and is therefore also dependent on slope as well as the quantity and type of load. The type of load carried by the stream is inextricably linked to the composition of the bed and banks which themselves are linked to channel gradient, so that the relative effects of sediment load, bed material size and gradient are difficult to separate. It would appear that steeper slopes tend to give rise to wider, shallower channels as does coarse bed material. For steep slopes which generate high transport rates and encourage channel migration, Chang (1979, 1980) predicted a rapid increase in width and decrease in depth with increasing slope which may indicate a tendency for braiding. Knighton (1984) suggests that channel size may be adjusted to the total sediment discharge, especially where the stream transports a large bed load, while channel shape is more closely related to the type of load. It has been found that channels carrying a high bedload tend to have a greater width-depth ratio than those carrying a predominantly wash load. Generally a river will attempt to maintain a channel morphology that is most suited to the transportation of its sediment load so that, if there is a change in the state of the load, the river will adjust its channel morphology to correct the imbalance (Morisawa, 1985).

The resistance of the bank to erosion and channel widening have an important effect on channel form. Bank material and riparian vegetation are two important variables influencing bank resistance.

The percentage of silt and clay in the channel banks has important implications for channel form as channel banks are more cohesive when they display a higher silt-percentage. Schumm (1960) showed that the form ratio tended to increase with the percent silt plus clay. Channels with high silt clay percentages are relatively narrow and deep, those with low silt-clay percentages tend to be wide and shallow. In stratified banks the maintenance of channel width depends on the strength of the different layers particularly the basal layer, the erosion of which may induce block failure and slumping due to gravity (Knighton, 1987).

Vegetation increases bank resistance which may lead to channel narrowing. Charlton *et al.* (1978) found that channels with grassy banks were on average 30 % wider and tree-lined ones up to 30 % narrower than the overall width-discharge relation would suggest. Other workers have found similar relationships (Clifton, 1989). Rowntree and Dollar (1996b), studying channels in the north eastern Cape of South Africa, found that form ratio was highly correlated to the density of woody bank vegetation. This relationship masked any possible correlation with bank material. Vegetation thus has an important effect on channel form, but the protective effect of vegetation is variable and difficult to quantify. A full review of the relevant relationships can be found in Thorne (1990) and Rowntree (1991).

3.5.3 Channel pattern or plan form

Channel pattern classifications can be used to describe the plan form of the reach. The simplest classification of channel pattern distinguishes two main groups: single thread and multi-thread. Single thread channels can be further subdivided into straight or sinuous and meandering; multi-thread channels can be subdivided into braided, and anastomosing or anabranching. All classes can be further classified in terms of their stability or degree of mobility.

Single thread channels

Very few natural channels are truly straight, most display some degree of sinuosity. A distinction can be made between straight and stable-sinuous channels and meandering channels on two counts: the observed degree of sinuosity and the lateral mobility of the channel. Straight and meandering channels have been delimited by an arbitrary sinuosity value of 1.5, where sinuosity is defined as the length of the active channel divided by the valley length (Richards, 1982) Meandering streams can be further identified as those which are actively migratory as a result of selective bank erosion and point bar development. Their sinuosity is the product of active, inherent processes, rather than a passive response to external influences, although their degree of morphological regularity reflects external environmental controls (Richards, 1982). For active meandering there is a need for sufficient energy for selective bank erosion, and sediment deposition. Meandering is thus the result of a medium to high power to resistance ratio.

A straight or stable-sinuous channel in contrast lacks the lateral mobility of a meandering river (Nanson and Knighton, 1996); sinuosity reflects the variability of bank materials, the influence of bank vegetation and random bank collapse. Straight channels are associated with a low power to resistance ratio. Low sinuosity reflects not only low stream power, but also coarse, relatively immobile sediments (pebble and cobble bed material). Bluck (1976) suggests a general down-stream trend of changing bedforms and channel patterns as bed material sizes decline. Upstream, coarse sediments in medial bars characterize low-sinuosity streams. As both bank and bed material becomes finer downstream the propensity for meandering increases.

It should be noted here that some of the very large meanders evident from maps for South African rivers are related to valley meandering rather than channel meandering. Bends occur because the stream is confined between valley bluffs which divert it back and forth across the valley floor. Thus a low-power stream is being diverted from a uniform flow direction by sedimentological and topographical constraints which it is incompetent to modify (Richards, 1982). These channels bear many of the characteristics of straight channels.

Meandering channels can be further classified according to their sinuosity, degree of regularity and level of mobility.

i) Sinuosity.	Richards (1982) suggested that total sinuosity is used i.e. total active channel length: valley length.
ii) Degree of regularity.	Kellerhals *et al.* (1976) recognised three categories of meander regularity: irregular meanders with only a vague repeated pattern; regular meanders with a clearly repeated pattern and a maximum deviation angle between the channel and down valley axis of <90°; and tortuous meanders with a more or less repeated pattern and a maximum deviation angle of >90°.
iii) The level of mobility.	Popov (1964) distinguished between embedded (incised non-meandering), freely meandering and limited (confined) meandering patterns.

Meander geometry can be described according to the terms specified in Figure 3.8

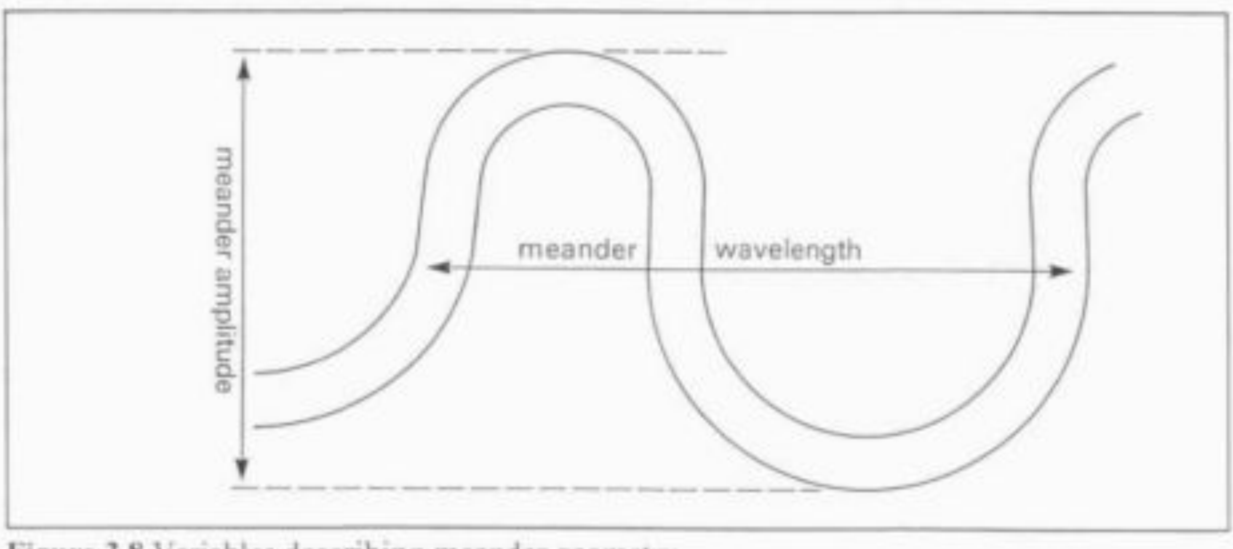


Figure 3.8 Variables describing meander geometry

Multi-thread channels

Braided channels

Braided reaches consist of two or more channels divided by alluvial bars, usually with one dominant channel. Channel dominance often shifts frequently between flood events. The containing channel tends to be less sinuous than single thread channels, but individual distributary channels may be quite sinuous. Braided channels develop where there is a high stream power to resistance ratio so that they are often associated with erodible banks. Overall channel width is therefore high.

Multi-thread channel patterns present a problem in that their form is partly stage-dependent. Bars which are exposed at low to intermediate flows may be inundated at higher discharges, thus transforming a braided channel into a single-thread channel. It is therefore appropriate to distinguish between laterally stable, straight or sinuous regime channels with braid bar morphology from laterally unstable shifting multi-thread channels with a braided pattern. The classification of braiding needs to be related to some appropriate flow event, but universal guidelines are currently lacking. A subclassification based on the degree of bar development may be relevant, ranging from occasional (widely separated single bars) to fully braided (many channels divided by bars and islands) (Knighton, 1984).

Braiding refers to the development of multiple islands within the confines of a single channel (Nanson and Knighton, 1996). Where the channel splits into two or more anabranches, separated by stable islands, the channel planform is described as anastomosing or anabranching.

Anabranching or anastomosing channels

Channels are classified as anabranching when the multi-thread channels are separated by stable islands. These islands may be formed from vegetated braid bars, be due to the divergence of flow around a resistant object or formed from channel avulsion from an extant floodplain. Anabranching channels have been observed as being characteristic of bedrock channels in the Sabie, where multiple channels have exploited joint patterns in the bedrock (van Niekerk *et al.*, 1995). Well developed anabranching channels have also been observed in the gorge of the lower Great Fish River (Rowntree, 1996b).

Nanson and Knighton (1996) distinguish between the terms anastomosing and anabranching. They note that many authors have restricted the use of the term anastomosing to channels with a high sinuosity, whereas anabranching can be applied over the full range of sinuosities. They define anabranching channels as "a system of multiple channels characterised by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull." (Nanson and Knighton, 1996, p.218). Nanson and Knighton recognise six types of anabranching river as detailed below and illustrated in Figure 3.9.

Type 1: Cohesive sediment anabranching river (anastomising rivers)
organic systems
organo-clastic systems
mud-dominated systems
Type 2: sand-dominated, island forming anabranching rivers
Type 3: mixed load, laterally active (meandering) anabranching rivers
Type 4: sand-dominated, ridge-forming anabranching rivers
Type 5: gravel-dominated, laterally active (meandering/.braiding) anabranching rivers
Type 6: gravel-dominated (including boulder), stable anabranching rivers

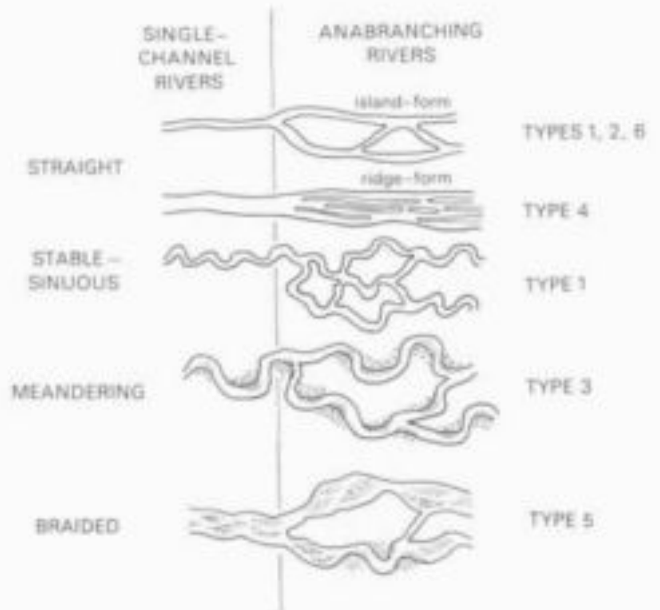


Figure 3.9 Classification of River Pattern according to Nanson and Knighton (1996)

Controls on channel pattern

It would appear that the creation of a particular channel pattern is dependent on the total energy available (Richards, 1982) relative to the resistance of the bed and banks and the size of sediment being transported through the system. The relationships are summarised in Figure 3.10. In a given sediment, higher rates of total, or potential, power expenditure on steep valley surfaces results in greater total sinuosity, which increases bed area by lengthening the channel and reducing the slope, or by increasing channel width, so that the excess stream energy is dissipated in overcoming extra frictional resistance. Meandering is one means whereby a river can adjust its energy loss and transporting ability. In both respects a meandering channel may be more efficient than a straight one. For meandering to occur in alluvial rivers there is a requirement for sufficient energy for bank erosion and sediment transfer, but sufficient bank resistance to prevent over widening. Beyond critical levels of slope, stream power and bank resistance, meanders give way to braided channels as the dominant planimetric form.

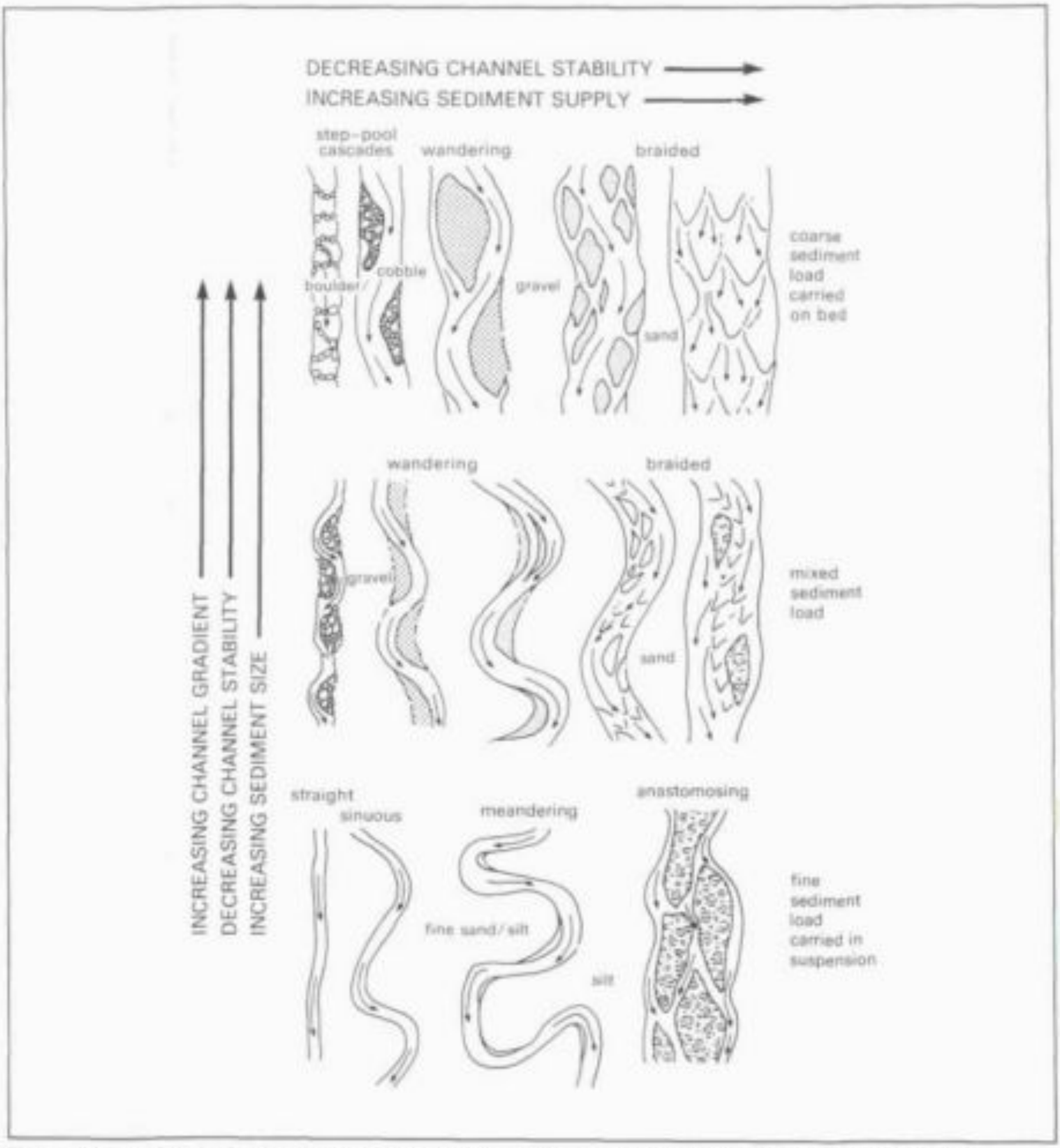


Figure 3.10 Controls on channel pattern formation, after Kellerhals and Church (1989).

Meandering

It has long been recognised that consistent reationships exist between meander parameters and channel width, where width acts as a scale variable of the channel system. Results from a variety of fluvial environments suggest that wavelength and radius of curvature are respectively 10 to 14 and 2 to 3 times channel width. Since width is approximately proportional to the square root of discharge, it is not unreasonable to expect that meander wavelength will also vary as $Q^{0.5}$. Although this relationship is well established (Knighton, 1984), controversy exists as to, firstly, whether discharge has a direct influence on wavelength or only an indirect one through width (Leopold and Wolman, 1960) and, if the influence is direct, which discharge is the most significant in shaping meanders. The argument has centred on whether bankfull discharge or a more frequent range of flows is more important (Carlston, 1965). Knighton (1984) recognises that meander geometry is probably related not to a single dominant discharge, but to a range of discharges whose competence varies with the materials in which the channel is cut. This suggests that if the discharge regime changes then so will the meander geometry, resulting in instability in the system with concomitant bank erosion as the channel adjusts.

Another influence on meander geometry is the boundary composition. Schumm (1967) used multiple regression equations to reflect the influence of boundary composition in non-gravelly streams.

$$\lambda = 1935\ Qm^{0.34}\ M^{-0.74} \qquad \textit{Equation 3.10a}$$

$$\lambda = 394\ Qma^{0.48}\ M^{-0.74} \qquad \textit{Equation 3.10b}$$

λ = meander wavelength
Qm = mean annual discharge
Qma = mean annual flood
M = magnitude, weighted % of silt-clay in channel perimeter.

These relationships show that, for a given discharge, meander wavelength decreases as the boundary, and particularly the channel banks, become more cohesive (increasing M). Meander wavelength is influenced by material properties through both width and channel sinuosity, varying directly with width and inversely with sinuosity. Channels with more cohesive materials will tend to be relatively narrow, deep and sinuous and have smaller wavelengths, at least for a range of materials up to medium sand.

Braiding

Braided channels do not occur as frequently as single-thread channels, but occur in a wide range of environments and at a large range of scales. Generally, braiding is favoured by high-energy fluvial environments with steep valley gradients, large and variable discharges, dominant bedload transport, and non cohesive banks lacking stabilization by vegetation (Richards, 1982). Various conditions have been suggested as conducive for the development of this channel pattern.

i) <u>An abundant bed load.</u>

Although it is generally assumed that braiding is not symptomatic of overloading, the availability of large amounts of sediment is regarded as necessary. The load should contain size fractions which the stream is locally incompetent to transport as they provide the initial deposits (Knighton, 1984). The presence of bars diverts the flow against the channel banks contributing to the bank erosion needed for the development of the wide shallow channel commonly associated with bed-load transport.

ii) Steep slopes

Evidence from empirical and theoretical studies indicate that braiding develops when the slope is above a threshold value (Leopold and Wolman, 1957; Schumm and Khan, 1972; Parker, 1976). The degree of braiding appears to increase as the slope steepens (Howard *et al.*, 1970; Parker, 1976; Chang, 1979). The increased slope is thought by Richards (1982) to be a response to a need for the maintenance of stream power for sediment transport.

Chang (1979) differentiates between braiding due to loading and channel bed aggradation, and braiding due to steep slopes. Braiding due to steep slopes is deemed capable of maintaining a quasi-equilibrium between discharge, sediment inflow and transport capacity. As summarised by Richards (1982, p211) "braided channel patterns reflect particular environmental conditions, and are no longer considered necessarily to represent disequilibrium in aggrading systems".

iii) High stream power

Knighton (1984) suggests that perhaps the critical factor is a high stream power (γQs) because braiding can persist at low slopes in large rivers. Thus braiding may be the result of either high discharge or high slope gradients or a combination of both. The concept of braiding thresholds in terms of stream power was first developed by Leopold and Wolman (1957) and has been developed further by a number of workers including Schumm (1979) and Newson (1992).

iv) Highly variable discharge

Rapid fluctuations in discharge are often associated with high rates of sediment supply. This also contributes to bank erosion and irregular bed-load movement, both being conducive to bar formation. Leopold and Wolman (1957) and Hong and Davies (1979), however, showed that braiding can be induced in laboratory studies under steady flow; this suggests that rapid discharge variation is not of primary importance.

v) Erodible banks

Banks composed of readily erodible material are an important source of sediment as well as being necessary for the channel widening characteristics of braided reaches. Without erodible banks any incipient bar deposits would tend to be destroyed rather than added to. Miall (1977) showed that rivers with resistant banks meander rather than braid.

Braiding has been observed on the channel floor of a number of South African rivers (lower Mvoti - KZN, Sundays River - Eastern Cape) in association with resistant banks. It is hypothesised that in these circumstances, braiding is associated with a high flow width-depth ratio at the specific bed forming flows. This requires further testing.

Controls on channel pattern: synthesis

Channel pattern has been explained as the result of particular combinations of stream power, perimeter conditions and sediment load and calibre. Braiding is enhanced by a combination of high stream power and high bedload transport, meandering by intermediate stream powers and wash load, straight or stable-sinuous by low stream power, low sediment load and cohesive banks. These relationships are depicted in Figure 3.10 adapted from Church (1992).

3.5.4 Reach classification

From the preceding discussion on reach morphology and associated processes the following criteria can be identified as important classificatory variables. These are presented in the order of scale, the direction of control between process and form and the derivation of data. Thus the first set of variables can be extracted from a topographic map whilst the second set of variables require field surveys and/or laboratory analysis of samples collected in the field.

Variables which can be classified from topographic maps

1. Valley floor

The valley floor is classified according to the presence or absence of sedimentary deposits and their relationship to the modern channel. More than one feature may be present. Features are defined in Section 3.5.2.

Flood plain
Erosional bench
Terrace
Valley side bench
Pediment
Valley floor absent

Although some of the valley floor features can be recognised from maps, field verification is necessary, especially for smaller features such as benches.

2. Lateral mobility or entrenchment

Confined, channel laterally confined by valley side walls or terraces

Moderately confined, channel course determined by macro-scale features, but some lateral migration is possible

Non-confined, channel free to migrate laterally over the valley floor (associated with flood plain)

3. Channel gradient

Channel gradient has been found to be well correlated to many other channel properties including pattern, channel type and bed material and reach type. It can therefore be used as a useful first approximation to the delineation of reaches from topographical maps. Channel gradient can readily be calculated from the blue-line network and contour intersection using a Geographic Information System such as Arc/Info. An alternative to channel gradient would be valley floor gradient which is the gradient of the valley floor regardless of the course of the channel. The ratio between the valley-floor and channel gradient is a measure of sinuosity.

4. Channel pattern

Single thread -	low sinuosity (SI<1.5) high sinuosity (meandering) (SI>1.5)
Multiple thread -	braided (may require field verification) anabranching (may require field verification)

Variables which must be classified in the field

5. Channel type

Bedrock	(can be further classified by geological formation, rock type, jointing, bedding etc.)
Mixed	
Alluvial	boulder bed, cobble bed, gravel bed, sandbed

6. Perimeter conditions

Bank composition	% bedrock, boulder, cobble, gravel, sand, silt+clay/ stratification
Bank vegetation	
Bed material composition	% bedrock boulder, cobble, gravel, sand, silt+clay
Instream vegetation	

7. Reach type

See Tables 3.3 and 3.4 for reach types in alluvial and bedrock systems

8. Channel form

Channel width (a measure of channel size)

Form ratio

Rosgen (1994) has incorporated many of these variables into a recent classification of stream types based on 450 rivers throughout the U.S., Canada and New Zealand. His scheme is presented in Figure 3.11 A modification of Rosgen's key could usefully be developed for South African rivers.

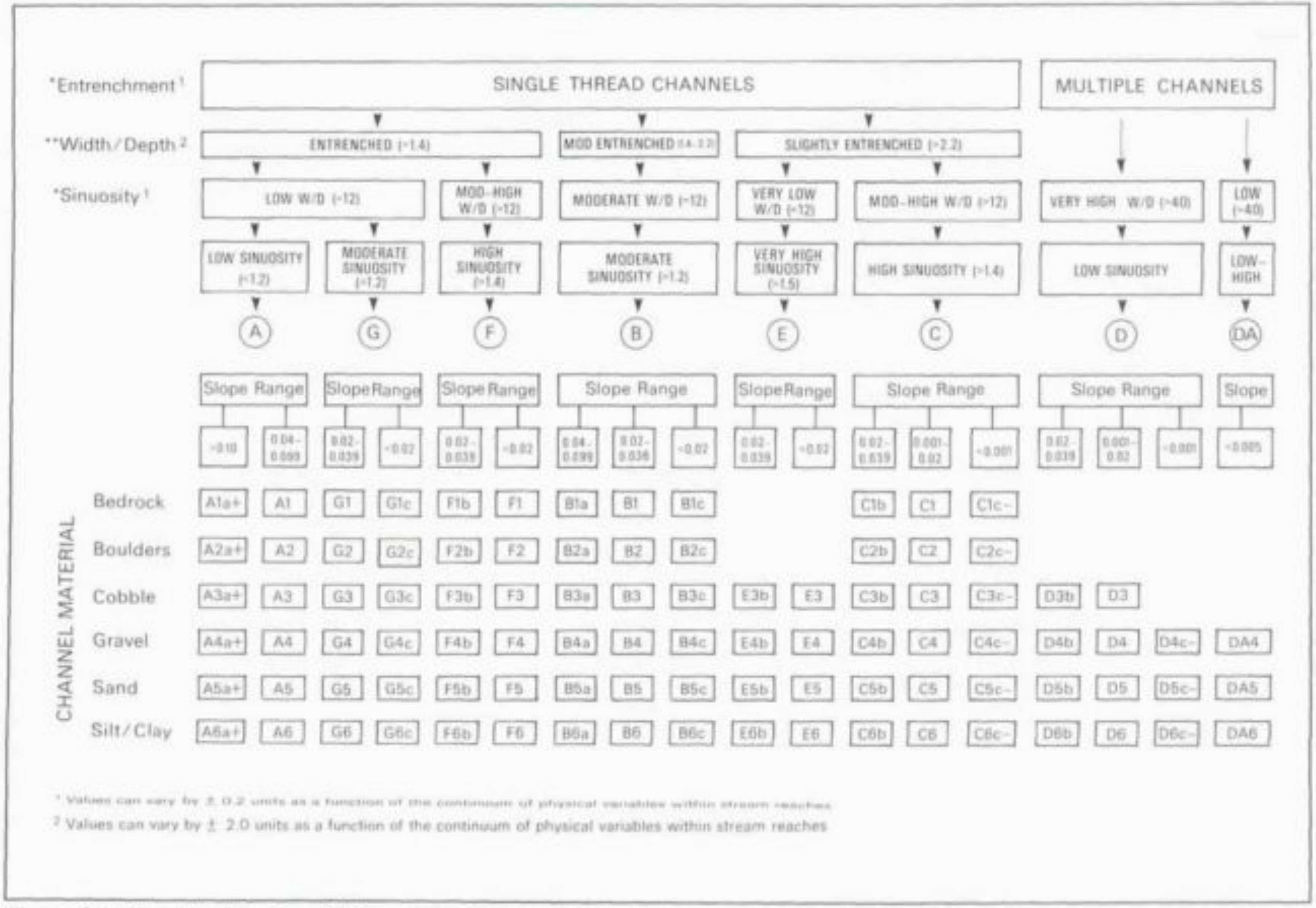


Figure 3.11 The Classification of Rivers (after Rosgen, 1994)

3.6 SEGMENT CLASSIFICATION

3.6.1 Zonation

Segments are defined in terms of the three driving forces, discharge, sediment load and regional slope gradient. In the early days of the development of the hierarchical classification, segments were defined simply as a length of channel along which there is no significant change in the imposed flow regime or sediment load. Recently a channel gradient component has been added so that segments are also characterised in terms of their regional slope. This modification came about largely as a result of discussions at a biomonitoring workshop in Cape Town in January 1996 (Brown *et. al.*, 1996). The inclusion of slope brings segments more in line with the idea of longitudinal river zonation which is ingrained in the ecological literature.

Channel segments may be composed of a composite of reach types due to variation in local control variables through the segment. However, due to a uniform set of driving forces (slope, discharge and sediment load) there should be a recognisable commonality within a segment. A single channel type should predominate: bedrock, mixed or alluvial boulder bed, cobble bed, gravel bed or sand bed. Initially it was assumed that segments were simply a convenient way to break down an individual river system into relatively homogenous sections; it was not anticipated that segments themselves could be classified in a meaningful way. Increased familiarity with a number of South African rivers (Table 3.8), however, has indicated that, if segments are related to ecological river zones, classification may be possible. As background to the biomonitoring workshop a number of such zones were identified; these were thought to be ubiquitous throughout South Africa (Table 3.7).

The eight zones are described below; these should be seen as a first approximation and can be expected to be modified in the light of further experience[1]. Gradients given with the definitions are those extracted from long profiles of the nine rivers given in Table 3.8 which have been studied in some detail by the authors. A strong degree[1] of correlation was observed between the geomorphological zone and gradient across the suite of rivers. Two long profile types were distinguished: the 'normal' profile which has a characteristic concave profile and the 'rejuvenated' profile which exhibits steepening in its downstream segments.

Channel segments are defined as lengths of stream channel which carry a spatially uniform discharge and sediment load along their length. Segment boundaries are defined by major tributary junctions at which there will be a significant change in the discharge of runoff or sediment passing through the channel. The channel network morphometry and its relationship to catchment characteristics as described under Zones (Section 3.7) is therefore an important consideration when delimiting segments. Identification of segment

[1] A modified version is given in Rowntree *et al.* (1998)

boundaries may be assisted by looking at stream order (Strahler, 1952) or link magnitude and network diameter (Shreve, 1966).

Table 3.7 Geomorphological zonation of river channels

A. Zonation associated with a 'normal' profile

Mountain headwall:	A very steep gradient steam (gradient 0.1- 0.7) dominated by bedrock with waterfalls, and plunge pools. Normally first or second order.
Mountain stream:	Steep gradient stream (gradient 0.01 - 0.07) dominated by bedrock and boulders with step pool morphology, waterfalls, rapids and pools, locally cobble or coarse gravels forming plane beds. Flood plain generally absent but lateral depositional bench type features may occur. Sinuous channel pattern.
Foothills:	moderately steep channel (gradient 0.002 - 0.008), gravel/cobble bed river commonly with pool-riffle or pool-rapid morphology, locally bedrock controlled. Narrow flood plain of sand and/or gravel normally present. Channel pattern meandering or braided.
Transitional:	mixed bed alluvial channel with sand and cobble/gravel, lower gradient (gradient 0.001 - 0.0036), pool-riffle morphology, sand bars. Flood plain often present.
Lowland:	low gradient alluvial sand bed channel (gradient 0.0002 - 0.002), fully developed meandering pattern (often tortuous) within a distinct flood plain. Increased silt content in bed or banks.

B. Additional zones associated with a rejuvenated profile

Upland plateau:	an upland low gradient channel, often associated with uplifted plateau areas as occur beneath the eastern escarpment; meandering sand bed regime channels or gravel bed rivers with pool-riffle morphology, meander cut-offs etc. (gradient 0.0007 - 0.0005 (0.01))
Gorge:	moderate to steep gradient, confined channel (gradient 0.005 to 0.33, commonly 0.01) resulting from uplift in the middle to lower reaches of the long profile, limited lateral development of alluvial features, channel dominated by bedrock, boulder or cobble with features of a mountain stream but channel of a higher order.
Rejuvenated foothills:	steepened section within middle reaches of the river caused by uplift, often downstream of gorge; characteristics similar to foothills (gravel/cobble bed rivers with pool-riffle/ pool-rapid morphology) (gradient 0.002 - 0.006) but of a higher order. A compound channel is often present with an active channel contained within a macro channel activated only during infrequent flood events. A flood plain may be present between the active and macro-channel.

Table 3.8 Selected river systems for geomorphological zonation studies. (Brown *et al.*,1996).

River	Biogeographic region	Biogeographic region number
Mogalakwena	Western Transvaal	6
Olifants	Southern and western Cape	7
Berg	Southern and western Cape	7
Eerste	Southern and western Cape	7
Buffalo	Drought Corridor	8
Mzimvubu	Southern Natal	9
Mvoti	Southern Natal	9
Tugela	Northern Natal	10
Sabie	Eastern Transvaal	11

3.6.2 Indices of network morphometry

Horton (1945) established the basis for, and gave an impetus to, the quantitative analysis of drainage networks by setting up a hierarchy of ordering which was later modified by Strahler (1952). Strahler's system has become the most widely adopted ordering system due to its practical simplicity. Under his method fingertip tributaries are designated as first order; successively higher orders are formed by the junction of two stream segments of the same order (Figure 3.12a). Analysing the morphometric properties of ordered stream segments, Horton derived relationships between order and number of stream length of given orders. Others following Horton's lead derived statistical relations of area, relief and slope with order. These are often referred to as Horton's laws of drainage composition (Morisawa, 1964). They demonstrate an orderly progression of catchment properties which are scale related. Stream order should therefore be a good first approximation to scale related changes down the channel network.

Several alternatives to ordering have been suggested and are largely based on the probabilistic-topological approach pioneered by Shreve (1966) and Smart (1968). They proposed the use of the term "link" for stream segments between junctions, between head and junction or between mouth and junction (Figure 3.12b). There are two kinds of links: 1) exterior links (sources) which extend from the stream head to the first junction, 2) interior links which are stream segments lying between two junctions (nodes) or junction and mouth. A network with n sources has n - 1 nodes and 2n - 1 links, of which n are exterior and n-1 are interior. The most important topological parameters are link *magnitude* and network *diameter*. The magnitude of a link is the number of sources upstream. The additive properties of magnitude overcomes the problems experienced in Strahler's ordering technique, where the stream discharge can change when a lower order tributary enters a higher order stream, but the order of a main stream remains unaltered. Diameter is the maximum link distance in a network and is a measure of the longitudinal extent of the network, with mainstream length as its geometric analogue (Knighton, 1984).

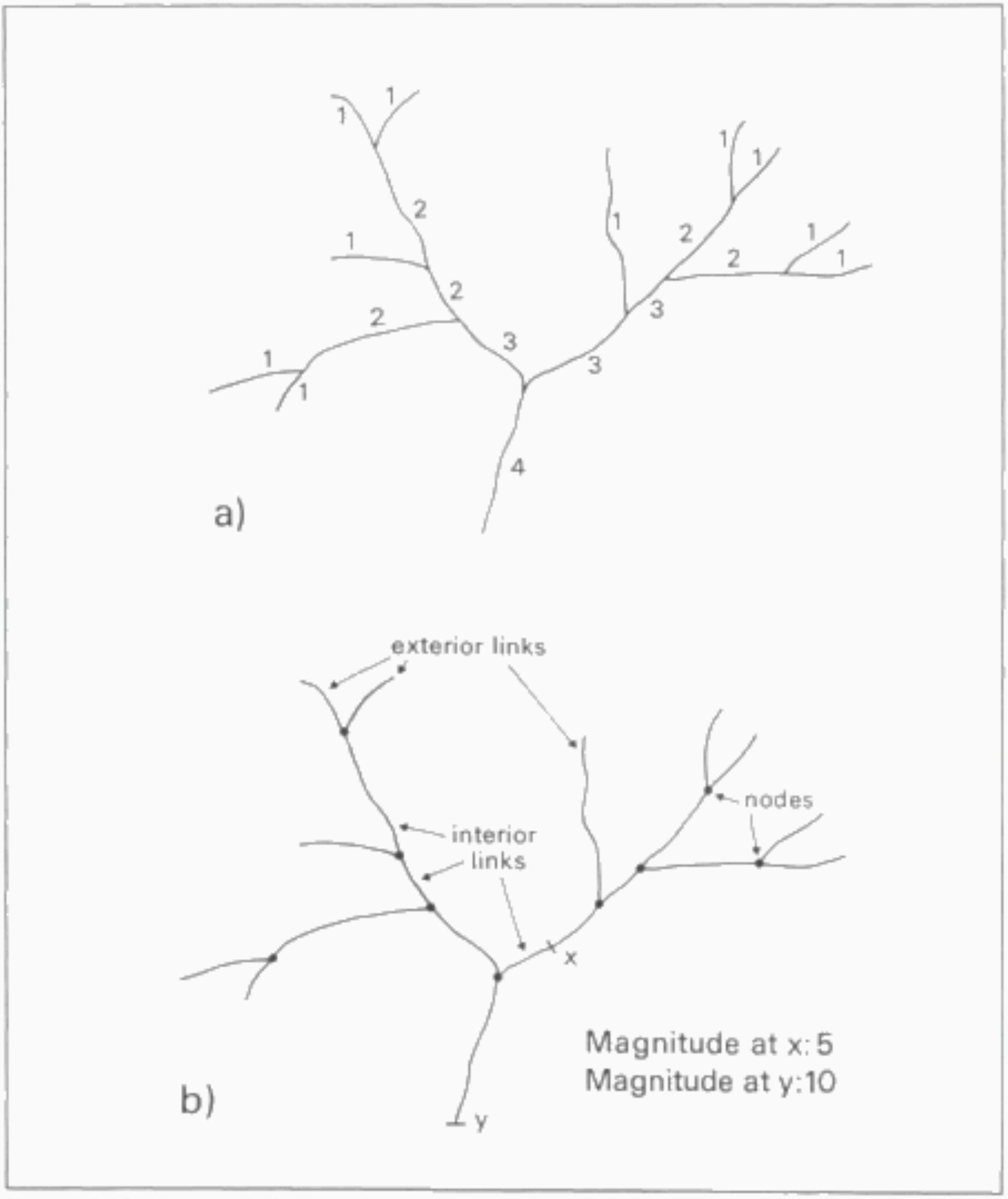


Figure 3.12 Stream Ordering of a) Strahler (1952) and b) Shreve (1966)

Within a single segment, channel adjustment is made in response to a specific discharge and sediment regime. Therefore at the segment level of the hierarchy an analysis is required of the dominant or channel forming discharge and the sediment load passing through the channel network. These are both a function of catchment characteristics and can be related to the next level of the catchment hierarchy: the response zone.

3.7 CATCHMENT ZONES

3.7.1 Introduction

Catchment zones are defined as areas within a catchment which are homogenous with respect to flood runoff and sediment production. The concept of homogenous response units is well established in the hydrological literature and has been applied to a number of catchment based models (England and Stephenson, 1970; Rudeforth and Thomasson, 1970). Similar concepts can be applied to sediment modelling.

Flood runoff and sediment production are the result of a complex set of interrelated processes which interact through time and space to determine channel inputs during storm events. Flood runoff can be considered as independent from sediment production in that it is the flow discharge which determines stream power and sediment transport capacity at any point in the channel. Sediment production cannot, however, be considered as independent of discharge as it is surface runoff which is largely responsible for the transport of sediment into the channels. Sediment models must therefore be based on sound hydrological models and the input variables into both type of model are similar. Natural catchment factors which influence both runoff and sediment production include climate, hillslope gradient, geology, soils and vegetation cover. This group of factors determines the potential for sediment production from the hillslopes. The density of the drainage network determines the rate at which the sediment can be delivered to the downstream channels. Superimposed on these natural factors are the human factors of rural landuse and urbanisation. It is this group of factors which are considered as the basis of defining response zones. The effect of each factor on runoff generation and sediment production will be considered in turn.

3.7.2 Climatic factors.

Runoff is the result of excess precipitation falling onto the land surface, whereas hillslope sediment entrainment and transport is to a large extent the result of rainfall detachment and transport by overland flow, or to mass movement processes which are triggered by saturation of the hillslope mantle. Climate, and particularly rainfall, is therefore a primary factor controlling both runoff and sediment production.

Whereas the total runoff from a catchment, as expressed by the mean annual runoff, depends on the long term balance between precipitation and evaporation, the distribution of runoff between storm flow and base flow depends more on the nature of individual storms: the type of precipitation, its frequency, intensity, duration and aerial extent. The erosivity of rainfall depends on the total storm energy as well as its potential for producing surface runoff. In South Africa most precipitation occurs as rainfall as opposed to snow or hail and the intensity, duration and distribution are highly variable, both in space and in time.

The classification of response zones with respect to climate is constrained by the availability of data at a catchment scale. In South Africa data is readily available for mean annual precipitation and potential evapotranspiration from the CCWR. Estimates of mean annual runoff are also available at a quaternary catchment level (Midgley *et al.* 1994). Synthesised data on storm characteristics is more difficult to come by. Smithen (1981) has produced data on rainfall erosivity for South Africa which is an important component of sediment yield estimation models. Smithen's data has been developed as an ARC/INFO data base by Rooseboom *et al.* (1992)

The effectiveness of a rainstorm in promoting surface runoff and erosion depends on slope, soil and vegetation properties as described below. Vegetation exerts a particularly effective control over erosion so that negligible rates of surface wash erosion are associated with a dense vegetative cover. Vegetation is itself a response to climatic factors which determine the availability of soil moisture. This association between climate and vegetation means that climate is a particularly effective way of zoning a catchment.

In 1958 Langbein and Schumm published a paper describing the relationship between climate and sediment yield for a large number of river catchments in the United States of America (Langbein and Schumm, 1958). Their results clearly showed that maximum sediment yields were measured for semi-arid areas due to the relatively effective rainfall combined with a low vegetation cover. As rainfall increased, so did the effectiveness of the vegetation cover so that sediment yields tend to fall off. Only in areas of extremely high rainfall may yields tend to rise again due to the increased efficacy of mass movement processes, especially in steeply sloping areas.

Although the general relationship presented by Langbein and Schumm has been much debated, the general arguments are believed to hold true for relatively undisturbed catchments. The relationship that they found for the USA is presented in Figure 3.13. Superimposed on this is the distribution of land in South Africa according to mean annual runoff. It is clear from this graph that much of South Africa falls within the climatic zone which is particularly susceptible to high sediment yields.

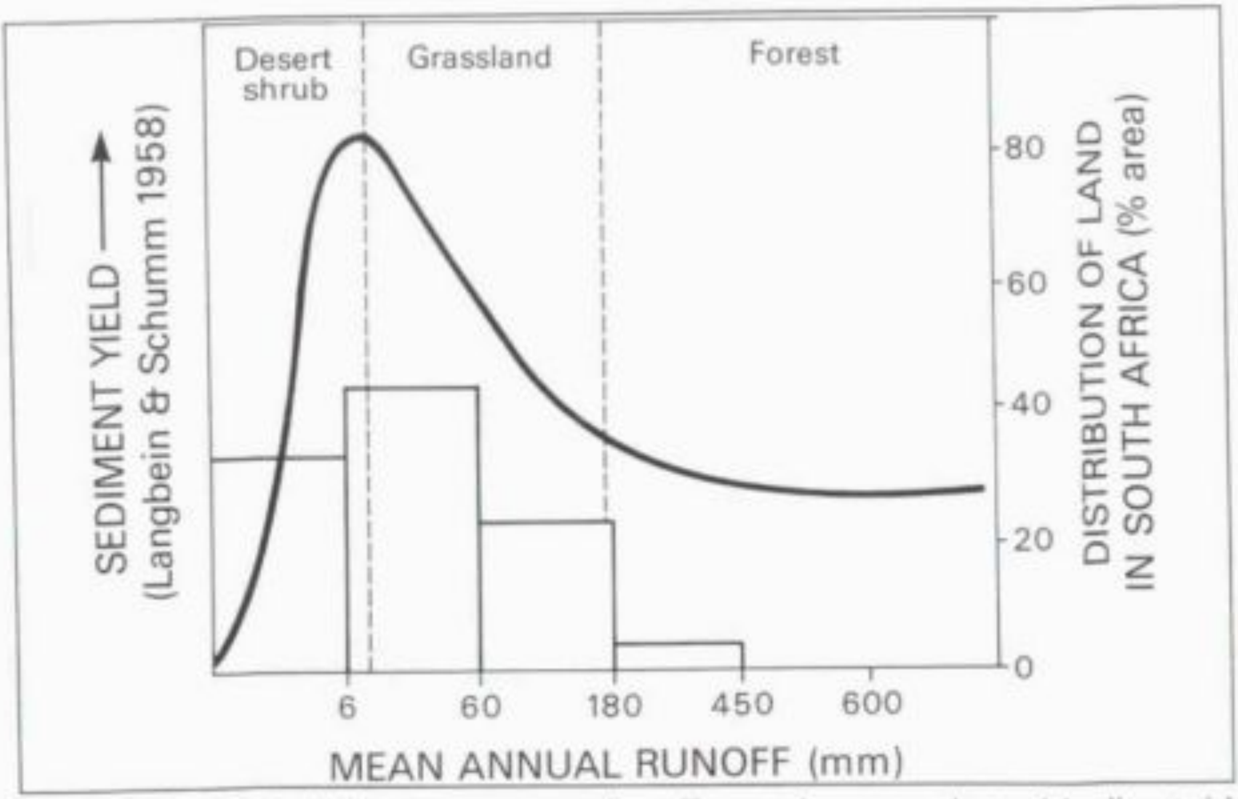


Figure 3.13 Relationship between mean annual runoff, vegetation cover and potential sediment yield (Langbein & Schumm, 1958). The curve shows the relationship for the USA; the bargraph shows the distribution of land in South Africa according to mean annual runoff.

3.7.3 Hillslope gradient and length

Hillslope gradient provides the energy for runoff and erosion. Steep slopes encourage overland flow and enhance the peakedness of the flood hydrograph. Sediment transport rates are also significantly increased. Slope length is another important factor effecting erosion rates as the amount of surface runoff increases incrementally down the length of the slope. Morgan (1986) gives a general relationship:

$$Qs \propto S^m L^n \qquad \textit{Equation 3.11}$$

where Qs is soil loss, S is slope gradient, L is slope length and m and n are exponents.

Morgan quotes a value of 0.7 for the slope length exponent but states that the value of the slope exponent for surface wash erosion has been found to vary between 1 and 2 depending on factors such as the soil particle size, the range of slope gradient itself and the climatic zone.

It is common to subdivide slope into a number of classes related to their erosion potential. Copeland (1985) suggests that the following slope classes are suitable as the basis for a land capability classification in areas of southern Africa where soil erosion is a potential hazard.

Percent slope (class)	Gradient (Upper limit)	Degrees (Upper limit)	Class
0 - 4%	0.04	2.3°	Gently sloping
>4%-8%	0.08	4.5°	Moderately sloping (I)
>8%-12%	0.12	7°	Moderately sloping (II)
>12%-16%	0.16	9°	Strongly sloping
>16%			Steeply sloping

Whilst slope gradient is a useful guide to the potential for both erosion and transport of sediment off the slopes, significant erosion by surface wash can take place on gentle slopes if the soil and vegetation conditions are conducive. Gully or donga erosion is often situated on gentle foot slope areas due to greater depth of sediment and an input of erosive runoff from up slope.

3.7.4 Geology

The geology of a catchment exerts a fundamental influence on both runoff and erosion. Rock type and structure both have a direct influence on the potential for ground water storage in a catchment and therefore on the partition of runoff between storm flows and base flows. This may also be reflected in the drainage density (Section 3.7.8). A permeable rock with high ground water storage potential has a few large streams with wide interfluves, in contrast to less permeable rocks which will tend to have a high drainage density. Depending on climatic influences, a large proportion of the drainage network of less permeable rocks will serve only to carry storm runoff, so that many channels will be ephemeral. The geological structure is probably most important in guiding the movement of ground water towards the streams. For example in a synclinal catchment it is probable that the time lags between rainfall and ground water flow peaks will be smaller than in the case of a catchment with horizontally bedded strata.

Sediment yield is related to geology through such factors as the weathering rate and the size distribution of the weathered products. For example, in the Eastern Cape a distinction can be made between erodible soils developed on the silts and mudstones of the Beaufort Series which give rise to fine textured dispersive soils and the dolerites which give rise to well structured clay soils with a lower erodibility. The quartzitic Table Mountain sandstones weather more slowly, producing coarse textured soils with very little silt and clay, thus accounting for the clear waters and widespread distribution of sand bed rivers in the lowlands of the Western Cape.

Geological maps are available at a range of scales for South Africa. The entire country is mapped at a scale of 1:1 000 000 and 1: 250 000. Geological reports accompany the 1: 250 000 maps. A useful summary for the country is provided by the publication which accompanies the 1:1 000 000 map (Geological Survey, Republic of South Africa, 1989).

3.7.5 Soils

Soil type is one of the key factors determining both runoff and sediment production zones in a catchment. Soil depth, texture and structure together determine the infiltration capacity, waterholding capacity and permeability. The ability of the soil to store and transmit water is a major factor determining storm response and therefore the potential for surface runoff, soil erosion and the generation of storm flow. Soils which inhibit infiltration produce rapid surface runoff and are also prone to surface erosion. Permeable soils are associated with subsurface flows which may still lead to storm runoff but are less prone to erosion.

Soil erodibility is partly a function of the potential of the soil to generate surface runoff, but is also a function of the ease at which soil particles can be detached. The most erodible soils tend to be poorly structured silts and fine sands. The dispersive nature of many South African soils makes them particularly prone to erosion by both surface and subsurface processes (Beckedahl *et al.*, 1988). Non-dispersive clay soils with greater structural development and increased cohesion may be less erodible. Soil organic matter is an important soil constituent associated with increased aggregate stability and decreased erodibility.

Organic matter and structural development are to some extent dynamic properties of the soil which can be significantly altered by land management. The erodibility of a soil may therefore alter over time. Non the less soils can be broadly grouped by soil series or soil form according to erodibility classes. Schmidt and Schulze (1989) have categorised South African soils according to their hydrological response, A classification of soils according to soil erodibility classes is given in Lorentz and Schulze (1995) in the report accompanying the ACRU 3.00 agrohydrological modelling system.

3.7.6 Vegetation

Vegetation plays an extremely important role in protecting the soil surface form erosion by rains plash and surface runoff. A dense vegetation cover reduces the energy of raindrop impact, thus inhibiting particle detachment and surface sealing, it aids infiltration through maintaining a porous surface horizon and improves soil structure through the addition of organic matter. A good vegetation cover can reduce erosion by an order of magnitude when compared to that from a bare soil. As the density of the ground cover decreases, erosion increases commensurately, with a sharp increase being observed for cover densities below 30%.

Although the role of vegetation is recognised as being critical, the relationship between vegetation cover and erosion rates is difficult to quantify. The protective effect of vegetation depends not only on the percentage cover *per se* but also on the species composition and the structure of the vegetation. A good ground cover of grass is far more effective than the equivalent aerial cover offered by shrubs because of the lack of surface protection. Where a ground cover or litter layer is absent in a forest, the tall trees may enhance splash erosion through leaf drip. Vegetation also shows distinct seasonal and life cycles in its growth form. These must be taken into account when modelling the effect of vegetation on both storm runoff and erosion.

The influence of vegetation on the distribution of runoff and sediment production is complicated further by the secondary relationship between climate and both runoff and vegetation discussed above. High effective precipitation results in a dense vegetation cover and high infiltration capacity. This means low runoff intensity and, as a result, low drainage density. Moreover, vegetation influences such aspects as interception, evapotranspiration and soil moisture movement, which further complicates the inter-relationship between vegetation and runoff.

A number of reports are available which assign erosion ratings to different vegetation classes. Lorentz and Schulze (1995) review available methods for deriving cover factors for the USLE (Section 3.8.9). It is clear from their report that deriving suitable ground cover classifications is a difficult and complex task. Not only is it necessary to consider the dominant cover type, but also the way in which it is managed, tillage practices, grazing impacts and so on.

3.7.7 Human Factors

Human factors largely influence runoff and sediment yields through their effect on the catchment factors discussed in the previous section. An important difference between these two groups is the time scale over which change takes place. Under natural conditions geology can be considered constant whilst soils and vegetation change slowly in response to long term environmental change. The impact of human activities tends to be much more rapid and can cause major disturbance to a system over a short time period. Impacts are discussed here under two sections, rural land use and urbanization.

Rural land use

The application of specific agricultural techniques and practices, particularly those causing a sudden change in catchment characteristics, for example vegetation cover, may have dramatic influences on run off, sediment yield and consequently drainage density. Runoff and sediment yield vary markedly with land use differences between catchments of similar lithology and climate (Richards, 1982). Major differences occur between forest, pasture and cropland, and the contrasts in sediment yield are greater than those in runoff. For example Sartz (1973) measured cropland runoff rates two to three times those found under pasture, while an order of magnitude difference was apparent in sediment yield per unit area. Lusby (1970) using paired watershed experiments showed that management practices are very important. The author demonstrated that an increased bare area in an overgrazed basin could cause a 30 % increase in runoff and a 45 % increase in sediment yield. Clearly then, changes of land use or management will affect runoff and sediment yield.

In South Africa the effects of land use are further complicated by the history of settlement and resettlement of different population groups in the country. The distinction between white owned commercial farms and traditional black homeland areas is important to the understanding of the distribution of land degradation in the country. Severe erosion in the former homeland areas is ubiquitous due to a high density of rural populations combined with a breakdown of the rural economy and local controls on resource use. In the white commercial areas erosion has also been widespread due to a combination of inappropriate farming methods, the use of monocultures and overgrazing. The more arid areas such as the Karoo and the Swartland have suffered from particularly severe erosion in the past.

It is important to realise that many of the erosion features that are visible in the landscape today originated in the first half of this century; erosion may be continuing at a lower rate at the present time. Hence morphological evidence of erosion such as severe rilling and gullying may not be indicative of current high erosion rates. Rooseboom and Harmse (1979) noted a general decrease in sediment yields in the Orange River from around 1940 which they attributed to a depletion in the availability of readily transportable sediment.

For the eroded sediment to be effective in terms of impacting on channel morphology, it must be transported from the site of erosion to the river channel. Although finer sediments may be washed off the hillslopes and through the channel system relatively quickly, the coarser sediment moves through a series of hillslope, flood plain and channel storages. Thus even after there has been a decline in hillslope erosion, the geomorphological impacts of the eroded sediment may be apparent for many decades (Meade, 1982).

Urbanization

Of considerable influence to the patterns of runoff and sediment production are the localized impact of urban development. Over large areas, infiltration capacity is considerably reduced, precipitation is caught by rooftops and roads, and is passed through drainage systems which have been designed to dispose of it into nearby streams as rapidly as possible. The result is that, immediately below large urban areas, there tends to be a marked and rapid build-up of surface runoff which will be accentuated where slopes are steep. Thus the runoff regime is flashier with shorter lag times and time bases, and with higher peaks. The increase in the peak discharge varies with the percentage of the basin urbanized and the nature of urban development.

Urban development causes a more complex cyclic variation of sediment yield, which is extremely high in the construction phase (2 to 200 times the natural yield) but usually greatly reduced at the completed development stage (Wolman, 1967; Walling and Gregory, 1970). At this time, suspended sediment concentrations may decline below levels in natural catchments.

The long term impact of urbanisation on sediment yields varies between developed urban areas and undeveloped urban areas. Urbanisation in Africa is characterised by large areas of peri-urban sprawl which often lacks tarred roads, adequate drainage systems and carries a complex network of footpaths.

Such areas present a considerable erosion hazard as has been discussed for a peri-urban area in Lesotho by Rowntree *et al.* (1991). Although South African urban areas are generally more developed than in many African countries, they increasingly have their share of less developed areas.

3.7.8 Drainage density

Drainage density is defined as the length of river channel per unit catchment area. It is therefore a measure of the efficiency of the catchment surface in transporting water and sediment to the outlet. The reciprocal of drainage density gives the average distance between river channels, half this distance is equal to the average slope length from divide to channel and therefore to the average maximum distance that water and sediment has to travel from its source on the hillslopes into the channel. Drainage density is related to those zone characteristics which effect runoff generation such as climate, geology , soils and vegetation discussed previously. Homogenous catchment zones should therefore have uniform drainage densities.

Measurement of drainage density presents a number of problems. Measurement depends on the definition used for a channel: most researchers would agree that both perennial and seasonal streams should be included, but there is more uncertainty as to the extent of the storm network. The usual source for drainage network data is the blue line network on a topographic map. Two problems arise (Kritzinger, 1993). Firstly the density of this network varies with the map scale. British geomorphologists recommend that the 1: 25 000 map is used as the standard, but maps of this scale are not available in South Africa. The 1: 50 000 map is probably the most suitable data source in South Africa as much detail is lost on the 1: 250 000 maps. A second problem of using maps as a data source comes back to the definition of a channel. Guidelines given to the map compilers working for the Surveyor General Office are vague so that it is left largely to the individual to make his or her own interpretation (Kritzinger, 1993). This leads to a lack of consistency between different map series and even different map sheets of the same series.

3.7.9 Modelling runoff and sediment yield

Runoff and sediment yield data is seldom available at the scale of the catchment zone so that it becomes necessary to estimate values from catchment characteristics. There are a number of well established hydrological models in use in South Africa. Sediment modelling, because of the more complex nature of the processes involved and the lack of data for calibration, is less well developed. The available models and approaches are reviewed briefly below.

Hydrological models

Hydrological modelling can be carried out at a range of spatial and temporal scales. The ability to calibrate the results, and the resulting confidence in the model output, varies with the scale at which modelling takes place. One of the most widely used models is the Pitman model originally developed in the early 1970s (Pitman, 1973). This model is designed to estimate real time monthly runoff from which indices such as the mean annual runoff from sub-catchments can be calculated. Midgley *et al.* (1994) has applied a later version of this model (the WRMSM90 model of Pitman and Kakebeeke, 1991) to the estimation of surface water resources in South Africa. The basic unit used was the quaternary catchment; naturalised monthly runoff was simulated for a 70-year sequence from 1920 to 1989. Simulated monthly runoff data is now available at the quaternary catchment level for the whole of South Africa.

The model outputs provide a valuable basis for evaluating the distribution of runoff zones within a catchment as well as providing insights into temporal variations in runoff. Both these sets of information are important to any catchment level geomorphological investigation. The model does not give any indication of flood levels, so has limitations with respect to detailed geomorphological investigations.

Other models are available which are capable of simulating daily runoff. These include the ACRU model developed by Schulze (1995) and the VTI model of Hughes and Sami (1994). These models require a significantly greater data base and far greater computing time to derive the simulated output. The ACRU model does not require calibration so can be applied to an ungauged catchment. The VTI model, requiring calibration against the hydrological record, can only be applied to gauged catchments, but, because of the calibration procedure, confidence in the results is high. Unfortunately confidence in flood peak estimates is lower because of calibration problems when floods overtop the capacity of the gauging weir. The ACRU model is a more physically based model which does not require calibration and can therefore be applied to an ungauged catchment. As a result data requirements regarding catchment characteristics are much greater and confidence in the results is lower. Whilst floods can be simulated, the accuracy of the simulation again remains uncertain.

Models such as the ACCRU model and the VTI model, because of their data and computing requirements, are applied on a user requirement basis. There is no readily available national level output available as is the case for the monthly output from the Pitman model. Both models have potential as inputs to a geomorphological model where there is the need, the time and expertise to apply them to individual catchments.

Sediment yield models

Sediment yield modelling presents many more problems than does hydrological modelling due to the greater complexity of the process and the lack of suitable data against which to calibrate the models. Sediment production depends on the interaction of surface runoff (the erosive force) and the availability of sediment and is highly variable over both time and space. The ideal sediment model will therefore be based on a fully distributed hydrological model which can apportion runoff into surface and subsurface flows for the different areas of the catchment for the separate storm events. The hydrological component must then be linked to an erosion and sediment transport routine that can model detachment and transport of soil particles both on the hillslopes and through the channel. Long and short term storage of sediment must be an integral component of a successful sediment model. In mountain areas mass erosion must also be accounted for.

These complexities have meant that a fully deterministic sediment model based on physical processes has not yet been developed. The alternative is to use an empirical approach based on observed relationships between sediment yield and catchment variables. A widely used soil erosion model is the Universal Soil Loss Equation (Wischmeier and Smith,1962). The Universal Soil Loss Equation was developed as a means of estimating long term soil loss from farmland in the USA. Its original application was as a guide to soil conservation practices. The method has been adapted with varying success for use at the catchment scale to predict sediment yield.

The Universal Soil Loss Equation is given as:

$$A = RKLSCP \qquad \textit{Equation 3.12}$$

This is an empirical equation which relates erosion rates to that from a standard plot of 22m in length with a slope gradient of 9% (0.09).

A The computed soil loss in tons per acre (multiply by a factor of 2.24 to give tonnes/ha).

R The rainfall factor is equal to the number of erosion index units in a normal year's rain.

$$R = \frac{EI_{30}}{100} \text{ for all storms} > 12.25\text{mm} \qquad \textit{Equation 3.13}$$

E is total storm energy = f(I), I is the total max. 30 minute intensity

Due to the lack of intensity data it is often necessary to extrapolate from daily or mean annual rainfall figures.

K The soil erodibility factor, the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow on a standard slope subject to a storm of one unit of rainfall energy.

Evaluation of the soil erodibility factor either requires many years of plot experimentation or evaluation from a nomograph which takes account of factors such as soil texture, organic content, structure permeability and so on. The nomograph is based on US experience and is not necessarily applicable to other areas.

LS The slope factor is calculated as

$$LS = \frac{\sqrt{L}}{100}(0.76 + 0.53S + 0.07S^2) \qquad \textit{Equation 3.14}$$

The value of LS is unity for a fallow field of standard slope and length.

The effect of slope gradient and slope length is in reality dependent on the processes operating on the slope and therefore varies with the other factors R, C and K. The separate factors are not independent although they are treated as such in the model.

C The cover factor or cropping management factor is the ratio of soil loss from a field with specified management and cropping to that from a fallow field of standard slope and length, subject to a storm of one unit of rainfall energy.

As with the soil erodibility factor, the cover factor must be based on many years of experimental results.

P The erosion control factor is the ratio of soil loss with contouring, strip cropping or terracing to one with straight row farming up and down the slope.

The USLE was developed for application to north American farming where the following conditions prevail: highly efficient, totally mechanised farming, cereal crops the dominant cover; no limit on availability of land, credit or advisory services, many years of empirical data and a strong scientific base. Hudson (1978) points to a number of limitations for its use in situations other than those for which it was designed. These are summarised as follows.

1. As with all empirical relationships, the results are valid only within the range of experimental conditions under which they are tested and there is no justification for expecting the same relationship to hold beyond the measured range.

2. Process relationships may vary from one environment to another. For example rainfall erosivity does not measure the potential for gully erosion. The soil erodibility factor does not distinguish between overland flow and splash detachment processes. Soils subject to rilling demonstrate a different slope relationship than those subject to sheet wash or splash.

3. Management and cropping systems differ significantly between environments.

4. The model is designed to predict long term erosion rates, i.e. mean annual soil loss, and should not be used to predict storm losses.

5. The model is designed to predict soil loss from individual fields or lands. It takes no account of sediment storage and should not be applied at a catchment scale to predict sediment yields.

6. There is nothing UNIVERSAL about the USLE.

The Universal Soil Loss Equation takes little account of hillslope hydrology. A number of models have been developed which take a halfway stance, linking a physically based hydrological model such as ACRU to a more empirical model such as the Universal Soil Loss Equation. A number of these model exist such as the ACRU sediment component (Lorentz and Schulze, 1995), and the ANSWERS (de Roo *et al.* 1989), and CALCITE (Bradbury, 1995) models. These models are limited by the limitations of the USLE itself; moreover they do not take into account sediment production by mass movement or gully erosion, both important processes in the South African context.

An important concept in linking hillslope erosion to channel sediment processes is that of the delivery ratio (Sdr). This is defined as the ratio of sediment yield at a point on the channel (Sy) to the average hillslope erosion rate for the upstream catchment (Eh).

$$Sdr = Sy/Eh \qquad \textit{Equation 3.15}$$

The sediment delivery is normally less than 1, the difference between Sy and Eh representing storage in the catchment. It is related to such factors as slope gradient, slope length and drainage density. The CALCITE model incorporates a sediment delivery function.

3.8 THE CATCHMENT OR DRAINAGE BASIN

The catchment is the land surface which contributes water and sediment to any given stream network. Classification of whole catchments allows comparison between systems and an assessment of the extent to which relationships established for one catchment can be extrapolated to another. Simple classification indices include geomorphological descriptors such as the basin shape, network shape, and measures of basin relief.

3.8.1 Basin shape.

The shape of the drainage basin reflects the space filling characteristics and distribution of links in the network (Morisawa, 1985). The assessment of basin shape can be used to explain certain hydrological processes, in particular the way floods are formed and move through the catchment. The shape of the catchment area is known to influence runoff through its effects on flood intensities, and on the mean travel time of a drop of water from its point of impact on the surface of the catchment to its point of exit in the main stream. In a generally square or circular catchment area, the tributaries often tend to come together and join the main stream near the centre of the area. Consequently, the separate runoff peaks generated by a heavy fall are likely to reach the main stream at approximately the same time, thereby resulting in a large and rapid increase in the discharge of the main stream. On the other hand, if the catchment area is long and narrow, the tributaries will tend to be relatively short, and more likely to join the main stream at intervals along its length. Elongated catchments are thus less subject to high runoff peaks.

Researchers have made numerous attempts to derive quantitative measures of basin shape which can be related to hydrological processes. Selby (1985) lists seven different measures, but unfortunately there is little consensus among researchers as to which of these various shape indices is the best indicator of catchment response. Many other factors over-ride the effect of shape. The adoption of a particular index depends more on data availability or ease of data capture rather than its theoretical basis. Studies carried out by Morisawa (1958) and Seyhan (1975, 1976) concluded that the elongation ratio (R_e) of Schumm(1956) had a good correlation with hydrological response. This is given by the equation:

$$R_e = D_c/L_b \qquad \textit{Equation 3.16}$$

where D_c is the diameter of a circle of the same area as that of the catchment and L_b is the basin length measured parallel to the axis of the main stream.

3.8.2 Network shape

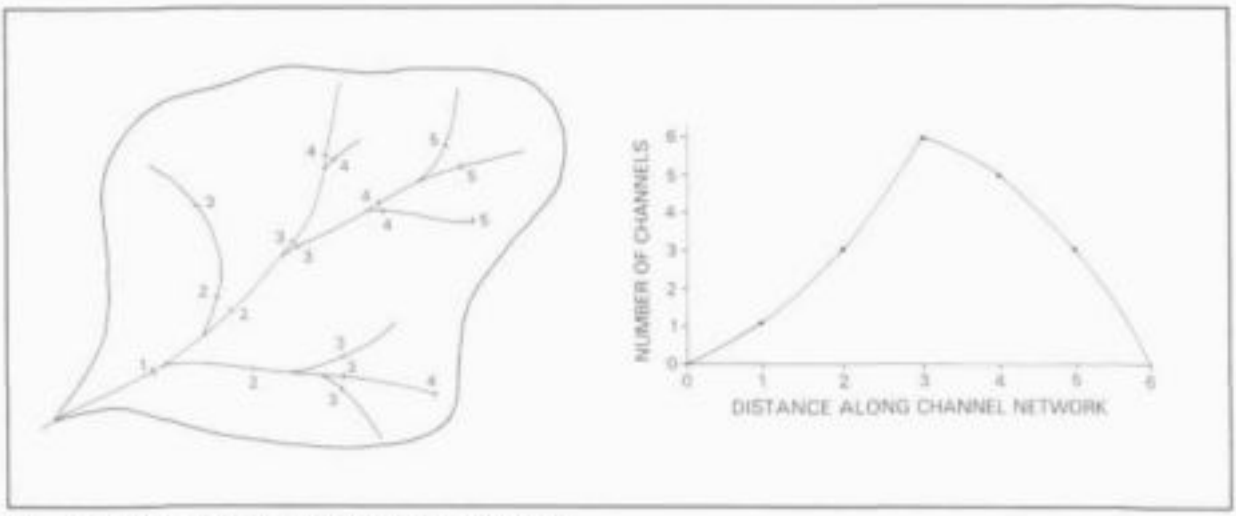
A more useful measure of the hydrological response of a catchment may be one which relates to the network shape rather than to the basin plan itself. Two indices are proposed, the bifurcation ratio and a stream frequency diagram.

The bifurcation ratio

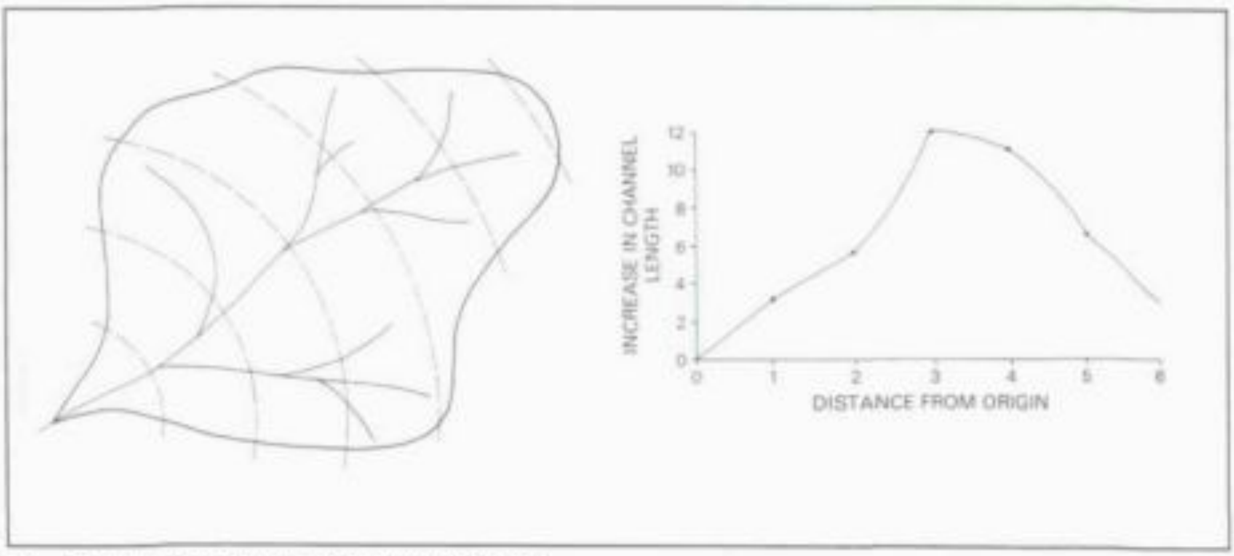
The bifurcation ratio R_b is a term introduced by Horton in 1932 to describe the structure of the drainage network. It is defined as the ratio of the number of streams of one order to the number of streams of the next highest order. For a simple bifurcating system the ratio would be 2. Strahler (1964) noted that for most catchments the average bifurcation ratio ranges between 3.0 and 5.0. Higher ratios indicate a high number of low order streams entering the next highest order, a condition often associated with elongated catchments.

The stream frequency diagram

The stream frequency diagram is a fuller description of the shape of the channel network. Newson (1975) describes its construction as follows. A pair of precision-adjustable dividers is set at an interval proportional to the size of the catchment and, beginning with a point at the catchment outlet, arcs are draw wherever they cross the streams contributing to flow at the outlet. The point is then transferred to each of these arcs in turn and the next arc step made up the channels. Terminating channel lengths are summed as fractions of a single arc step and added to the channel count at that distance (Figure 3.14a).



a). Stream Frequency Diagram (Manual)



b) Stream Frequency Diagram (Digital).

Figure 3.14 Stream frequency diagrams.

With the advent of GIS technology it should be possible to develop relatively quick methods for deriving equivalent data. It may be more appropriate to use an index of channel length derived by measuring the total channel length contained within successive arcs of a uniformly increasing increment drawn from the catchment outlet (Figure 3.14b).

Map scale and arc length both have an effect on the shape of the stream frequency diagram. Obviously the amount of detail increases at larger scales, but it is interesting to note that the gross form is preserved at scales as small as 1:250 000. Newson (1975) recommends the use of 1: 25 000 scale maps which are not available in South Africa. For large catchments an arc length of 1km was considered appropriate (Newson, 1975). A national GIS cover of the drainage network at a scale of 1: 250 000 is readily available for South Africa, covers at a scale of 1: 50 000 are available locally. An arc length of 1 km was considered by Newson (1975) as appropriate for use in large catchments in the UK; a longer arc length would be suitable for use at the 1: 250 000 scale in South Africa.

Modern hydrological thinking points to the areas immediately next to the channels as the main contributing area for storm runoff or sediment. The stream frequency diagram or its equivalent should therefore provide a useful catchment scale index for estimating both the flood hydrograph and the spatial distribution of sediment inputs into the channel system.

3.8.3 Basin relief

As with basin shape, it is difficult to derive a single number which meaningfully quantifies slope and relief over an entire drainage basin. The simplest measure is maximum basin relief which is the difference in height between the basin mouth and the highest point on the basin perimeter; this value divided by the horizontal distance over which it is measured gives the relief ratio (Schumm, 1956). This relief ratio measures the overall slope of a drainage basin and provides an index of the intensity of erosion processes operating on the basin slopes (Hadley and Schumm, 1961; Strahler, 1964). Catchment slope is of particular importance because it affects the lateral and vertical movement of water and sediment.

Another catchment scale measure of relief is the hypsographic curve, this is a graph of the cumulative percentage of the area of a drainage basin above or below a given height. The hypsometric curve gives a first approximation to the amalgamated long profile of all tributaries and indicates the altitudinal range within the catchment as well as the slope distribution.

3.9 CONCLUSION

The hierarchical model promoted in this report describes the linkages between the catchment which supplies water and sediment to the channel network, the drainage network through which the sediment and water are routed, and the channel morphology at the reach scale which provides the habitat for stream organisms. For each level of the hierarchy, this review has outlined the important processes operating, the variables which control the rate and direction of those processes and the resulting channel morphology. The literature on fluvial geomorphology is vast and in a review such as this which encompasses a large range of scales it has not been possible to cover all pertinent literature, nor to explore all relevant concepts in detail. The most often cited and relevant literature for this review includes texts and edited volumes by Calow and Petts (1992), Knighton (1984), Morisawa (1985), and Richards (1982, 1987). It is hoped that the most important aspects have been covered and that the reader can be directed to the original sources for further information.

CHAPTER FOUR
THE HYDRAULIC BIOTOPE CONCEPT

4.1 INTRODUCTION

The need for a classification system which links the biotic (ecological) and physical (geomorphological) components of river systems has been stressed by Naiman *et al.* (1992, Abstract), who state that:

> "A wide range of identifiable stream types occur naturally in drainage networks. Classification systems for streams have a long and complicated history, with most classification systems having only restricted or regional application. It is becoming increasingly apparent that the conservation potential of a stream is closely related to stream type, demanding that a universal approach to stream classification be developed. The literature suggests that the fundamental elements of an enduring stream classification system should relate to an ability to encompass broad spatial and temporal scales, to relate structural and functional attributes to disturbance regimes, to reveal underlying mechanisms controlling stream features, to be cost effective, and to result in a broad level of understanding among resource managers. Unfortunately no historic or extant classification systems meet these criteria completely, even though two recent hierarchical approaches are reasonably comprehensive (Rosgen, 1985, 1994, & Cupp 1989). *Our review suggests that renewed efforts be made to link physical channel features and biotic characteristics in predictive models which encompass a range of stream types. We conclude that an ability to correctly assess conservation potential requires an enduring classification system as a foundation for management efforts*" (author's italics).

A pervasive theme in the more recent literature concerned with lotic ecology is the application of hydraulic indices to the characterisation of riverine habitats. As evidenced by the organisation of the First International Symposium on Habitat Hydraulics (1994) and subsequently, the Second International Symposium on Habitat Hydraulics in 1996 (Leclerc *et al.*, 1996), considerable effort is being put into this research area by scientists throughout the world. Hydraulic simulation models have been developed which relate hydraulic characteristics to flow discharge. One of the most widely used models for addressing the relationships between species habitat and the physical components of the river environment is the instream flow incremental methodology (IFIM; Bovee, 1982). This model was originally developed as a tool to manage river flows in response to pressure from game fish lobbyists in North America. At the core of the IFIM is a suite of computer models and procedures which allows the calculation of change in habitat (or weighted usable area, WUA) with changes in discharges. This is referred to as the physical habitat simulation model (PHABSIM), and is dependant on a detailed understanding of the habitat requirements of selected target species (eg trout). The PHABSIM component of the model uses water depth, velocity, stream substrate and cover to predict the amount of available habitat for fish location (Bovee, 1982). These variables have become standard for the calculation of habitat preference curves for aquatic organisms by lotic ecologists throughout the world. A simplified explanation of that part of the IFIM procedure as performed by PHABSIM is as follows: at a particular discharge, the pattern of distribution of physical habitat (depth, velocity, cover and substrate) is evaluated over a length of the stream. This is combined with habitat suitability curves for a particular species/life stage to determine a WUA for that discharge. The distribution of physical habitat is re-evaluated at each discharge and computations for WUA repeated.

Although this model has potential as a useful link between lotic ecology and fluvial geomorphology for river classification, a number of problems exist. A critical limitation on the use of habitat simulation models is the lack of well-defined habitat suitability curves. Since these curves are essentially empirical correlations, some authors (Nestler *et al.*, 1985) state that the curves may be non transferable from one stream to another. The development of habitat preference curves is costly, with Bovee (1986) estimating a cost of U.S. $10 000 per species/life stage. This approach is therefore highly impractical for large regions.

In producing a habitat time series an assumption is made that the structure of the stream channel does not change under the range of flows simulated. However, channels can realistically be expected to change, both naturally and in response to flow regulation, altering the available habitat (Bleed, 1987).

A strong criticism of the IFIM has centred on the ecological interpretation of the weighted usable area index. Gore and Nestler (1988) and King and Tharme (1994) review and comment on the criticism put forward by a number of authors. They suggest that the WUA should be treated as an index of available physical habitat rather than an indicator of actual biomass or species numbers, and that this is the appropriate level of utility of PHABSIM as a management tool.

It was apparent to the present authors that the use of hydraulic simulation models such as the IFIM were perhaps not the most appropriate to create links between lotic ecology and geomorphology for the purpose of classification. Factors that led to this conclusion were: the use of scale dependent variables such as velocity and depth means that data is non transferrable between rivers; the enormous costs involved in learning and running such a model make its widespread application prohibitive (King & Tharme, 1994); the fact that the IFIM does not account for morphological changes with increasing or decreasing discharge provides a somewhat static and unrealistic output; finally the lack of ecological, geomorphological and hydraulic data in less developed countries such as South Africa provides for poor data inputs and therefore virtually useless results.

An important omission from hydraulic simulation models such as IFIM and from general ecological research has been a rigorous and objective habitat classification together with measurable parameters for definition. These are particularly important aspects of a classification system for comparison of findings between and within streams. This realisation has been picked up by researchers from New

Zealand (Jowett, 1993) and England (Padmore *et al.*, 1996, Padmore, 1997). These researchers, in parallel with the work presented here, are attempting to provide a more rigorous and objective technique for habitat classification and characterisation.

One of the requirements of a hierarchical model for South African rivers was that it should provide a relatively simple and inexpensive scale-independent link between lotic ecology and geomorphology, a task substantially more difficult than one would first imagine. Frissell *et al.* (1986) recognised this link as occurring at a "microhabitat" scale. These are defined as patches within morphological units that have relatively homogenous substrate type, water depth and velocity. Frissell *et al.* (1986) go on to justify the use of this scale in understanding the distributions and trophic and life history adaptations of stream organisms (Linduska, 1942; Cummins & Lauff, 1969; Rabeni & Minshall, 1977; Hynes, 1970), the structure and dynamics of stream communities (Dudgeon, 1982; McAuliffe, 1983; Wevers & Warren, 1986) and behavioural ecology of fishes and aquatic invertebrates (Smith & Li, 1983; Hart, 1981).

The ideas of Frissell *et al.* (1986) are theoretically sound but difficult to put into practice within a classification system. An important limitation of their system, along with many habitat models, is the inability to transfer depth, velocity and substrate data from one site to another to compare features at the 'microhabitat' scale. The research presented in this project represents an attempt to develop further the ideas of Frissel *et al.* (1986) into a rigorous habitat classification system for inclusion in the hierarchical geomorphological model. The developmental nature of this research has meant that many different aspects of the study have been progressing in parallel, with interim results being used to improve or redirect research as the case may be.

4.2 RESEARCH QUESTIONS

4.2.1 Is the term microhabitat ecologically acceptable?

A relatively detailed examination of the ecological literature (Wadeson, 1994) provided evidence that the widespread and often indiscriminate use of the term microhabitat or habitat by many ecologists was incorrect. Whittaker *et al.* (1973), Price (1975) and Ward (1992) are a few authors who make a clear distinction between the term 'habitat', the abiotic environment of a **species**, and the term 'biotope', the abiotic environment of a **community**. This distinction has been taken up by many South African authors (Harrison & Elsworth, 1959; Chutter, 1970 and de Moor, 1990). The research presented in this report focuses on areas within the stream which are of an approximate scale of 1 m^2. These areas are characterised by distinctive flow conditions. Theoretically this area has special ecological significance for the distribution of aquatic biota. Participants of a workshop held in Citrusdal (Rowntree, 1996a) argued that the correct term describing an area of instream flow which has specific hydraulic characteristics should be 'physical biotope' as this excluded any effects of the biota themselves on environmental conditions in that area. Following this workshop, King (*pers.comm.*) has suggested the use of the term 'hydraulic biotope' to avoid the possible implication that physical habitat incorporates variables such as water chemistry and temperature. The term hydraulic biotope has been adopted for this research and may be defined as a spatially distinct in-stream flow environment characterised by specific hydraulic and substrate attributes (Wadeson, 1996).

4.2.2 How have hydraulic biotopes been described in conventional ecological literature?

In the ecological literature there are numerous references to channel form features which have been given terms commonly associated with fluvial geomorphology (riffles, pools and rapids), or are given descriptive terms which are specific to lotic ecology (runs, cascades, chutes, glides etc.). These features have special ecological significance because they provide the physical environment for various communities of organisms. In this report they are referred to as classes of the hydraulic biotope.

4.2.3 Is there consistent terminology for the naming of hydraulic biotopes?

To answer this question two tasks were initiated: the first involved a search of the ecological literature to review a broad spectrum of global and South African examples of hydraulic biotope terminology together with their definitions. The second task, which was initiated at the same time, involved consultation with prominent South African ecologists to determine the most commonly used hydraulic biotope terminology together with their definitions.

Literature review

The initial literature search exposed a considerable number of hydraulic biotope terms, these are given in Table 4.1 It must be realised that virtually every ecological document dealing with the biota of flowing water makes reference to some 'habitat' or another. The references given in Table 4.1 represent a fraction of the literature available, but are used to demonstrate the diverse terminology frequently used to describe 'habitats'. Of special significance in this table is the fact that many authors do not define the terms used, appearing instead to rely on intuition for the recognition of the different features. The use of the different hydraulic biotope terms is reviewed below. This review highlights two important points. Firstly, there is a lack of consistency in the use of different hydraulic biotope terms, with different terms applied to similar features or the same term applied to different features. Secondly, the review illustrates the importance of velocity, depth and substrate for the characterisation of different hydraulic biotopes.

Table 4.1 The use of hydraulic biotope terms, and the extent to which they are defined. (● = no definition ; □ = definition given.)

	1	2	3	4	5	6	7	8	9	10	11	12	13
AUTHOR	POOL	BACKWATER	GLIDE	FLATS	RUN	RIFFLE	STICKLE	RIPPLE	RAPID	CASCADE	WATERFALL	STONES IN CURRENT	STONES OUT CURRENT
Allen (1951)	□			□	□	□	□	●	●	□			
Tebo (1955)	●					●				●			
Harrison & Elsworth (1959)	□			□	□	□	□	●	●	□		●	
Chutter (1970)				□	□		□			□		●	●
Hynes (1970)	□				●	□							
Platts (1979)	●					●							
Savage & Rabe (1979)	●		●			●				●			
De Leeuw (1981)	□		□			□					□		
Moyle *et al* (1955)	●		●		●	●							
Pridmore & Roper (1985)	●	●			□	●							
Frissel *et al.* (1986)	●					●							
Grossman & Freeman (1987)					□	□							
Bisson *et al* (1982)	□	□	□			□				□			
Botton et al (1988)						□							
Anderson & Morison (1989)	□	□	□		□	□			□	□	□		
Hogan & Church (1989)	●		●			●							
Barmuta (1990)	●					●							
de Moor (1990)	●					●				●			
Reice *et al* (1990)	●					●							
Barbour (1991)	●		●		●	●							
Shields *et al* (1991)	●					●							
Gore *et al* (1991)	●				●	●							

Pools:

AUTHOR:	*DEFINITION*
Allen (1951)	A pool has water of considerable depth for the size of the stream, current generally slight, flow smooth apart from a small turbulent area at the head of some pools. Velocity less than 38.5 $cm.sec^{-1}$. Depth greater than 46 cm.
Harrison & Elsworth (1959)	The authors use Allen's classification, but describe velocities of less than 30.8 $cm.sec^{-1}$.
De Leeuw (1981)	This is an area of the stream that is deep and of slow velocity relative to contiguous hydraulic types.
Bisson et al. (1988)	These authors recognise 6 different types of pools according to their hydraulic characteristics (after Bisson *et al.* 1982). Velocities range from 4 $cm.sec^{-1}$ to 24 $cm.sec^{-1}$. Depths range from 7 cm to 45 cm.
Anderson & Morison (1989)	Where the stream widens or deepens and the current declines. Depth greater than 50 cm.

The term pool is widely used (20 out of 23 authors), but is defined by only 5 of them. There is general agreement that depth and velocity are important criteria, but there is a lack of consistency as to limiting values; this variation is undoubtedly related to the scale of the river channel.

Backwaters:

AUTHOR:	*DEFINITION:*
Bisson *et al.* (1988)	These occur along the channel margin and are caused by eddies behind large obstructions. Average velocity 6 $cm.sec^{-1}$. Average depth 19 cm.
Anderson & Morison (1989)	Cut off section away from the channel which is larger than 20 % of the channel width. The depth for a reasonable size will be less than 35 cm.

There is general agreement for the recognition of backwaters.

Glide:

It is interesting to note that 8 of 23 authors refer to glides. The 3 definitions agree that the flow must lack pronounced turbulence, however there is some disagreement on the defining depth and substrate. It appears as though glides are equivalent to runs.

AUTHOR:	*DEFINITION:*
De Leeuw (1981)	This is a section of flowing water (slow to fast, shallow to deep) with the surface unbroken by bed material.
Bisson *et al* (1988)	These are found between pools and riffles, characterised by shallow water that lacks pronounced turbulence. Average velocity 20 $cm.sec^{-1}$. Average depth 11 cm.
Anderson & Morison (1989).	Small currents surface unbroken and smooth. Depth less than 10 cm and gradient 1 - 3 degrees.

Flats:

AUTHOR:	*DEFINITION:*
Allen (1951)	Flats have water of slight to moderate current and generally smooth flow, but of less depth than in pools. Velocity less than 39 $cm.sec^{-1}$. Depth less than 46 cm.
Harrison & Elsworth (1959).	These authors use Allen's definition, but recognise critical velocity of less than 30 $cm.sec^{-1}$ and critical depth of less than 46 cm. The authors see this feature as being very similar to backwaters.
Chutter (1970)	This author uses Allen's definition.

'Flats' is a term not found in the more recent literature; it seems to have been replaced with glide. Confusion arises in the above definitions because authors refer to both flats and runs. There is little consensus as to what criteria for velocity determine the limiting values.

Run:

It appears as though there are two different classifications within this hydraulic biotope: those who follow Allen (1951) and the rest. Allen suggests that current velocity is sufficiently fast to produce some surface disruption (which he terms turbulent flow), whereas the other authors recognise a run as having a sufficient depth : velocity ratio to prevent surface disruption.

AUTHOR:	*DEFINITION:*
Allen (1951)	These are found in water of moderate to rapid current which is fairly deep. Flow usually turbulent. In such places the stream is usually of less than average width. Velocities greater than 38 $cm.sec^{-1}$. Depth greater than 23 cm.
Harrison & Elsworth (1959)	These authors refer to Allen's classification. Runs in sandy areas are shallower. Velocities greater than 30 $cm.sec^{-1}$. Depth greater than 30 cm.
Chutter (1970)	This author uses Allen's classification.
Pridmore & Roper (1985)	The authors found that runs were deeper, narrower and slower flowing than riffles.
Grossman & Freeman (1987)	Runs are areas with measurable current, but no surface disruption.
Anderson & Morison (1989)	Small but distinct and uniform current with the surface unbroken.

Riffle:

AUTHOR:	*DEFINITION:*
Allen (1951)	This falls under Allen's 'stickles'. Shallow water with a rapid current and usually a broken flow. Such conditions are often described as 'ripples', 'rapids' or 'riffles'. Velocity more than 38 $cm.sec^{-1}$. Depth less than 23 cm.
Harrison & Ellsworth (1959)	These authors use Allens classification but give velocities of more than 30 $cm.sec^{-1}$ and depth of less than 30 cm
Grossman & Freeman (1987).	Riffles are shallow areas with high average velocities, marked surface disruption and with rubble - gravel substrata.
De Leeuw (1981)	This is a shallow area (generally) of a stream, where the water surface is broken into waves by bed material wholly or partially submerged.
Bisson et al. (1988)	These are shallow, possess moderate current velocity and turbulence. Have a gradient of less than 4%, average velocity 35 $cm.sec^{-1}$, average depth 13 cm.
Boulton *et al.* (1988)	An average width of 9 m, a substratum of stones ranging in size from 15 to 25 cm and a current velocity ranging from 20 to 130 $cm.sec^{-1}$.
Anderson & Morison (1989)	Moderate currents, surface unbroken but unsmooth. Depth 10 cm - 30 cm, gradient 1 - 3 degrees.

Like pools, the term riffle is widely used (22 of the 23 authors), but is only defined by 7 authors. As with pools, velocity and depth are recognised as important criteria, but there is little consensus as to the limiting values. Added to these criteria is the importance of gradient (3 authors) and substrate (3 authors). The term 'stickle' and 'ripple' are included in this definition by Allen (1951) and his followers, Harrison and Elsworth (1959), and Chutter (1970).

Rapid:

AUTHOR:	*DEFINITION:*
Anderson & Morison (1989).	Strong currents, rocks break surface. Depth greater than 35cm, gradient 3 - 5 degrees.

The term rapid is not one used very often by ecologists and is included in 'stickles' in the older literature and in 'riffles' in the more recent literature. However the above author recognises the feature as being uniquely determined by the large substrate and high velocity.

Chutes:

The term chute was used only by Hynes (1970) but no definition was given.

Cascades:

Together with pools, riffles and runs, the cascade is one of the most commonly used hydraulic biotope terms (9 of 23 authors). Amongst the 9 users are 5 definitions. Again the definitions seem to be divided into two camps, those who recognise a step-like series of small waterfalls and pools (Bisson *et al.*, 1988; Anderson & Morison, 1989), and those who recognise a highly turbulent flow related to a high substrate size to depth ratio (Allen, 1951; Harrison & Elsworth, 1959; Chutter, 1970). There is no consensus as to what depth, or velocity criteria are the limiting values for definition.

AUTHOR:	*DEFINITION:*
Allen (1951)	Water in which a steep gradient, combined with a bed of stones or rocks large in proportion to the size of the steam, produces a very irregular rapid flow, often with some white water.
Harrison & Elsworth (1959)	These authors agree with Allen's definition, but conclude that cascades and small waterfalls only occurred where streams were flowing down mountain valleys. Velocity 77 cm.sec^{-1}. Depth 10 to 46 cm.
Chutter (1970)	This author refers to Allen's classification.
Bisson *et al.* (1988)	These have a gradient steeper than 4%. Consists of stepped series of alternating small waterfalls and shallow pools. Average velocity 24 cm.sec^{-1}. Average depth 10 cm.
Anderson & Morison (1989).	Strong currents, step height less than 100cm with gradients 5 - 60 degrees.

Waterfall:

AUTHOR	*DEFINITION:*
De Leeuw (1981)	This is a very fast white water cascade (often vertical). Only its length, width and depth are measured. Height is also measured if it is deemed a problem to fish passage.
Anderson & Morison (1989).	Height greater than 100 cm, gradient greater than 60 degrees.

Although waterfalls may be recognised as being separate from cascades, their defining criteria, that is width, depth and height, makes recognition highly subjective due to lack of quantification.

Stones in and out of current:

AUTHOR:	*DEFINITION*
Chutter (1970)	There is no definition given in the literature, but one was obtained by personal communication with the author in 1992. It was suggested that stones out of current meant the presence of gravels, cobbles or boulders in a body of water where flow velocity was low enough to allow the deposition (on the stones) of fine sediment and detritus which can be seen from the surface. Stones in current was taken to mean the presence of the above mentioned substrate in any feature where there was no settling of fine sediment or detritus, that is Chutter recorded current speeds within this environment.

The use of the terms 'stones in and out of the current' separates hydraulic biotopes into two broad classes based on depositional environments for fine sediments. It follows that stones out of current would be likely to include such features as pools and backwaters while stones in current would includes riffles, runs, flats, rapids, cascades and waterfalls.

Consultation

At the same time as carrying out a literature review, informal discussions took place with lotic ecologists who were actively involved in field research. As a supplement to these discussions, a seminar paper was presented to the local ecological community in 1993. The main aim of these discussions was to ascertain what were the most commonly used terms to describe instream flow environments, and to try to determine the criteria for their recognition. As with the literature review referred to above, numerous terms were being used by different researchers but very few were defined. The lack of consistency in the naming and recognition of different hydraulic biotope classes made it impossible to compare the physical characteristics of these features within or between different rivers. It was realised that the first hurdle that needed to be overcome for the further development of the hydraulic biotope concept was the acceptance of a standardised terminology for the description of hydraulic biotopes.

4.2.4 Is it possible to obtain consensus from the South African ecological community for standardised terminology and definitions of hydraulic biotopes?

Bisson *et al.* (1982, 1988) provide perhaps the most widely accepted hydraulic biotope (habitat) definitions for instream flow environments common within small streams. These authors recognised three broad types of habitat significant for fish: riffle (low gradient, rapid and cascade), pool (secondary channel, backwater, trench, plunge, lateral scour and dammed) and glide. These hydraulic biotopes are characterised by gradient, depth, velocity, cover and substrate types. These definitions of Bisson *et al.*

(1982) are determined at low flow and are to some degree stage dependent. Unfortunately the classification is not very useful in a predictive sense because it is not coupled to a process-based classification system. For the development of a South African classification it was felt that the system of Bisson *et al.* (1982) would not be entirely appropriate as the classification had to be of equal value for small and large streams, for vertebrates and invertebrates and be stage independent. The ideas of these authors were considered and formed a framework for further development.

Table 4.2 The definition of hydraulic biotopes after King *et al., pers.com.*

HYDRAULIC BIOTOPE:	*DEFINITION*
POOL	This is a feature which has through flow. The combination of velocity and depth allows depositions of fine particulate matter over substrate of all sizes. A very slow velocity i.e. from slow to almost still.
RIFFLES	These flow over cobbles, gravel and boulders and have a shallow depth relative to bed material size. They consist of rapid, super-critical flow[1] and indicate a distinct gradient change of the water surface. At increased discharge riffles become runs i.e. they vary temporally.
RUN	A run has tranquil flow, no broken water on the surface, found with any substrate. There is no obvious stream bed gradient change. There is a higher depth to substrate size ratio than for riffles.
BACKWATER	These are 'hydraulically detached' features where there is no through flow of water. Movement of water occurs through a single entrance/exit. All substrate types are present, but are generally covered by fine silt and sand (area of deposition). The depth may be variable with a low to zero velocity.
CASCADES	These consist of free falling water in a step like fashion over bedrock.
WATERFALLS	These are similar to cascades, but higher. There is more free fall of water relative to horizontal movement. Height is the most important defining variable.
GLIDE	This is a shallow, unconstricted, smooth flow over bedrock. Bed roughness is relatively low. It becomes a run over bedrock at higher flows.
CHUTE	This consists of narrow constricted flow over bedrock. Depth produces smooth flow at the surface. If flow becomes super- critical, the feature becomes a rapid.
RAPID	This feature is similar to a glide, but has broken water. It occurs over bedrock or boulders. The critical feature is velocity, which must be high, together with the form ratios (width : depth) which must be low.

[1] Consequently found to be dominated by subcritical flow, with local areas of supercritical flow.

In July 1992 a field trip was organised by Dr Jackie King (Freshwater Research Unit, University of Cape Town) to visit research sites on the Olifants River. These sites were being used to assess the Instream Flow Incremental Methodology (IFIM), a project funded by the WRC. Participants of this field visit included Dr Jay O'Keeffe and Dr Caroline Palmer (Ecologists, Institute for Water Research, Rhodes

University), Dr Jackie King, Dr Jenny Day, Ms Rebecca Tharme and Mr Sean Eekhout (Ecologists, Freshwater Research Unit, University of Cape Town), Dr Kate Rowntree and Mr Roy Wadeson (Geomorphologists, Geography Department, Rhodes University) and Professor Barry Hart (Ecologist, Water Studies Centre, Monash University, Australia). These participants make up the King *et al.* (*pers.com*) referred to in this chapter. Although this list of scientists is far from comprehensive in terms of the ecological expertise available in South Africa, they do represent some of the most prominent academics involved in the type of research which involves the use of hydraulic biotope terms.

This field trip provided an ideal venue and opportunity for informal discussion on the standardisation and definition of hydraulic biotope terminology. Common consensus was obtained from the researchers present for the naming and description of ecologically significant hydraulic biotopes common within South African rivers (Table 4.2). It is important to note that the validity of the ecological significance of these features had not been tested at the time of this study and was based purely on field experience.

A noticeable feature of the definitions of hydraulic biotope terms given in Table 4.2 is their descriptive nature. This continues the tradition of a high degree of subjectivity for the identification of hydraulic biotopes, but provides a slightly more rigorous definition that requires less intuition. It was always recognised that the information in Table 4.2 would provide the initial template for the standardisation of terminology and for the definition of hydraulic biotopes. It was envisaged that this would be continuously refined and adjusted in response to developments within the broader concept.

The results from the Olifants field trip were combined with those from the literature search, together these were considered within a broader geomorphological perspective and were published in the South African Journal of Aquatic Sciences (Wadeson, 1994). The main aim of this paper was to encourage discussion and feed back amongst lotic ecologists for the overall concept of the hydraulic biotope. The paper attempted to introduce the hydraulic biotope as a scale of feature which is nested within the broader geomorphological unit making up channel form. It also introduced the idea that the distribution of hydraulic biotopes may be highly variable in time as a response to changing discharge. The paper provided the initial impetus for the further development of the hydraulic biotope concept; this research has a number of different foci including the ecological significance of hydraulic biotopes (Emery, 1994; King & Tharme, 1994) application of the concept to other rivers (Padmore 1977; Arthington, Griffiths and Bisbare *pers. comm*) and further development within South Africa (this report).

The development of a standardised terminology and definition for hydraulic biotope classes has been ongoing with inputs from various researchers at all stages of the study. The most recent consensus was reached during a workshop held in Citrusdal, Western Cape, in February 1995 (Rowntree, 1996a). This workshop brought together researchers and practitioners from the related fields of fluvial geomorphology, hydraulic engineering and stream ecology to discuss the hydraulic biotope concept as a common point of interest for the various disciplines. The workshop was convened specifically to address the hydraulic biotope concept and to explore its potential as a tool to assess environmental instream flow requirements. Participants at the workshop included many of those present at the Olifants River in 1992 with the addition of Professor Malcolm Newson (Geography Department, University of Newcastle Upon Tyne). The presence of Professor Newson was particularly significant because of his extensive experience in fluvial research and because of parallel studies being undertaken together with Ms C. Padmore in the United Kingdom.

Participants at the Citrusdal workshop had all been exposed to the hydraulic biotope concept either in terms of active research or simply through discussions with the project researchers. One of the aims of this meeting was to produce a more rigorous hydraulic biotope classification to allow recognition of different classes using consistent field criteria. In the hydraulic biotope concept it is assumed that the interaction of flow hydraulics and substrate determines the physical environment experienced by the biota at this scale. Workshop participants provided the following discussion on the importance of these two variables on the distribution of stream biota.

Flow distributes food and oxygen, scours out sediment and keeps rock surfaces free of fine silt or algae. In cobble beds benthic organisms live both on top of and underneath stones. Stability of the substrate under different flows is important. Near-bed hydraulics related to depth of the laminar sub-layer and boundary shear stress may be the critical variables. For fish, flow depth and velocity profiles are probably more important than near-bed conditions and substrate (except when spawning). Because hydraulic enclaves such as backwaters are important for hydraulic cover, the spatial distribution of hydraulic conditions should be considered.

Hydraulic biotope classes can be related not only to hydraulic conditions, but also to sedimentation characteristics. A riffle by nature is clean and free of fine sediments, even at low flows, whereas runs have more variable sediment conditions. Under good catchment conditions with low silt production, cobbles would be clean and well populated with invertebrates. Where sand or other fine material dominates the sediment load, smothering of cobbles may reduce available habitat for stream organisms. At low flow a run may become clogged, needing flushing flows to maintain its physical diversity. Pools are areas where fine silts and organic detritus tend to accumulate.

It was agreed by workshop participants that the hydraulics of flow represents a highly complex mix of conditions for which a simple surrogate may be needed. Professor Malcolm Newson suggested a visually defined flow type as a useful index. Flow type is determined primarily from the appearance of the water surface, which may vary from smooth through rippled to broken with standing waves. A first attempt to classify flow types as developed during the workshop is given in Table 4.3.

Table 4.3 The classification of flow types

Flow types	Definition
No flow	no water movement
Barely perceptible flow	smooth surface, flow only perceptible through the movement of suspended matter.
Smooth boundary turbulence	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 surface	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.
Chaotic flow	complex mixture of continuously varying flow types associated with unsteady, pulsating flow; common at high flows.
Boil	the direction of flow is predominantly vertical, with strong horizontal eddies; boil forms on the surface of the water.

Flow type is thought to be directly related to the Froude number of the flow and to boundary roughness. It thus takes into account the interaction of flow velocity, flow depth and substrate characteristics, all variables deemed to be of ecological significance. Flow type is independent of scale and can be applied equally to large or small streams.

Although bed conditions have a direct effect on flow type through the development of turbulent eddies, flow type does not distinguish directly between different substrates. Substrate size class needs to be considered in its own right due to its important role in determining habitat and hydraulic cover. For example bedrock has a low surface heterogeneity and thus low numbers and diversity of biota. Cobble beds, with good hydraulic cover and variety of habitats, may have between 1000 - 20 000 invertebrates per m^2 whereas a sand bed may have less than 1000 invertebrates per m^2 because of its unstable and uniform character. After discussion at the Citrusdal workshop a substratum component was added to flow type to provide a better objective definition of hydraulic biotope classes. For simplicity a modified version of the Wentworth scale was used as shown in Table 4.4. A bedrock component was included due to the widespread occurrence of bedrock channels throughout South Africa.

Prior to the Citrusdal workshop (February 1995), a series of pilot studies had been completed by both this researcher and others. The combined experience of researchers involved in these studies was to be used at the Citrusdal workshop to create a revised edition of acceptable terminology and definition of hydraulic biotopes. Utilising the newly defined classification of flow (Table 4.3) and incorporating substratum (Table 4.4) a new table of hydraulic biotope terms and definitions was produced (Table 4.5).

Table 4.4 Substrate classes (Wentworth scale) adapted from Brakensiek *et al.* (1979).

Substrate class	Particle diameter mm (b-axis)
Silt	< 0.0625
Sand	0.0625 - 2
Gravel	2 - 64
Cobble	64 - 256
Boulder	> 256
Fractured bedrock	bedrock with significant cracks and crevasses which afford some cover.
Smooth bedrock	bedrock lacking cracks or crevasses
Cliff	a vertical bedrock face

Table 4.5 The revised definition of hydraulic biotopes (from Citrusdal workshop, Rowntree, 1996a)

Hydraulic Biotopes	**Definition**
Backwater	A backwater is morphologically defined as an area along-side but physically separated from the channel, but connected to it at its downstream end. Water therefore enters the feature in an upstream direction. It may occur over any substrate.
Slack Water	A slack water is an area of no perceptible flow which is hydraulically detached from the main flow but is within the main channel. It may occur at channel margins or in midchannel areas downstream of obstructions or secondary flow cells. It may occur over any substrate.
Pool	A pool is in direct hydraulic contact with upstream and downstream water but has barely perceptible flow.
Glide	A glide exhibits smooth boundary turbulence, with clearly perceptible flow without any surface disturbance. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Thus glides could only occur over cobbles at relatively high flows. Flow over a glide is uniform such that there is no significant convergence or divergence.
Chute	Chutes exhibit smooth boundary turbulence at higher flow velocities than glides. They typically occur in boulder or bedrock channels where flow is being funnelled between macro bed elements. Chutes are generally short and exhibit flow acceleration.
Run	A run is characterised by a rippled flow type and can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. It may be useful to distinguish fast and slow runs in terms of the degree of ripple development. A fast run has clear rippling, a slow run has indistinct ripples.
Riffle	Riffles may have undular standing waves or breaking standing waves and occur over coarse alluvial substrates from gravel to cobble.
Rapid	Rapids have undular standing waves or breaking standing waves and occur over a fixed substrate such as boulder or bedrock.
Cascade	A cascade has free-falling flow over a substrate of boulder or bedrock, but the flow maintains contact with the substrate. Small cascades may occur in cobble where the bed has a stepped structure due to cobble accumulations.
Waterfall	A waterfall has free falling flow over a cliff, where a cliff represents a significant topographic discontinuity in the channel long profile.
Boil	A boil flow type may occur over any substrate and consists primarily of vertical flow.

4.2.5 Is there an objective technique for the recognition of hydraulic biotopes?

A review of the literature and discussions with lotic ecologists highlighted an immediate problem when referring to hydraulic biotopes: the fact that their identification has been based on an intuitive 'feel' for the flow conditions being experienced in an area or at a point. It is only through field experience that a researcher can quickly and consistently recognise the various hydraulic biotope classes. This leads to a number of problems related to the validity of data comparison either within or between rivers and, particularly, between researchers. This problem is highlighted in this chapter by the inconsistent use of terminology. There is an obvious need for an objective technique for hydraulic biotope classification

The logical progression from hydraulic biotope definitions derived at the Citrusdal workshop was the development of an objective technique for hydraulic biotope classification. By combining flow type and substrate class in a matrix (Figure 4.1) an objective method was initiated for visually identifying and defining the hydraulic biotopes that had hitherto been intuitively recognised by lotic ecologists. The matrix was modified during the workshop proceedings after field testing in a nearby tributary of the Olifants River. The matrix has shown sufficient promise to be adopted as a standardised technique for all further research initiated since the workshop. The matrix still requires considerable development and testing, but provides a useful initial tool for hydraulic biotope identification and classification.

HYDRAULIC BIOTOPE MATRIX

SUBSTRATE

Silt	Backwater	Pool	Glide					Boil
Sand	Backwater	Pool	Glide	Run			Mixed	Boil
Gravel	Backwater	Pool	Glide	Run	Riffle		(Complex	Boil
Cobble	Backwater	Pool	Glide	Run	Riffle	Cascade	mosaic	Boil
Boulder	Backwater	Pool	Chute	Run	Rapid	Cascade	at very	Boil
Fractured bedrock	Backwater	Pool	Chute	Run	Rapid	Cascade	high flows)	Boil
Smooth bedrock	Backwater	Pool	Glide	Run	Rapid	Cascade	Mixed	Boil
Cliff						Waterfall		
	No flow	Barely percept-ible flow	Smooth & turbulent	Ripples	Undular or breaking standing waves	Free falling	Chaotic flow	Vertical flow

FLOW TYPE

Figure 4.1 The hydraulic biotope matrix (after Rowntree, 1996a)

Plate 4.1 to 4.10 illustrate the various hydraulic biotope classes that may be recognised using the hydraulic biotope matrix. Note that boils are absent because of their rarity in the fluvial environments considered within this study.

4.2.6 Do hydraulic biotope descriptor variables allow transference from one scale to another?

Underpinning the naming and defining of various hydraulic biotopes is an understanding by ecologists that the distribution and abundance of stream organisms is strongly correlated with spatial patterns of the flow regime. From the previous definitions it can be seen that conventionally these flow patterns have been defined using such characteristics as depth, velocity, channel width and substrate size; these are obviously site specific and scale related, therefore not necessarily transferable.

A review of the hydraulic engineering literature (Chapter 5) demonstrates that indices such as Froude number, Reynolds number, 'roughness' Reynolds number and shear velocity could prove to be extremely useful values for the characterisation of hydraulic biotope flow conditions. These indices combine variables of depth, velocity and substrate size into a single value. Of particular significance for the numeric classification of flow is the fact that the indices describing mean flow conditions (Froude and Reynolds number) are dimensionless and scale independent thus allowing a comparison of flow characteristics within and between different fluvial environments.

The potential of hydraulic indices as classificatory values for the characterisation of different hydraulic biotopes is considered at some length in Chapter 6.

4.2.7 How do hydraulic biotopes respond to changes in discharge?

An important revelation from discussion with lotic ecologists was that they recognise hydraulic biotopes as being temporally unstable. In other words hydraulic biotopes transform from one class to another in response to changing discharge. For example a pool biotope with low flow velocities and good depth during base flow conditions may become a run biotope as velocities increase faster than depth during a flood event. Similarly riffles may be converted to runs as the influence of substratum is progressively drowned out during higher flows. An understanding of the pattern and direction of hydraulic biotope transformation is extremely important if the hydraulic biotope concept is to have any use as a tool for the assessment of environmental instream flow requirements.

The collection of data to assess hydraulic biotope transformation in response to changing discharge is time consuming because of the requirement of repeated measurements at precise points along a transect, at a number of different discharges. During the earlier stages of development of the hydraulic biotope concept, emphasis was placed on the characterisation of hydraulic conditions within and between the different classes. This meant that early research design did not adequately allow for the testing of hydraulic biotope transformation, even though repeated measurements were made in both the Great Fish River and the Olifants River at different discharges. These pilot studies simply confirmed earlier statements made by lotic ecologists that hydraulic biotopes do undergo transformation. A detailed study carried out in the Buffalo River attempted to address more fully question 4.2.7 - how do hydraulic biotopes respond to discharge? This study considered the composition and distribution of hydraulic biotope classes in response to changing discharge within morphological units (Chapter Six).

The response of flow characteristics of hydraulic biotope classes in response to discharge is also an important method of determining the validity of the matrix as an objective tool for the recognition of hydraulic biotopes. As discussed previously it is assumed that flow type is an adequate surrogate for the complex mix of flow hydraulics occurring within the hydraulic biotope. If this is so, similarly classified features should demonstrate consistent hydraulic characteristics, irrespective of discharge. This theory is tested to some extent in this research. Unfortunately as the formalisation of an objective hydraulic biotope classification through the matrix occurred late in this study, through much of this research hydraulic biotopes were identified more subjectively. It is felt that these circumstances do not allow definitive statements to be made about the validity of the matrix at this stage.

4.2.8 Summary

Areas within a river which are subjectively recognised as having distinct hydraulic and substratum characteristics are considered to have special ecological significance because of their influence on the distribution of aquatic organisms. These spatially distinct areas have traditionally been called 'habitats', a term considered by many ecologists as being incorrect because it refers to a fine scale of resolution in which a selected species interacts with its environment. An alternative descriptor is the 'biotope' which refers to a larger scale feature than the 'habitat' in which communities of organisms interact with their instream environment. This term is more appropriate for most ecological studies because it is at this scale (>1 m^2) that sampling tends to occur. This term may still be semantically incorrect because most sampling strategies only *assume* different community structure within the different selected flow and substratum conditions. these subjectively recognised differences in flow and substratum conditions that determine the scale of ecological sampling. The term 'hydraulic biotope' is suggested as the most appropriate because it clearly implies the importance of hydraulic flow conditions for the recognition of ecologically significant patches.

There are a large number of 'habitat' terms used by lotic ecologists to describe instream flow environments. Some terms are more commonly associated with fluvial geomorphology (riffle, pool, rapid), but do not refer to the geomorphological process, form or scale of feature. This has important implications for the prediction of the response of hydraulic biotopes to changes in the flow and sediment regime.

A number of descriptive terms are arbitrarily used by lotic ecologists to describe "habitats" (stickle, ripple, run, chute, cascade, glide). These features are loosely defined and subjectively recognised making comparison between different studies all but impossible. A common feature of all 'habitats' is that they are characterised by velocity, depth and substratum, variables that are temporally unstable, site specific and non-transferrable.

The hydraulic biotope concept is primarily concerned with resolving some of the problems indicated above. The need for standardised terminology and definitions for hydraulic biotopes has been addressed within a workshop document (Rowntree, 1996a). These terms and definitions have been accepted within South Africa as 'working' ones, they will be regularly reviewed and refined as the hydraulic biotope concept is continually developed. At a workshop held in Citrusdal, Western Cape, South Africa, a hydraulic biotope matrix, utilising flow type and substratum, was devised as a preliminary tool for the objective recognition of hydraulic biotope classes (Rowntree, 1996a). It is recognised that this method is in the early developmental stages and requires considerable refinement and testing. Detailed studies presented later in this report attempt to provide initial feedback for the potential of the technique as a valid tool for hydraulic biotope classification. The characterisation of hydraulic biotopes using scale dependent variables is to be addressed within this research by considering the use of dimensionless hydraulic indices. The influence of discharge on the classification of hydraulic biotopes is recognised as an important aspect of the hydraulic biotope concept. Research described within this report attempts to address this issue.

4.3 THE HYDRAULIC BIOTOPE AND FLUVIAL GEOMORPHOLOGY

4.3.1 Introduction

Many of the hydraulic biotope terms given in the preceding section are related to terminology used to describe morphological features. Pools, riffles and rapids are all cases in point. Through the course of this research it became increasingly clear, however, that both the time scale and space scale over which these features endure differs depending whether one is observing from an ecological or geomorphological perspective.

A morphological unit (*sensu* geomorphology) occurs at the approximate spatial scale of the channel cross-section and is stable over the time span of years or decades. It is either a bedrock or sedimentary feature whose overall form relative to adjacent features determines its classification. Flow hydraulics do not define the feature, but particular patterns of flow are strongly associated with different morphological units. These flow patterns are, however discharge dependent. Thus a riffle is defined as a transverse bar of gravel or cobble with a steep front face. At low discharges the flow over a riffle is relatively fast and shallow, with significant standing waves or white water. The riffle can be clearly distinguished from the tranquil flow through an upstream pool for which the riffle acts as a hydraulic control. As discharge increases the flow velocity in the pool increases, while the proportion of rapid flow initially increases in the riffle. At high discharges the riffle is drowned out and no longer acts as an hydraulic control for the pool. The flow characteristics of the riffle and pool merge, the water surface slope becomes uniform across the two morphological units and there may even be a flow reversal, with faster flow in the pool than the riffle.

A hydraulic biotope is defined in terms of its flow and substrate characteristic. These depend both on the channel morphology and the prevailing flow conditions. For example, within a morphological pool at low discharge the dominant hydraulic biotope will be a pool, with possibly some backwater areas. As discharge increases and velocity increases faster than depth in line with pool hydraulic geometry, much of the pool flow will be converted to run. The case of a riffle is even more complex. At low flows the individual clasts making up the riffle may form local hydraulic controls creating a mosaic of hydraulic biotopes including pools, runs and riffles. As the discharge increases these individual hydraulic controls are drowned out and hydraulic biotopes merge and are transformed from one class to another. At high discharges runs may come to dominate this morphological unit. Thus hydraulic biotopes are discharge dependent and may change over the time span of days to a few hours. Also, one morphological unit may contain several biotopes so that the spatial scale on which they should be measured is much smaller than the morphological unit, in the order of 1 m^2. Hydraulic biotopes can be conceptualised as vertical cells within the flow.

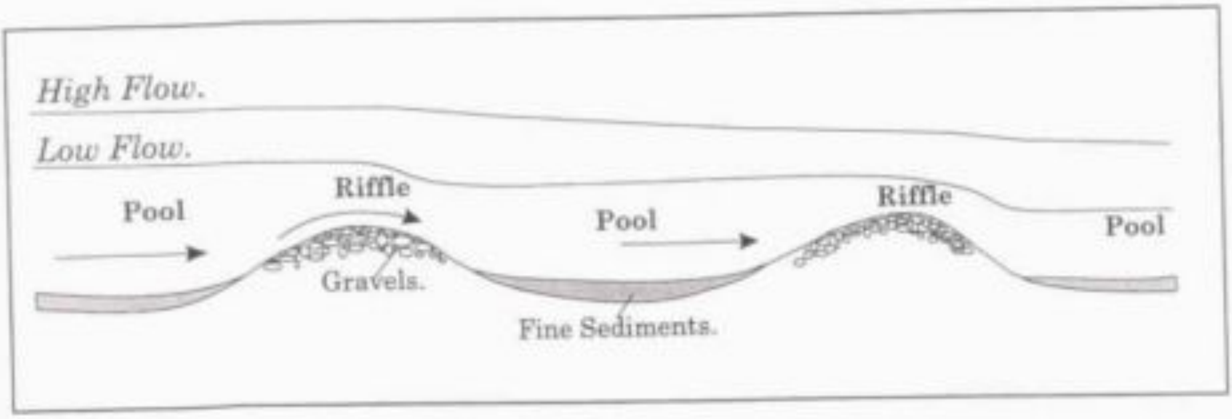


Figure 4.2 Characteristic profile of pools and riffles, showing changes in depth and water surface slope with increasing discharge

n both the ecological and geomorphological literature there has been a tendency not to differentiate between the two groups of features, although, according to the thesis addressed by research presented in this report, morphological units and hydraulic biotopes belong to distinct groups, defined at different spatial and temporal scales. A comparison of habitat terms applied in the ecological literature to morphological units is given in Table 4.6. These habitat terms were explained more fully in section 4.2.3. Because of the widespread application of common terms to both type of feature it is not considered practical to derive a separate terminology for each group as has been recommended by Finlayson (*pers. comm.*). To avoid confusion it is recommended that the morphological units be referred to by the simple morphological name whereas associated instream habitats be described by their hydraulic biotope classes as defined in Table 4.5 and should carry the qualifier 'biotope'.

Table 4.6 Morphological units and their associated hydraulic biotopes

ALLUVIAL CHANNELS

Morphological Unit	Associated hydraulic biotope
Riffle *(Sand and Gravel bed channels)*	**Riffle:** Allen (1951), Harrison and Elsworth (1959). De Leeuw (1981), Grossman and Freeman (1987), Bisson et al. (1988) Boulton *et al.* (1988), Anderson and Morison, King *et al.* (pers.comm. 1992) **Stickle**. Chutter (1970),Allen (1951), Harrison and Elsworth (1959) **Run** Pridmore and Roper (1985).
Pool *(Sand and Gravel bed channels)*	**Pool:** Allen (1951), Harrison and Elsworth (1959), De Leeuw (1981) . Bisson et al. (1988), Anderson and Morison (1989), King *et al.* (pers.comm. 1992) **Backwater:** Anderson and Morison (1989), King *et al.* (pers.comm. 1992) **Run:** Chutter (1970), Allen (1951), Harrison and Elsworth (1959) **Glide :** De Leeuw (1981), Bisson et al. (1988), Anderson and Morison (1989), King *et al.* (pers.comm. 1992) **Flats**. Allen (1951), Harrison and Elsworth (1959)
Step-Pool or Cascade (Boulder bed channels)	**Cascades**: Allen (1951), Harrison and Elsworth (1959), Chutter (1970), Bisson *et al.* (1988), Anderson and Morison (1989) **Waterfalls**: De Leeuw (1981), King *et al.* (pers.comm. 1992)

BEDROCK CHANNELS

Morphological Unit.	Hydraulic Biotope Equivalent.
Waterfall.	**Cascades**: De Leeuw (1981), Bisson *et al.*(1988), Anderson and Morison (1989), King *et al.* (pers.comm. 1992) **Falls:** De Leeuw (1981) **Waterfalls:** .Anderson and Morison (1989), King *et al.* (pers.comm. 1992)
Pool	**Pools:** Allen (1951), Harrison and Elsworth (1959), De Leeuw (1981), Bisson *et al.* (1988), Anderson and Morison (1989), King *et al.* (pers.comm. 1992) **Run :** Allen (1951), Chutter (1970), King *et al.* (pers.comm. 1992) **Glide**: De Leeuw (1981), Bisson *et al.* (1988) **Cascade:** Bisson *et al.* (1988)
Step-Pool or Cascade (bedrock)	**Cascades**: Allen (1951), Harrison and Elsworth (1959), Chutter (1970), De Leeuw (1981), Bisson *et al.* (1988), Anderson and Morison (1989) **Waterfall**: De Leeuw (1981), King *et al.* (pers.comm. 1992)
Rapid	**Cascade**: Allen (1951), Harrison and Elsworth (1959), Chutter (1970) **Rapids**: Anderson and Morison (1989), King *et al.* (pers.comm.1992) **Chutes:** .King *et al.* (pers.comm.1992)

NB: The list of morphological units given above is far from comprehensive. Reference is made to the most commonly recognised units to demonstrate the potential relationship between morphological units (which occur at the transect scale) and hydraulic biotopes (which occur at the point scale). A more comprehensive list of the morphological units encountered during the course of this research is given in Chapter 3.

4.3.2 Morphological units, associated hydraulic biotopes and ecological significance

Morphological units were discussed in some detail in Chapter 3 within two geological settings, namely alluvial and bedrock channels. This same structure will be retained here in order to consider the relationship between the morphological unit and the hydraulic biotope. Different morphological units have characteristic groups of hydraulic biotopes associated with them. These will be described below for a number of alluvial and bedrock features. Except where specified, the association will be that observed at baseflow conditions as these by definition are those most frequently experienced.

Alluvial channels

Three general classes of alluvial channels are recognised - sand bed, gravel bed and boulder bed channels. These were described in Chapter Three. Each of these channel types has a different association of hydraulic biotopes.

Sand beds

Three distinctive hydraulic biotopes which are regularly associated with sand bed channels are *pools*, which tend to occur on the outside of meander bends, *runs or glides*, which occur as a result of shallower flow over sediment deposits, and *riffles*, which tend to be a result of transverse deposition of somewhat coarser sediment (Wadeson, 1996).

River ecologists have paid little attention to sand bed rivers because their lack of physical diversity can be associated with poor species diversity (Hynes,1970). As explained by Church (1992), the centre of a sand bed channel may be a hostile environment, where high sediment transport maintains a homogeneous substrate and high velocities extract large energy tolls on benthic organisms. These hydraulic conditions were observed by the authors in the Olifants River, Western Cape (Wadeson, 1996). If flow occurs within riparian vegetation along the channel margin, it may provide a more favourable hydraulic environment and provide food and refuge. Biotopes associated with fringing vegetation are more important than hydraulic biotopes in sand bed rivers (Chutter, pers. comm).

Gravel beds

Gravel bed rivers are characterised by distinct pool and riffle morphology, which is probably the morphological sequence most often referred to in the ecological literature. The sequence of hydraulic biotopes associated with these morphological features has been described above (Section 4.3.1). It should be noted that ecologists often group all hydraulic biotopes/morphological features associated with rough water, especially riffles and rapids. These two features, however have very different substrates and provide different habitat in terms of bed stability, bottom conditions and cover so should be clearly separated.

Cobble and boulder beds

The dominant morphological units associated with large cobble / boulder channels are the step-pools of Grant *et al.* (1990). Hydraulic biotopes that have been associated with these morphological unit are pools, rapids and cascades. It should be noted that the geomorphological terms rapid and waterfall are more generally associated with features in bedrock channels, where they are formed as a result of gradient and geology. It is recommended, therefore, that the term cascade rather than waterfall be retained for hydraulic biotopes associated with step features in cobble and boulder beds.

When channels are dominated by step-pool morphology they are considered as 'small channels' (Church, 1992) and to have limited fishery value (in North America), because they are too steep to be colonised and often lie beyond impassable barriers. An argument in favour of the fishery value of these features in South Africa is that they may house small pockets of endemic fish species which are protected from alien predator species, such as trout and bass, which cannot overcome the obstacles stated above. These bedform features may be very important for invertebrate production and for the recruitment of organic material (Church, 1992).

Plane beds are also common in wider, lower gradient cobble and boulder channels. Runs and glides tend to dominate this morphology at low to medium flows, with slack water forming along the channel margins and in the lee of boulders or large cobbles. Riffles, chutes and cascades may all occur locally.

Bedrock channels

Bedrock channels contain a number of morphological units as listed in Table 4.6. These units differ from those found in alluvial channels due to the fixed nature of the substrate and the erosional nature of many of the features. Geology plays a strong role in determining the effect of flow on channel form. Cover for benthic organisms depends on the degree of fracturing in the rock, development of erosional forms such as potholes and cups, or the presence of a fine layer of coarse sediment. Where weathering rates are high rock debris often collects immediately downstream of waterfalls or cataracts.

Hydraulic biotopes associated with bedrock features are probably more varied than is the case for alluvial features. Pools, runs and backwaters are all common, glides occur over bedrock pavement, whilst chutes, rapids and cascades are associated with steeper or more broken sections. Riffle flow will only occur over local accumulations of coarse debris.

4.4 CONCLUSIONS

The term 'hydraulic biotope' is suggested as a more appropriate term than 'habitat', for the description of ecologically significant instream flow environments. A distinction is made between these temporally unstable features and the more stable channel form features recognised in fluvial geomorphology. A standardised terminology is introduced to describe the more common hydraulic biotope classes observed in South Africa. The problem of a standardised objective technique for biotope classification is addressed and a possible solution presented in the form of the hydraulic biotope matrix. It is envisaged that the biotope matrix will provide the impetus for the further development of a more rigorous technique.

An examination of the definition of geomorphological units and their associated biotopes shows that although there is often a coincidence of geomorphological and ecological terminology there are also significant discrepancies. Geomorphologists are concerned with broad scale features defined in terms of gross structure and form, which ecologists further subdivide on the basis of flow hydraulics and substrate availability. The subdivision of geomorphological pools into pool and run hydraulic biotopes is a good example of this.

Ecologists not only subdivide morphological features into smaller spatial units, but also recognise temporal changes in biotope definitions because of biotic response to changes in physical conditions. To a geomorphologist a pool-riffle sequence remains as such regardless of flow discharge. The biotope associated with each morphological unit may change as discharge changes. For example a pool with low flow velocities during base flow conditions may become a run as velocities increase during a flood event. Similarly riffles may be converted to runs as they are drowned out during high flows.

An important distinction made by geomorphologists, but not explicitly recognised by ecologists, is that between alluvial and bedrock features. The form and spatial distribution of alluvial features are closely related to discharge patterns and sediment supply so that upstream developments which alter these will also impact on the morphological units. In contrast, bedrock features, which are strongly controlled by the resistance of the geological strata and the long term erosional history of the river, respond more slowly and in a less predictable way to such disturbances. As ecologists become more concerned with the impact of channel change on the available in-stream environment it is important that they distinguish hydraulic biotopes hydrolic in terms of their likely response to change. The distinction between an alluvial riffle and a bedrock rapid therefore should be of significance to both geomorphologists and ecologists.

Plate 4.1 Backwater hydraulic biotope

Plate 4.2 Slack water hydraulic biotope

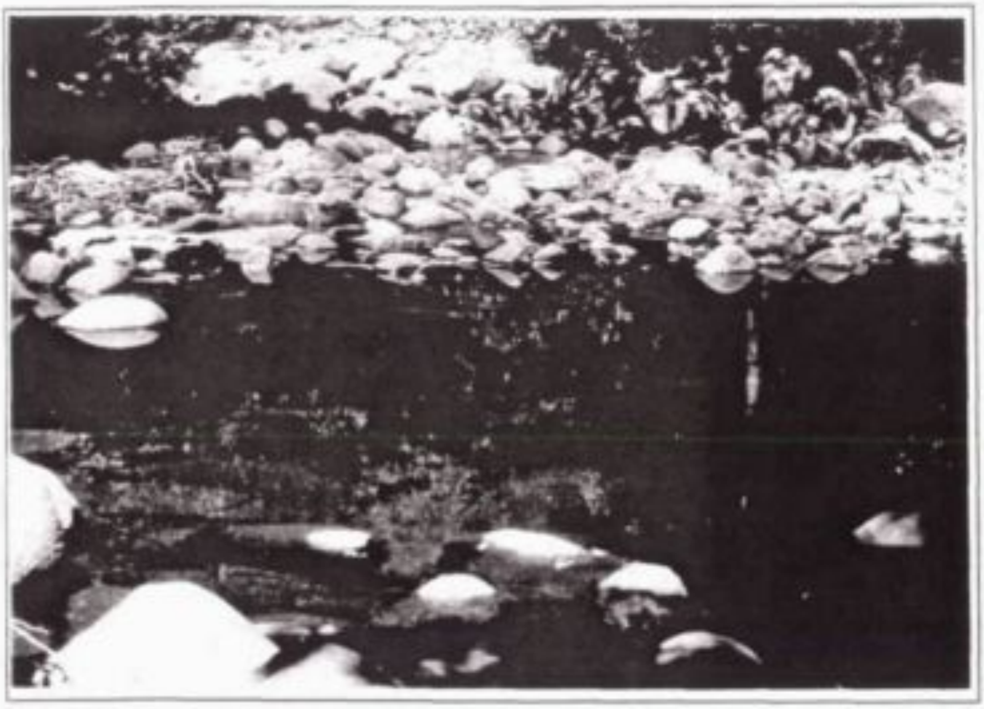


Plate 4.3 Pool hydraulic biotope

Plate 4.4 Glide hydraulic biotope

Plate 4.5 Chute hydraulic biotope

Plate 4.6 Run hydraulic biotope

Plate 4.7 Riffle hydraulic biotope

Plate 4.8 Rapid hydraulic biotope

Plate 4.9 Cascade hydraulic biotope

Plate 4.10 Waterfall hydraulic biotope

CHAPTER FIVE

FLOW HYDRAULICS AND THE INSTREAM FLOW ENVIRONMENT

5.1 INTRODUCTION

The hydraulic biotope has been defined as a spatially distinct instream flow environment, characterised by specific hydraulic and substrate attributes. It is appropriate, therefore, to consider the hydraulic relationships which determine hydraulic biotope characteristics, their measurement and derivation of hydraulic indices. The following review represents an examination of the hydraulic literature relating to the flow of water in open channels. This review is largely modelled on the seminal engineering texts of Chow (1959) and Henderson (1966), together with the ecological interpretations of Davis & Barmuta (1989) and Gordon *et al.* (1992). Before starting this review it is appropriate to heed the words of Simon (1981, preface) who eloquently describes some of the shortcomings of engineering hydraulics.

> "During the past century enormous progress has been made in the understanding of the fundamental laws of the mechanics of fluids. Powerful mathematical techniques are now available for putting these fundamental principles into practice. Yet, most practical hydraulics problems still defy these theoretical solutions. Practical hydraulics is perhaps as much an intuitive art as a science.
>
> One of the reasons for the theoretical uncertainty of hydraulics is the large number of ill-defined variables that enter into even some of the simplest practical problems. The often unknown interdependence of these pertinent variables makes it impossible to develop reliable answers on the basis of fluid mechanics principles alone. Therefore to consider hydraulics as simply experimental fluid mechanics is a faulty oversimplification.
>
> ...without a judicious dose of hydraulic uncertainty, fluid mechanic principles lend themselves to endless theoretical refinements. With increasing theoretical complexity goes an impression of increasing precision and accuracy. Then, with the manipulative perplexities resolved, the student may have a false impression of understanding".

Paying heed to the above words of caution, this review attempts to provide essential information for the practical description and simplification of highly complex, indescribable, real world hydraulics as they can be applied to the scale of the hydraulic biotope.

With few exceptions, a study which deals with the movement of water within natural channels is dealing with flow conditions in open channels as opposed to pipe flow. The concepts relating to flow in channels with a free surface are the most complex of the science of hydraulics. The primary difference between pipe flow and open channel flow is that in open channels the cross sectional area of the flow is variable and depends on many other parameters of the flow. In general the treatment of open channel flow is somewhat more empirical than that of pipe flow (Chow 1959).

5.2 THE MACRO ENVIRONMENT

5.2.1 Definitions

Before discussing some of the theory and parameters necessary to describe flow hydraulics, a brief definition and description of the most commonly used terms in stream hydraulics is given following those of Gordon *et al.* (1992).

Depth (d):	the vertical distance between the water surface and the streambed.
Stage (y):	the vertical distance from some fixed datum to the water surface.
Discharge (Q):	the volume of water passing through a stream cross section per unit time.
Top width (W):	the width of the stream at the water surface.
Cross sectional area (A):	the area of water across a given section of the stream.
Wetted perimeter (P):	the distance along the stream bed and banks at a cross section where they contact the water.
Hydraulic radius (R):	the ratio of the cross sectional area to the wetted perimeter $R = A/P$.
Hydraulic depth (D):	the ratio of the cross sectional area to the top width $D = A/W$. In streams which are very wide in relation to depth (a width-to-depth ratio of about 20:1 or more) the hydraulic radius and hydraulic depth are almost equal and approximate the average depth of the stream (Gordon *et al.* 1992).
Velocity (V):	the rate of movement of a fluid particle
Shear velocity (V_*):	a measure of shear stress (force acting parallel to the flow).
Kinematic viscosity (ν):	the ratio of dynamic viscosity to density

5.2.2 Velocity

Velocity may be defined as the rate of movement of a fluid particle from one place to another. It varies in a natural channel with both space and time and the average cross-section velocity may be simply calculated as $V = Q/A$.

Velocity tends to increase as slope increases and\or as bed roughness decreases. The frictional resistance imposed on flow near a streambed, streambank and near the surface retards velocity. The frictional resistance, together with turbulence, causes variations in the distribution of velocity with time, depth, across a section, longitudinally and spirally.

Variation with time

Flow velocities at any point in a stream fluctuate rapidly because of surges and turbulent eddies, this turbulence may have profound implications for the organisms living within it. Morisawa (1985) noted that fluctuations in velocity often appear to have a cyclical or "pulsing" pattern, rather than a random trend. This means that the most common method of measuring velocity at a point using a current meter, is actually a time averaged value.

Velocity will also change in response to changing discharge. This property is most commonly dealt with under the heading hydraulic geometry. Hydraulic geometry describes the way in which depth, width and mean velocity vary with discharge (Leopold & Maddock 1953; Chapter 3, Equations 3.7a, b & c). How these variables change with discharge at a particular location is determined by the shape of the channel at that location ("at-a-station"). In a narrow, bedrock channel, velocity will increase quickly as discharge increases, this is in contrast to a slower increase in velocity if the channel is alluvial, shallow and wide.

Variation with depth

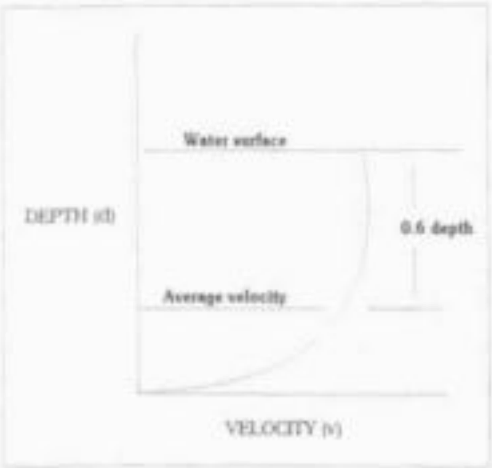
If a number of velocities are measured at different depths above a point in the channel they can be plotted against one another to show the vertical velocity profile. This velocity profile may be influenced by the channel shape, bed roughness and the intensity of turbulence.

In a "typical" velocity profile (Figure 5.1a), maximum velocity tends to occur just beneath the water surface. The depth of this maximum velocity varies with the proximity of the measuring site to the streambank. The closer one is to the channel margin, the deeper is the maximum velocity (Chow, 1959). Surface velocities, and hence the shape of the velocity profile, may be influenced by resistance with air and\or floating vegetation.

In the centre of broad rapid streams the velocity profile may show the maximum velocity at the free surface (Figure 5.1b). As explained by Morisawa (1985), mean velocity in a cross section varies inversely as the depth. This means that as the water gets shallower, the position of the maximum velocity is lowered beneath the surface.

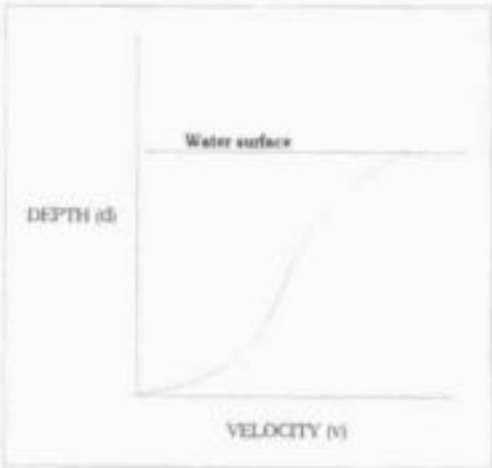
When the depth of "roughness elements" such as rocks, boulders, plants, woody debris, etc. is high in relation to the depth of water, water velocities within and above the protrusions become highly variable. Jarrett (1984) demonstrated this phenomena in shallow, steep cobble and boulder - bed streams in mountainous areas where S shaped velocity profiles (Figure 5.1c) are sometimes apparent.

If the velocity varies logarithmically with distance from the stream bed, it can be demonstrated mathematically that the mean value of velocity, v, occurs at about 0.6 of the water depth measured downwards from the water surface. This is the point at which velocities are measured if only one reading is taken (Gordon *et al.*, 1992).



a) A 'typical' velocity profile

b) Velocity profile of a broad, rapid stream



c) Velocity profile of a shallow, steep mountain stream

Figure 5.1 Characteristic velocity profiles

Variation across a section

Velocities tend to increase towards the centre of a stream and decrease towards the perimeter because of frictional resistance at the bed and banks. Isovels, lines joining points of equal velocity, can be plotted as a map of a stream cross section. Where isovels are close together, velocity gradients, and thus shear stresses are higher. This situation is common towards the outer bank of a river at a bend.

Longitudinal variation

Patterns of velocity variation can be shown within a channel section by plotting mean vertical or surface velocity isovels. These plots can give an indication of velocity variability down a channel and can be useful to identify such things as potential areas for bank erosion or available habitat for a particular species.

Spiral flow variation

Spiral flow is a consequence of frictional resistance and centrifugal force. In a stream, water is hurled against the outside banks at bends, causing the water surface to be "super-elevated". This increase in elevation causes a gradient, promoting flow movement from the outer to the inner bank. A spiralling motion is generated along the general direction of flow (Petts & Foster, 1985). Compared to the forward, downstream currents, secondary lateral and vertical currents are relatively small, yet they cause the mainstream current to vary from a predictable course and contribute to energy losses and bank erosion at bends (Gordon *et al.*, 1992). Spiral flow will affect hydraulic biotope characteristics as well as movement of food particles as drift.

Velocity measurements

A current meter such as the Price type AA is the most commonly used instrument to measure water velocity in South Africa, and was the instrument used in this research. This current meter only measures the velocity of water at a specific point. The method of calculating hydraulic indices at a point involves the determining of the average velocity within a column of water above that point, this cannot be easily deduced from a single point velocity (Roux, 1991). The most accurate method to determine the average velocity within a vertical column of water is to measure velocity at a number of points. Average velocity may also be approximated by measuring velocity at only a few points (or only one point), and then using a known relation between those velocities and the average velocity in the vertical.

The two-point method of measuring velocity is relatively easy and accurate (within 1% of the true mean if the vertical velocity curve is parabolic in shape (Roux, 1991), but can be time consuming. This method requires the measurement of velocities at 0.2 and 0.8 depth below the water surface. This method is not suitable for depths less than 0.75 metres because the flow meter is too close to both the water surface and the stream bed to give accurate results. It is important to note that the velocity profile may be distorted by overhanging vegetation in contact with the water and submerged objects; these features make this technique unreliable and require the addition of a third measurement at 0.6 depth from the water surface. This is an extremely time consuming technique and still requires an adequate depth of water (> 0.75m).

An alternative technique is the six-tenths depth method which requires a single velocity measurement at 0.6 depth from the water surface. This technique is generally used when water depth is between 0.1m and 0.75m and when time constraints are an issue. Although this technique is not as accurate as a multiple point or two and three point method it is frequently the only option.

5.2.3 State of flow

The behaviour of open channel flow is governed basically by the effects of viscosity and gravity relative to the inertial forces of the flow.

Viscosity

Viscosity relates to how rapidly a fluid can be "deformed" and is temperature dependent, with cold water being more viscous than warm water. Depending on the effect of viscosity relative to inertia, the flow may be laminar, turbulent or transitional. Flow is *laminar* if the viscous forces are so strong relative to the inertial forces that viscosity plays a significant part in determining flow behaviour. In streams, laminar flow may exist as a thin coating over solid surfaces, or where flow moves through the small openings between rocks in a streambed and through dense stands of aquatic weeds. Here the fluid moves in parallel "layers" which slide past each other at differing speeds but in the same direction.

Flow is *turbulent* if the viscous forces are weak relative to the inertial forces. In turbulent flows the water particles move in irregular paths which are neither smooth nor fixed, but which in the aggregate still represent the forward motion of the entire stream. Turbulent flow can only be defined statistically as the average conditions expressed by millions of water molecules (Gordon *et al.*, 1992). Turbulence occurs at all scales, with eddying at one scale causing eddying at other scales.

Viscosity is an important factor in laminar flow, but becomes relatively insignificant in turbulent flows. Viscosity tends to dampen turbulence and promote laminar conditions. Acceleration has the opposite effect, promoting instability and turbulence. The resistance of an object or fluid particle to acceleration or deceleration is described by a measure called inertia. This is the tendency of an object to maintain its speed along a straight line. It is what keeps a particle of fluid going until it is "aggressed upon by an external authority" (Vogel, 1981, p67). Hence high inertial forces promote turbulence, high viscous forces promote laminar flow. The ratio of inertial forces to viscous forces thus gives an indication of whether the flow is laminar or turbulent.

The effect of viscosity relative to inertia can be represented by the *Reynolds number*. It is defined as:

$$Re = VL/v \qquad \textit{Equation 5.1}$$

where V = velocity ($m.s^{-1}$), L = characteristic length (m) considered to be equal to the hydraulic radius (R) or to cell depth (d), v = the kinematic viscosity of water ($m^2.s^{-1}$)

In an investigation of the transition between the two types of flow, Reynolds found that the flow always became laminar when the velocity was reduced so that Re dropped below 2000. This point of transition is called the critical Reynolds number . From experimental data, the transitional range of Re for open channels is usually considered to be 500 - 2000, flow being either laminar or partly turbulent (Chow, 1959).

As indicated by Gordon *et al.* (1992), low Reynolds number conditions are of little interest to engineers but appear to be highly significant for bacteria or protozoans or other microscopic organisms which, because of their small "characteristic lengths", operate at the Reynolds numbers in the range of 10^{-4} to 10^{-5} (Purcell 1977). Here inertia is irrelevant in comparison to viscosity and movement stops immediately when propulsion ceases. The advantage of life at low Reynolds number is that the organism is protected from the action of turbulence by a thick "coating" of highly viscous fluid. This may have certain disadvantages in that mixing is impeded and, therefore, so too is the transport of energy, nutrients and gases to an organism, and the transport of wastes away from it.

Aquatic invertebrates may experience "the best of both worlds", both laminar and turbulent flow. *Laminar flow* may exist in streams as a laminar sublayer (to be discussed). Statzner (1988) points out that some aquatic invertebrates start life at Reynolds number of about 1 - 10 in the laminar layer, but when they reach their adult form, they may live in conditions of Re = 1000 or higher in the turbulent flow.

Gravity

The effect of gravity upon the state of flow is represented by a ratio of inertial forces to gravity forces. This ratio is given by the *Froude number* (Fr) which has been described by Henderson (1966, p39) as a "Universal indicator of the state of affairs in free surface flow".

The Froude number is defined as:

$$Fr = V/\sqrt{gL} \qquad \textit{Equation 5.2}$$

where V is the mean velocity ($m.s^{-1}$), g is acceleration of gravity ($m.s^2$), L is characteristic length (m) which is often taken as hydraulic depth (D) or cell depth (d)

If critical flow can be located in a stream, the flow rate can be determined from the critical depth (d_c) yielding the equation:

$$V_c/\sqrt{gd_c} = 1 \qquad \textit{Equation 5.3}$$

From this three flow classes can be designated.

Fr < 1 is subcritical (or slow or tranquil) flow

Fr = 1 is critical flow

Fr > 1 is supercritical (or fast or rapid) flow

If the Froude number is less than unity, the role played by gravity forces is more pronounced, so that flow has a low velocity relative to depth and is often described as tranquil or streaming. If the Froude number is greater than unity, the inertial forces become dominant so that flow has a high velocity relative to depth and is often described as rapid, shooting or torrential.

In the mechanics of water waves, the critical velocity $\sqrt{gd}$ represents the speed of a small wave on the water surface relative to the speed of the water, called wave celerity. At critical flow the wave celerity is equal to the flow velocity. Any disturbance to the surface will remain stationary. In subcritical flow the flow is controlled from a downstream point and any disturbances are transmitted upstream. By comparison, supercritical flow is controlled from an upstream point and any disturbances are transmitted downstream.

The direction of wave propagation can be used to locate regions of subcritical, critical and supercritical flow in a stream (Gordon *et al.*, 1992). An object contacting the water surface will generate a V pattern of waves pointing downstream. If the flow is subcritical, waves will appear upstream of this object, whereas they do not appear when the flow is supercritical.

In streams, most of the flow will be subcritical; supercritical flow can be found where water passes over and around boulders, and in the spillway chutes of hydraulic structures. Usually it is accompanied by a quick transition back to subcritical flow (a hydraulic jump), which appears as a wave on the water surface.

The Froude number is gaining acceptance as an index for characterising local scale habitats (Wetmore *et al.*, 1990, Jowett, 1993; Wadeson, 1994). It has been recognised as a criterion to distinguish between pools and riffles (Wolman, 1955; Bhowmik & Demissie, 1982); its potential utility as a hydraulic biotope descriptor has been demonstrated firstly by the similarity of the Froude numbers calculated for like habitats described in studies by Allen (1951), Jowett (1993) and Wadeson (1994) and secondly by its relationship to benthic invertebrate abundance for some species (Orth & Maughan, 1983; Jowett *et al.*, 1991; Jowett, 1993; Emery, 1994). A particular feature of the Froude number is that, being based on the ratio of velocity to depth, it is independent of scale so that large and small features classify together if bulk flow conditions are similar. In contrast, the Reynolds number, based on the product of depth and velocity, is scale dependent and therefore incorporates the magnitude of hydraulic variables.

5.2.4 Regimes of flow

The combined effect of viscosity and gravity may produce any one of four regimes of flow in an open channel.

1) Subcritical-laminar : where Fr is less than 1 and Re is in the laminar range.
2) Supercritical-laminar: when Fr is greater than 1 and Re is in the laminar range.

3)	Supercritical-turbulent:	when Fr is greater than 1 and Re is in the turbulent range.
4)	Subcritical-turbulent:	when Fr is less than 1 and Re is in the turbulent range.

The first two regimes are not commonly encountered in applied open channel hydraulics, since the flow is generally turbulent in the channels considered in engineering problems. However these regimes occur frequently where there is very thin depth - this is known as sheet flow.

5.2.5 Types of flow

Figure 5.2 presents a summary of the different types of flow:

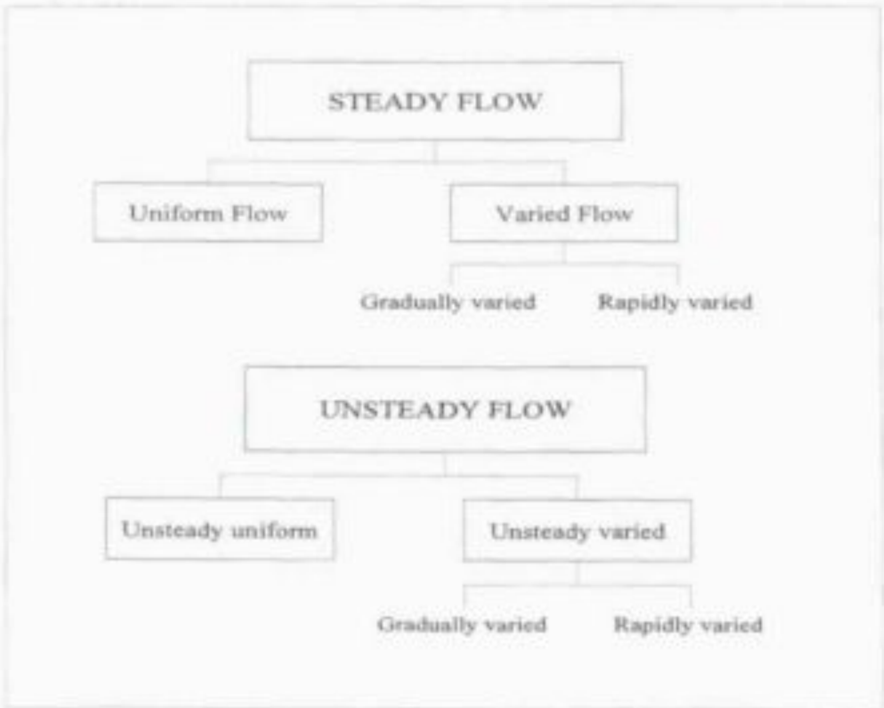


Figure 5.2 Summary diagram of different flow types

Steady and unsteady flow

Flow is said to be steady or unsteady depending on how it behaves over time. Flow is said to be steady at a point if the depth and velocity of flow do not change or if they can be assumed to be constant during the time interval under consideration. This assumption is necessary for the study of most open channel problems. Although turbulence causes the velocity to continuously fluctuate throughout most of the flow, it can be considered steady if values fluctuate equally around some constant value (Smith, 1975).

The flow is unsteady if the depth changes with time, for example when waves or eddies travel past the point and the water level and/or velocity change from one moment to the next, a common occurrence as storm events cause discharge to rise and fall in channels.

Uniform flow and varied flow

"Open channel flow is said to be uniform if the depth and velocity of flow remain constant over some length of channel of constant cross section and slope" as shown in Figure 5.3 (Gordon *et al.*, p 266, 1992). Uniform flow may be steady or unsteady depending whether or not the depth changes with time. The assumption of steady uniform flow conditions considerably simplifies the analysis of water movement in streams (Gordon *et al.*, 1992). Since unsteady uniform flow is rare, the term "unsteady flow" is used to designate unsteady varied flow exclusively.

Varied flow may be further classified as either rapidly or gradually varied (Gordon *et al.*, 1992). If the depth changes abruptly over a relatively short distance as at a bedrock step, the flow is rapidly varied; when changes are more widely spread as in a pool, the flow is gradually varied.

In *gradually varied flow*, depth, area, roughness, and/or slope change slowly along the channel. A mathematical description of the water surface shape can be derived from principals of energy and continuity. The standard step method which requires an iterative solution is most commonly used and is described by Chow (1959) and Henderson (1966).

Rapidly varied flow occurs over relatively short lengths of channel and it is typically a location of high energy loss. Examples are hydraulic jumps, where the flow changes from supercritical to subcritical, and hydraulic drops, where the reverse occurs.

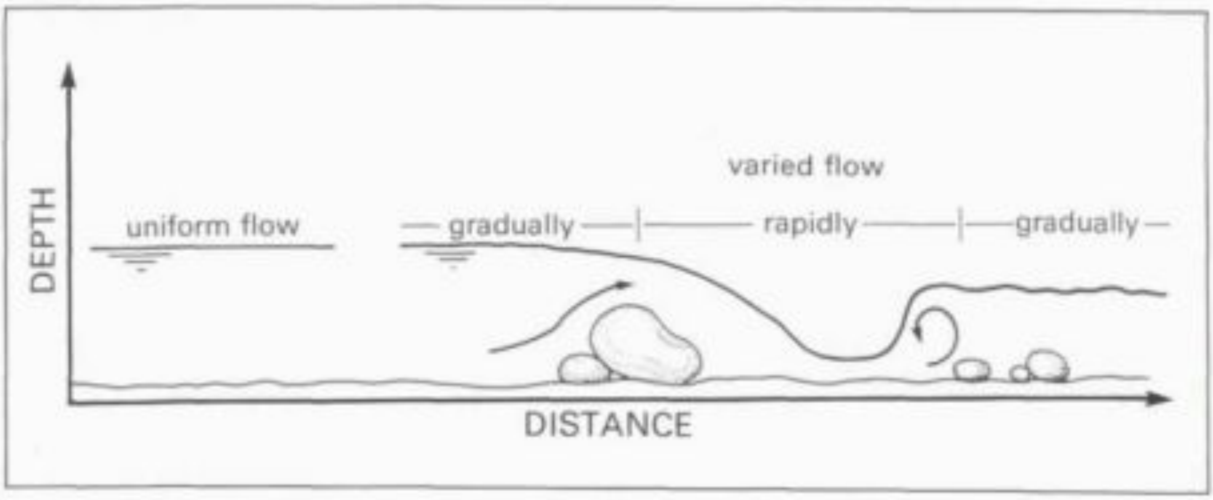


Figure 5.3 Classification of open channel flow.

Hydraulic drops occur where flow accelerates - for example as it passes over an obstacle, through a passage, or from a mild slope to a steep slope. Hydraulic jumps take place where upstream supercritical flow meets subcritical flow, such as at the downstream side of large boulders, below narrows created by rock outcrops or where the slope changes from steep to mild. Because of the sudden reduction in velocity, hydraulic jumps are associated with highly turbulent conditions, whitewater and large losses of energy. Since they are such effective energy dissipaters they are often encouraged in the design of spillway chutes and structures for dissipating the erosive power of water. This also explains the high degree of energy dissipation observed in rocky headwater channels. Fish often capitalise on the backflow in the standing waves of hydraulic jumps to give them a boost upstream (Hynes, 1970).

The length of flow affected by the hydraulic jump ranges from four to six times the downstream depth. Its appearance is influenced primarily by the upstream Froude number, with the channel geometry having a secondary effect. Froude numbers can serve as a basis for classifying hydraulic jumps (White, 1986): it should be noted that hydraulic jumps are not possible if the upstream flow is subcritical (Froude >1).

Froude 1.0 - 1.7	= Standing wave or undular jump.
Froude 1.7 - 2.5	= Weak jump.
Froude 2.5 - 4.5	= Oscillating jump (unstable).
Froude 4.5 - 9.0	= Steady jump (stable).
Froude > 9.0	= Strong jump.

Flow in natural channels is typically varied, unsteady, turbulent and subcritical. Uniform, steady and laminar conditions, however, are often assumed in order to simplify the equations which describe flow. The various categories are useful for classifying the flow environments experienced by aquatic organisms, and they give insight into the usefulness and limitations of equations which have been based on theoretical definitions of flow conditions. The theory of open channel flow assumes flow in channels with constant cross section and slope (prismatic). We need to be aware of words of caution from Chow (1959, p 72) "In applying the theory to irregular natural channels we are stretching thin the boundaries of truth and must interpret results with judgement and caution".

5.3 THE MICRO ENVIRONMENT

5.3.1 The Boundary Layer

The term "boundary layer" was originally coined in 1904 by Ludwig Prandtt, a German engineer. The term refers to the area of influence that a solid surface has on the fluid that comes into contact with it. In a stream the boundary layer caused by the presence of the stream bed extends to the water surface. Within this, smaller boundary layers exist on the surface of rocks or snags, fish or aquatic insects; in fact, many organisms live within the boundary layer of other organisms. The boundary layer is therefore difficult to delimit. As Vogel (1981, pp 129) says "most biologists seem to have heard of the boundary layer, but they have the fuzzy notion that it is a discrete region rather than the discrete notion that it is a fuzzy region".

The classic engineering approach to boundary layer theory is to first discuss the development of boundary layers in the simplest case of flow around a smooth, sharp nosed, flat plate oriented into the flow. The distribution of velocity and shear stress around the plate are influenced both by the nature of the flow: whether laminar or turbulent, and the nature of the solid: whether rough or smooth. Although flat plates may not have any ecological significance, the relationships developed are useful in describing the patterns of velocity near surfaces within streams.

On a sharp, flat plate oriented into the flow, the boundary layer begins at its leading edge (Figure 5.4). A stagnation point occurs at this leading edge, where the velocity of the oncoming flow is zero. Downstream for some distance, the flow across the plate is laminar. As the fluid moves further along the plate, layers are slowed down and the laminar layer grows. The thickening of the laminar boundary layer continues until the thickness is so great that the flow becomes unstable and deteriorates into turbulence. The transition point occurs at some critical value of Reynolds number given by most authors as Re = 500 000

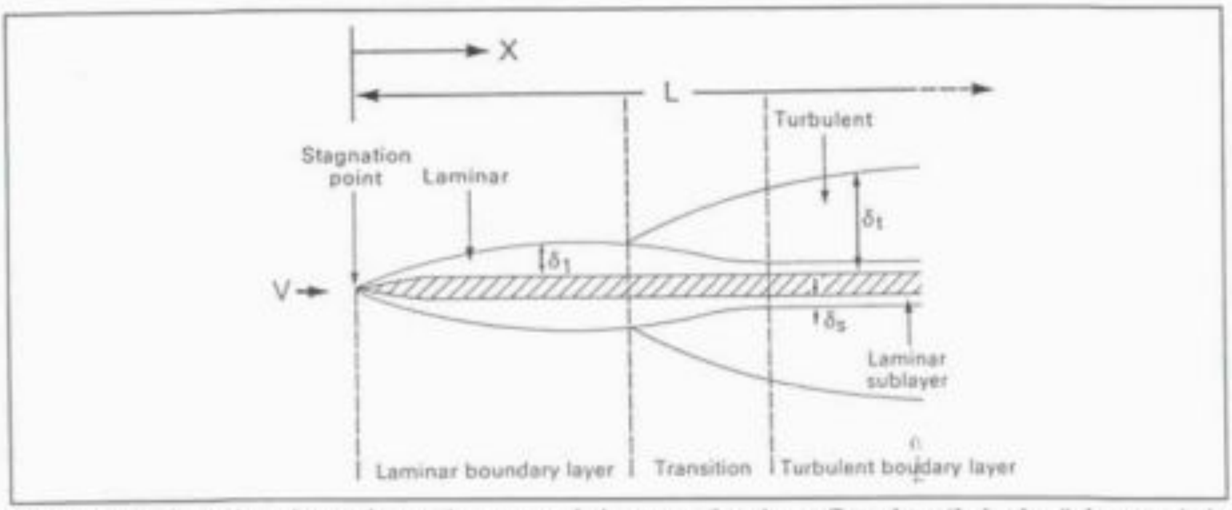


Figure 5.4 Boundary layer formation around the top of a sharp flat plate (L is the "characteristic length", V is the approach velocity, x the distance from the leading edge and δ the boundary layer thickness (for l, laminar; t, turbulent and s, viscous sublayer regions). From Gordon *et al.* (1992).

In the turbulent region the boundary layer grows more rapidly than the laminar layer. In the turbulent region a very thin layer of laminar flow still exists near the solid surface. This layer is called the laminar sublayer or viscous sublayer. This model of boundary layer phenomena is only valid under specific conditions; when the approaching flow is laminar or the plate itself is moving through still water and the plate itself is smooth. If the oncoming flow is turbulent or the leading edge of the plate is rough, turbulence will set in much sooner.

"Life in the boundary layer" usually refers to the organisms which live in the relatively slower velocity region of flow near solid surfaces such as the surface of rocks or the leaves and stems of aquatic plants (Gordon *et al.*, 1992). The rest of this chapter considers those indices which are commonly used to characterise flow conditions experienced close to the channel bed, within or close to the region of the boundary layer.

5.3.2 Shear Velocity

Velocities near the stream bed are much lower than those in the water column because of the frictional effects of the stationary bed. Shear stresses at the stream bed are high and the parameter of interest to stream ecologists is the shear velocity (V_*). Shear velocity V_* can theoretically be estimated using the following equation:

$$V_* = \sqrt{gds} \qquad \textit{Equation 5.4}$$

where: g = acceleration due to gravity, d = depth, s = slope of the water surface.

In practice the calculation of shear velocity at a point, using this equation, is very difficult because of the problem or measuring water surface slope at the scale of the hydraulic biotope..

An alternative method is to derive shear velocity from the velocity profile obtained from field measurements where

$$V_* = \frac{5.75}{\tan\alpha} \quad \text{and} \quad \tan\alpha = \frac{V_1 - V_2}{\log Z_1 - \log Z_2} \qquad \textit{Equation 5.5}$$

V_1 = velocity at depth Z_1, and V_2 = velocity at depth Z_2 (the slope of the logarithmic profile : Smith, 1975)

This method works reasonably well in relatively deep water and where a log linear velocity profile can be assumed. Where flows are shallow, or a high bed roughness distorts the velocity profile, this method is no longer applicable.

A third method was proposed by Smith (1975) for use where Equation 5.4 or 5.5 are inapplicable. Required measurements are the mean velocity (v), depth (d) and height of the substrate element (k) to be known.

$$V_* = \frac{v}{5.75 \times \log(12.3d/k)}$$ (Smith, 1975) *Equation 5.6*

Smith (1975) indicates that the value of relative roughness (depth relative to the height of the substrate element) varies from more than 0.2 for a shallow stream flowing over a shingle bed to less than 0.0002 for a deep flow over fine clay sediments. Thus, in rocky streams, the shear velocity is approximately 1/10 of the mean velocity but in sandy streams only about 1/30 of the mean velocity (Davis & Barmuta, 1989).

This method of calculation was considered to be the most appropriate for the research carried out in this project because of the problems of shallow water and highly variable bed topography.

5.3.3 The Laminar sublayer

The *thickness of the laminar sublayer* (δ), the region close to the bed where flow is entirely laminar, can be obtained from the expression:

$$\delta = 11.5\ v / V_*$$ *Equation 5.7*

where v is kinematic viscosity
V_* is shear velocity.

The height of roughness elements (k) relative to the thickness of the laminar sublayer is an important determinant of flow conditions near the bed. Conditions are considered to be hydraulically smooth when $k < \delta$ and hydraulically rough when $k > \delta$ (k is the roughness height and δ is the thickness of the laminar sublayer).

5.3.4 Concepts of Surface Roughness

In engineering fluid mechanics the very existence of the laminar sublayer is dependent upon how rough the surface is. A surface is said to be hydraulically smooth if all the surface irregularities are so small that they are totally submerged in the laminar sublayer. If the roughness height extends above the sublayer it will have an effect on the outside flow, and the surface is said to be hydraulically rough. Hydraulically rough conditions will be most prevalent in streams. However where the surface irregularities become very small in comparison to the water depth, hydraulically smooth flow can occur. The effective height of the irregularities forming the roughness elements is called the roughness height (k). The ratio of the roughness height to the hydraulic radius (k/R) is known as the relative roughness (Rrel).

$$Rrel = k/R$$ *Equation 5.8*

A *'roughness' Reynolds number* (Re_*) can be developed using shear velocity (V_*) and the roughness height (k).

$$Re_* = V_* k / v$$ *Equation 5.9*

V_* is a measure of shear stress expressed in velocity units ($m.s^{-1}$)

A surface is considered hydraulically smooth if $Re_* < 5$, hydraulically rough if $Re_* > 70$, and transitional at $5 < Re_* < 70$ (Schlichting, 1961). Thus, the flow near a solid surface will be disturbed if either (1) the roughness elements increase in height or (2) the velocity increases, causing the laminar sublayer to become smaller than the height of the projections. Davis and Barmuta (1989) state that the 'roughness' Reynolds number appears to be an excellent habitat descriptor since it combines the effects of velocity and substrate type.

5.3.5 Spacing of Roughness Elements

As indicated by Davis and Barmuta (1989) there is not necessarily a correlation between particle diameter and substrate roughness. Ziser (1985) notes that the emphasis should be on the spaces between particles rather than the particles themselves because it is the spaces that provide the immediate microhabitat of much of the stream benthos. More important, perhaps, is the fact that the space or distance between substrate elements may be a major determinant of the flow microenvironment.

Roughness flow classes

Morris (1955) classified flow over rough surfaces ('roughness' Reynolds number greater than 70) into three categories based on different roughness sizes and longitudinal spaces: isolated roughness flow, wake interference flow and skimming flow. Davis and Barmuta (1989) added a fourth category: chaotic flow. These flows are determined by the presence and structure of wakes developing behind each roughness element and are strongly dependent on the bed topography relative to flow depth.

Five flow classes can therefore be recognised:

SMOOTH FLOW	→	
	→	isolated roughness
	→	wake interference flow
ROUGH FLOW	→	skimming flow
	→	chaotic flow

These flow categories will be termed roughness flow classes to avoid confusion with flow types as used to describe surface characteristics of hydraulic biotopes. These roughness flow classes are depicted in Figure 5.5.

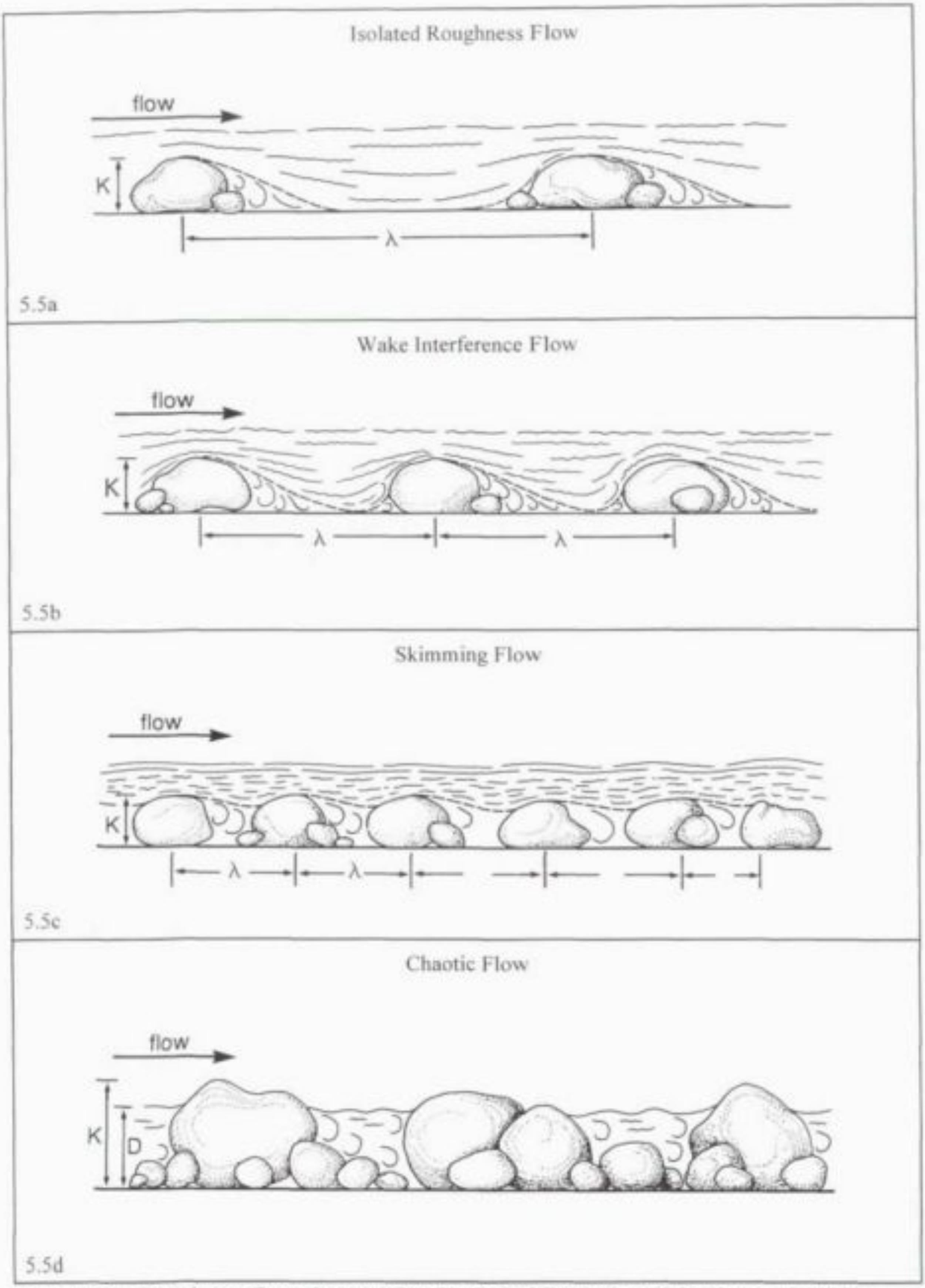


Figure 5.5 Roughness flow classes (after Davis and Barmuta and Gordon et *al.* 1992)

Isolated roughness flow

When the roughness elements are far apart the vortices in the wake behind each element are completely dissipated before the next element is reached, this is termed isolated roughness flow (Figure 5.5a). This will occur when k/λ approaches zero (k is roughness height and λ is the longitudinal distance between the crests of roughness elements in the direction of flow).

Wake interference flow

Roughness elements are closer together and the eddies from the elements interact, causing intense turbulence (Figure 5.5b). Here, roughness height is relatively unimportant compared to the spacing. The depth of flow above the crest of the elements becomes important since it will limit the vertical extent of increased turbulence. This will occur when y/λ is small (ratio of depth of water above roughness element to the longitudinal distance between the crests of roughness elements in the direction of flow). Wake interference flow can also be calculated from $j/D > 1$ (ratio of groove width between roughness elements to depth).

Skimming Flow (Quasi smooth flow)

When the roughness elements are close together the flow skims across the crests and the spaces between the elements are filled with much slower water containing stable eddies (Figure 5.5c). The surface acts almost as if it is hydraulically smooth. Skimming flow occurs when k/λ approaches 1 (k being roughness height and λ being distance between roughness crests), or when $j/D < 1$ (ratio of groove width between roughness elements to depth).

Exposed roughness flow (Chaotic flow)

All the above considerations apply where the depth of water is much greater than the height of the substrate. Where the depth is equal to or less than three times the height of the substrate roughness, or the rocks or boulders extend all the way through the flow, the near-bed flow conditions are extremely complex (Nowell & Jumars, 1984). Davis and Barmuta (1989) introduced a fourth category which they characterised as having super-critical 'white water', most common in riffles. Elements protrude through the water surface and flow conditions become very complex as water flows over and around these large obstacles (Figure 5.5d). It seems to represent an extreme form of wake interference flow. Chaotic flow occurs when $D/3k < 1$ (the ratio of depth to three times roughness height).

The measurement of roughness height and roughness spacing

Gordon *et al.* (1992) indicate that typically some characteristic diameter of the stream bed material such as the d_{50} or d_{85} (percentile values for sediment particle size) is used as the roughness height. There are, however, a number of potential problems in the use of these values to represent roughness height:

- there is not necessarily a correlation between particle diameter and substrate roughness with differences likely to be found due to particle shape and packing;

- the calculation of mean diameter requires considerable disturbance of the bed, this presents a problem in a research framework which requires a succession of hydraulic data to be collected over a period of time at the same point.

As substrate interacts with flow near the bed, any analysis of the flow in the microenvironment requires that a value be obtained for the height to which a substrate element projects into the water column (k) and the distance between substrate elements (l).

The method employed in this research to obtain roughness height and roughness spacing required the building of a profiler similar to that described by Ziser (1985). The profiler consists of 50 aluminium rods, one set of 50 cm long and another of 100 cm long. Each rod is 5mm in diameter and the width of the frame is 50cm (Figure 5.6, Plate 5.1). Two different lengths of rod were necessary in this study because of the occasional presence of very large substratum.

Chow (1959) notes that the position from which the roughness height is measured is a matter of dispute. He assumed that k was measured from a datum that lay at a distance 0.5 k below the average bottom of the stream bed. For this research k was considered to be equal to the mean height of clearly defined substrate elements within the width of the frame, and taken from a datum equal to the lowest point within the frame as illustrated on Figure 5.6. At each point data from the longitudinal and cross profiles were combined.

The distance between substrate elements, together with the groove width between them, was calculated simply as a mean value for all clearly defined particles. Values were obtained separately for the longitudinal and cross profiles at each point.

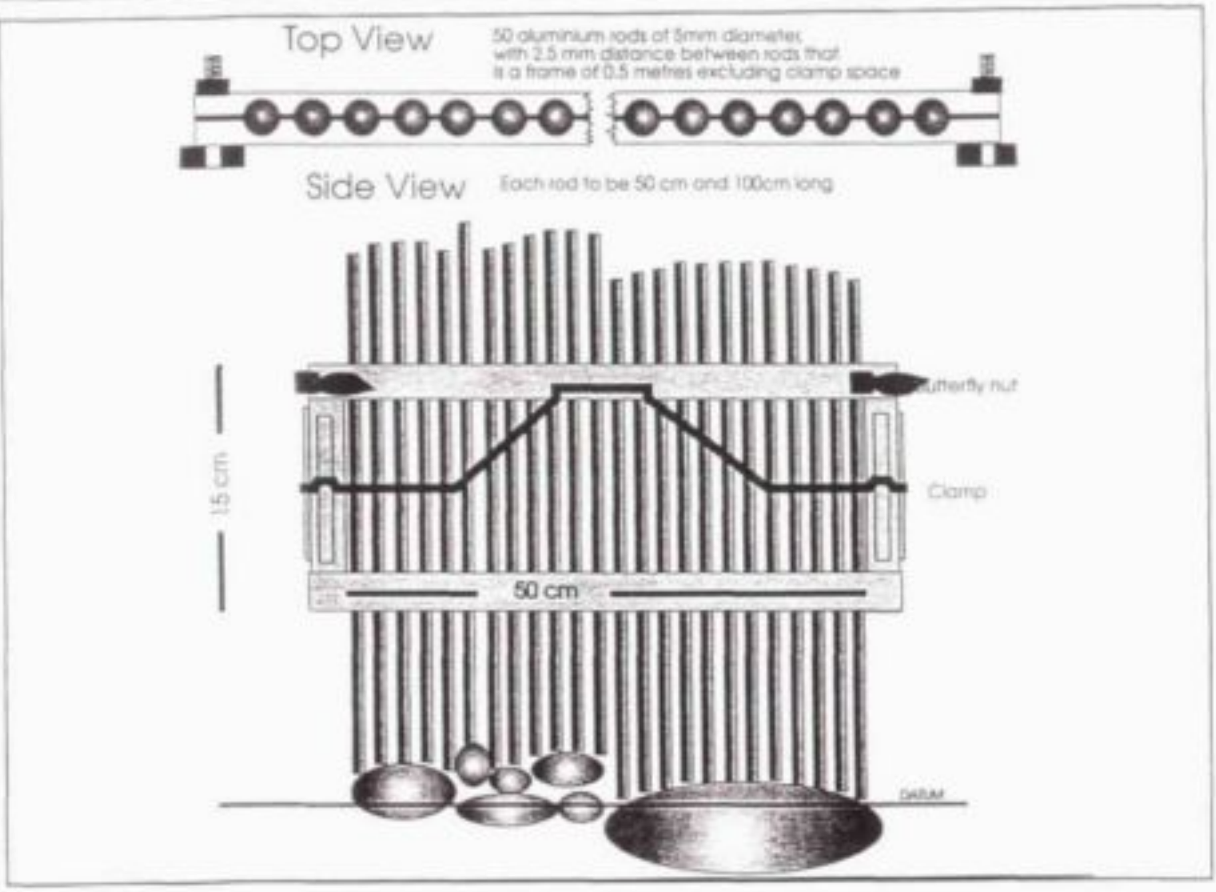


Figure 5.6 Diagram to show specifications of the frame used to measure roughness height.

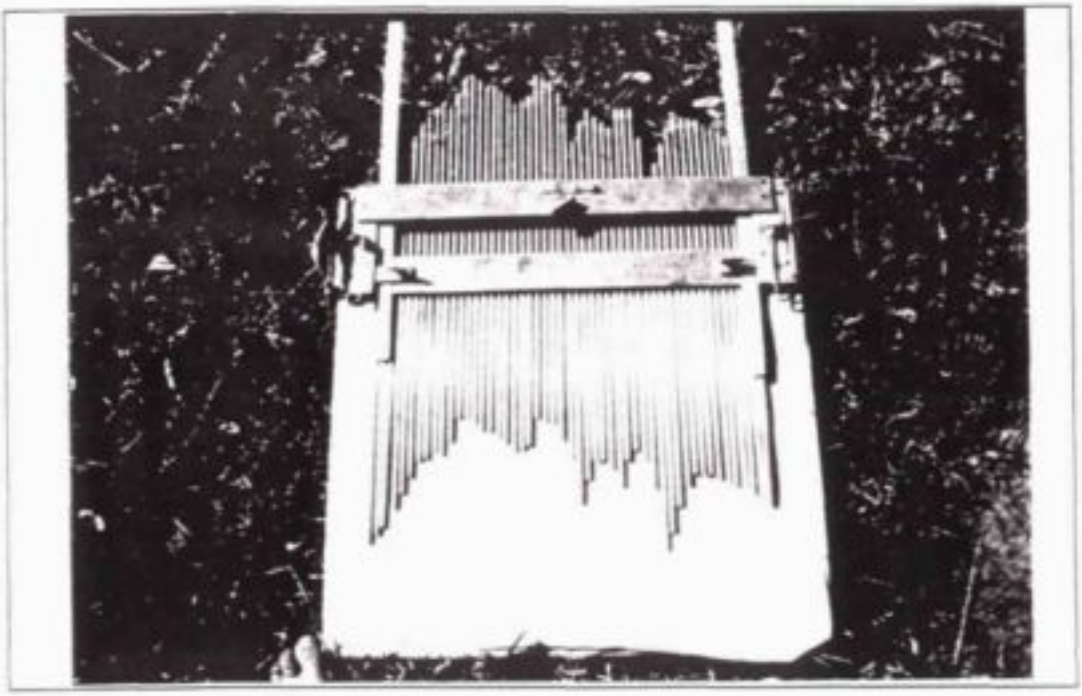


Plate 5.1 Photograph of frame used to measure roughness height.

5.4 CONCLUSIONS

The flow of water down a river channel due to gravity may be described as mean motion (Smith, 1975); it may be characterised by two numbers: the Reynolds number and the Froude number, both of which can be considered as indicators of flow conditions experienced within a column of water. The Reynolds number describes whether the mean flow is laminar or turbulent, and the Froude number describes whether the flow is subcritical, critical or supercritical. A particular feature of the Froude number is that, being based on the ratio of velocity to depth, it is independent of scale so that large and small features classify together if bulk flow conditions are similar. In contrast, the Reynolds number, based on the product of depth and velocity, is scale dependent and therefore is a measure of the magnitude of hydraulic variables.

By combining the Froude and the Reynolds numbers, mean flow may be classified as either subcritical-laminar, subcritical-turbulent, supercritical-laminar and supercritical-turbulent. Supercritical-turbulent and subcritical-turbulent are the most commonly occurring flows in streams and rivers (Chow, 1959).

The use of velocity and depth by lotic ecologists as defining variables to describe important instream habitats suggests that they have special significance to the aquatic biota living there. These two variables are the key components of the hydraulic indices describing mean motion of flow (the Reynolds number and the Froude number). The fact that both these indices are dimensionless and that the Froude number is independent of scale, allows one to hypothesise that these indicators of flow may be extremely useful indices for the characterisation of hydraulic biotopes.

The patterns of flow within the microenvironment form an important component of the physical habitat for aquatic organisms. A number of simple measures are available to describe the flow conditions near river beds. Hydraulic indices which are likely to have special significance to the aquatic biota, and hence the classification of near bed hydraulic biotopes, are the shear velocity (as it relates to the laminar sub-layer) and the 'roughness' Reynolds number. It is hypothesised that if relationships are shown to exist between the hydraulic indices describing mean motion (Reynolds and Froude numbers), and the hydraulic biotope, so too might there be relationships between the hydraulic indices describing the microflow environment and the hydraulic biotope.

Davis and Barmuta (1989) after Morris (1955), recognised five near bed flow regimes; they may be either hydraulically rough or hydraulically smooth. Hydraulically rough flow can be further classified as either chaotic flow, wake interference flow, isolated roughness flow or skimming flow (Figure 5.5 & 5.7). These flow classes are largely based on measures of bed topography and as such are less likely than surface flow conditions to show good relationships with the hydraulic biotopes described in Chapter 4.

The hypothesis that the indices describing both mean and near bed flow conditions may show associations with hydraulic biotopes needs to be tested. If this research confirms such associations, these hydraulic indices may provide a quantitative basis for the classification of hydraulic biotopes. This classification will assist the comparison of similar features both within and between different fluvial environments.

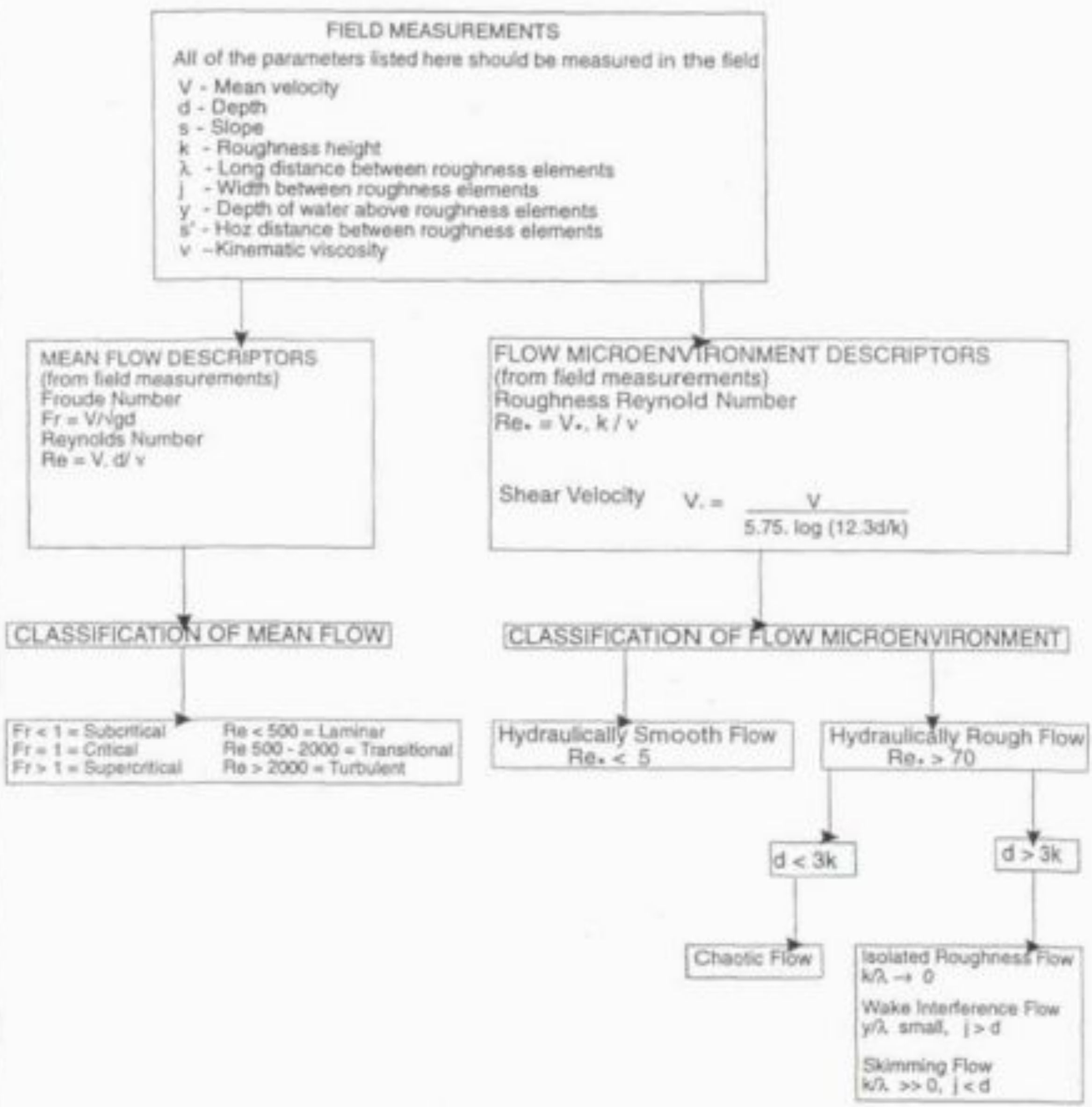


Figure 5.7 The classification of flow, after Davis and Barmuta (1989).

CHAPTER SIX
CLASSIFICATION OF HYDRAULIC BIOTOPES

6.1 INTRODUCTION

Hydraulic biotopes have been recommended as the basic unit to describe the instream habitat for aquatic organisms (Chapter 4). From reviews of the ecological literature and consultation with South African ecologists it would appear that hydraulic biotopes (or equivalents) are widely recognised at an intuitive level as being ecologically meaningful and there is an obvious, if ill defined relationship between these hydraulic biotopes and morphological units recognised by geomorphologists. It has been found that common consensus amongst ecologists exists as to the identification of hydraulic biotopes based largely on surface flow characteristics. In response to this, and in order to provide a more objective classification technique, a hydraulic biotope matrix was developed at the Citrusdal Workshop (Rowntree 1996a) and was presented in Chapter 4. It was assumed in the development of this technique that the observed surface flow is an indication of the complex mix of hydraulic characteristics of the flow profile. This assumption requires testing before the hydraulic biotope matrix can be accepted as a reliable classificatory tool. This chapter describes research which was designed to test the validity of the hydraulic biotope classification in terms of flow hydraulics. The ecological validity of the classification was not addressed at this stage.

From a review of the hydraulic literature (Chapter 5), it would appear that the Reynolds number and the Froude number, two dimensionless numbers that characterise mean motion of flow down a river channel due to gravity, may be useful indices for the characterisation of different flow environments. As described in Chapter 5, the Reynolds number represents the ratio of inertial forces (the resistance of an object or fluid particle to acceleration or deceleration) to viscous forces (how rapidly a fluid can be deformed) and provides information on the laminar or turbulent nature of the flow. The Froude number relates inertia forces to gravity forces and is important wherever gravity dominates as in open channel flow. It is used to differentiate tranquil or sub critical flow ($Fr < 1$) from rapid or super critical flow ($Fr > 1$) (Chow, 1959). Both values are easily calculated from depth and mean velocity, variables commonly collected during ecological surveys.

Whilst the Froude and Reynolds numbers describe the mean flow conditions in the water column, they do not relate directly to conditions at the bed. For benthic organisms it is the near bed flow hydraulics which determine the habitat. Near bed hydraulic variables discussed in Chapter 5 include roughness Reynolds number, shear velocity and shear stress. Flow patterns near the bed can be described in terms of boundary roughness. If hydraulic biotopes are a meaningful classification of flow conditions, they should show consistency for these near bed conditions as well as for the mean flow.

Although a number of researchers have referred to the potential usefulness of these simple flow indices such as the Froude and Reynolds numbers for the characterisation of different flow environments (Statzner *et al.*, 1988; Davis & Barmuta, 1989), there have been few attempts to relate them to the hydraulic biotope classifications recognised by limnologists. In a recent study in New Zealand, Jowett (1993) found that the use of simple classification rules based on water surface slope and either velocity/depth ratio or Froude number, correctly classified 65 - 66% of riffle, run and pool habitats in a gravel bed river. Jowett's study was primarily concerned with the spatial distribution of hydraulic biotopes and there is no mention of temporal variation due to changes in discharge.

The research on hydraulic biotopes undertaken in the present project progressed through a number of pilot studies during which ideas on classification and measurement developed. These finally came together in an in-depth study based in the Buffalo River. The first study was at a single site in the Great Fish River, where flow regulation enabled the study of hydraulic biotope dynamics at a range of discharges (Wadeson, 1994). Four transects were set up across a riffle, two runs and a pool. In this early study no attempt was made to distinguish between morphological units and hydraulic biotopes, but attention was paid to variability both within a morphological unit at one discharge and variability between discharges. Considerable variation was noted both within transects and between discharges. This study pointed to the need to classify hydraulic biotopes for each measuring cell rather than for the whole transect, and to reclassify hydraulic biotopes at the different discharges. A second study in the Molenaars River, Western Cape, used cell classifications in order to study the spatial variability within different morphological units located in four separate reaches. Although useful at a general level, rigorous classification methods had not been developed either in relation to channel morphology or to hydraulic biotopes so that it is difficult to use the data to test hydraulic biotope classifications. This study was a useful exercise in underlining the need for standardised data collection methods which were used in subsequent surveys.

A third study was carried out in the Olifants River in the western Cape, focussing on a sand bed reach. This provides a useful comparison to the Buffalo River study which included boulder, cobble and bedrock reaches. The two studies together thus encompass a wide range of channel types. In both studies data was collected at a range of discharges. The Olifants study looked only at mean flow conditions, whilst the Buffalo study incorporated data collection enabling near bed hydraulics to be considered. These two studies are presented in this chapter. Full details of all four studies are given in Dr Wadeson's PhD thesis (Wadeson, 1996).

6.2 THE OLIFANTS RIVER, WESTERN CAPE, SOUTH AFRICA

6.2.1 Introduction

During December 1993, a series of experimental releases from Clanwilliam Dam on the Olifants River were initiated by Dr Jackie King and Dr Jim Cambray with the assistance of the DWAF, in an effort to stimulate spawning of endemic yellowfish below the dam wall. This exercise provided an ideal opportunity for co-operative research to study the effect of changing discharge on hydraulic biotope dynamics in a sand-bed river.

A site was chosen some kilometres below the dam wall in a sand bed channel. This provided a significant contrast to the cobble or gravel bed rivers more commonly researched. In gravel bed channels the perimeter remains relatively stable except during infrequent high magnitude discharges, whereas in sand bed channels the bed is highly mobile and readily moulded into different bedforms under the sculpting influence of changing flows (Simmons & Richardson, 1966). The resulting bedforms impose resistance to the flow and affect local velocities, depths and sediment transport. These dynamic structures and associated flow environments together define the hydraulic biotope in sand bed rivers.

6.2.2 Aims

The aims of this research were twofold. The first was to establish whether or not the hydraulic biotope relationships established for gravel bed rivers held true for sand bed channels. The second was to examine the extent to which hydraulic biotope characteristics for selected sand bed morphological units would be impacted by changes in flow.

6.2.3 The study area

The catchment of the Olifants River is situated some 250 km north-west of Cape Town in the winter rainfall region of the Western Cape (Figure 6.1). As a consequence floods are frequent during the winter months from May to September, whilst under natural conditions low summer base flows persist from October through to April (King & Tharme, 1994). Morant (1984) describe the geology of the upper catchment, above Clanwilliam Dam, as being comprised of coarse grained quartzitic sandstones and quartzites of the Table Mountain Group (Cape Supergroup). As a consequence the stream sediment load is dominated by a sandy bedload with minimum suspended load as is confirmed by the remarkable clarity of flood waters. The sediment yield of the 2033 km^2 catchment above Clanwilliam Dam is given by Rooseboom (1992) as 134 $t/km^2/a$, but for the 736 km^2 catchment between Clanwilliam and Bulshoek this is reduced to 17 $t/km^2/a$. Hence large volumes of sediment have been trapped in the upper dam since it was built in 1935. Above Clanwilliam Dam the channel is characterised by an assemblage of bedrock, gravel bed and sand bed reaches, immediately below the dam the channel is armoured with bedrock and gravel sections, but within half a kilometre this has given way to a predominantly sand bed channel which continues for 23 km as far as Bulshoek Dam.

A study site was selected in the sand bed channel 6.5 km downstream of the dam wall. The selected reach included a range of representative morphological units as shown in Figure 6.2. Sand bed channels are generally more homogenous than their gravel bed counterparts, but it was possible to distinguish two pools separated by a riffle which was wider, shallower and had a surface armour of fine gravel. The upstream channel section was of particular interest in that it was distinguished by the passage of a large sand wave that was passing through the channel. This had a steep wave front which advanced 14 m down the channel during the 3 day observation period. The channel behind the wave front had a highly mobile, 'liquefied' bed which had a relatively flat cross-section. The flood plain was characterised by numerous flood channels and pools. Vegetation along the banks and on sand bars increased stability and provided important habitat. Phragmites was an important component of the bank vegetation, whilst the alien species *Eucalyptus grandis* was common on the flood plain.

6.2.4 Methods

Data collection

The two main objectives of the study were as follows. The first was to monitor changes in the physical and hydraulic conditions within the channel as flow discharge increased; the second was to assess the influence of changing flow on hydraulic biotope classification in a sand bed channel. Specific objectives were to ascertain the occurrence and extent of bed instability, to measure rates of sediment transport as flow increased and to monitor the temporal variation of selected hydraulic characteristics as discharge increased.

Three flow releases were made during a four day period, giving a total of four discharges during which measurements were taken. The 'baseflow' prior to the first release was measured at the site as 5.16 m^3sec^{-1} The first release of 8 m^3s^{-1} lasted for 3 hours. The last two discharges on the two following days were of a similar magnitude (12 m^3s^{-1} at the dam wall) but were of a different duration from each other, 3 hours and 12.5 hours respectively.

Five transects were set out across the channel as indicated in Figure 6.2. The transects represented a range of morphological units including pools (Transect 2 & 5), riffles (Transect 3 & 4) and a planar sand wave (Transect 1). A planar bed is defined as one which has an extensive plane surface and lacks the undulating topography characteristic of pool-riffle beds. The cross-section form was surveyed using a Total Survey Station during initial baseflow conditions. The bed profiles at each transect were estimated during subsequent flow events from measurements of flow depth together with water level surveys.

The bed material across each transect was sampled at between two to five points depending on the width of the transect. The sediment was sampled to a depth of 15 cm using a coring device. The particle size of the samples was analysed subsequently using the dry sieving method outlined in Gordon *et al.* (1992).

Stage was monitored at one point in the channel using a stage plate. Flow depths and velocities (0.6 depth from the surface) were measured at one metre intervals across each transect during the period of maximum flow for each event. Although the flow was released at the dam wall at a constant discharge for a period of between 3 and 12 hours, by the time the released water reached the survey site the rising and falling limbs of the discharge had become greatly attenuated, but the period of constant flow had

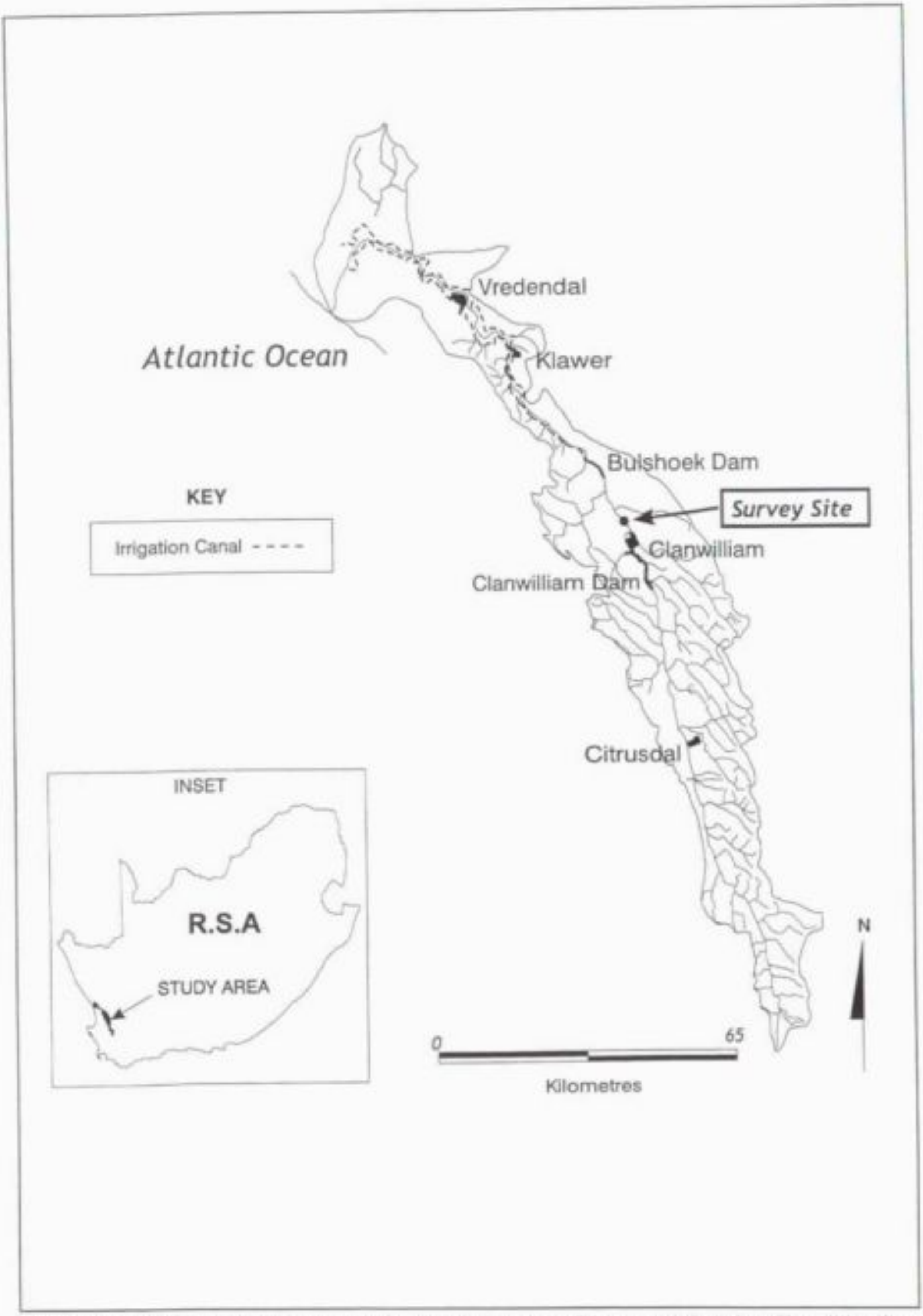


Figure 6.1 The Olifants River Catchment showing the location of the survey site below Clanwilliam Dam

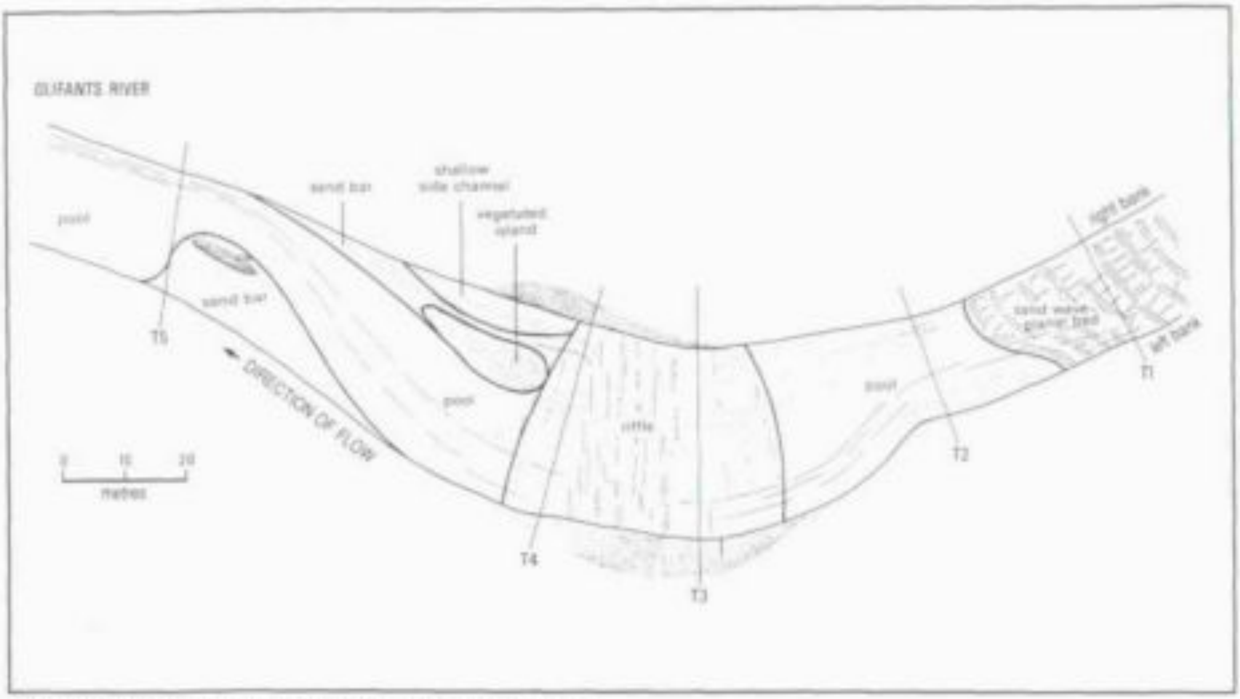


Figure 6.2 Plan view of Olifants River study site

been greatly shortened. It was not possible, therefore, to monitor all transects at exactly the same discharge, except under initial baseflow conditions. Discharges estimated using the velocity area method are given in Table 6.1.

Table 6.1 Flow discharges measured at the survey site

Date	13-12-93	14-12-93	15-12-93	17-12-93
Transect		Discharge (m^3s^{-1})		
1 Sand wave	5.16	8.35	10.88	9.73
2 Pool	5.16	8.10	10.71	10.06
3 Transverse gravel bar	5.16	8.02	10.71	10.39
4 Transverse gravel bar	5.16	7.94	10.55	10.79
5 Pool	5.16	7.94	10.22	11.20

Sediment load was monitored using a Helley Smith bedload sampler (Emmett, 1980; Gordon *et al.*, 1992). A composite of 10 samples, each taken over a two minute period, was collected at each transect during each flow discharge. The composite sample was later analysed for total sample weight and particle size distribution using dry sieving.

Hydraulic biotopes were intuitively classified in the field as a series of points across each transect. This was carried out using the concepts and ideas which are formalised in Table 4.1. Because of the homogeneity of the substratum only three hydraulic biotope classes were recognised, namely sand riffles, sand runs and sand pools. At each new discharge, the hydraulic biotopes along each transect were reclassified.

Data analysis

The particles size distribution of the stream bed was estimated from the bulk samples collected for each transect, whilst the particle size of the transported sediment was estimated from the samples collected at each discharge using the Helley Smith sampler. Plots are given in Figure 6.3 and 6.7 as cumulative frequency curves.

Transects were plotted at the four flow discharges to indicate changes in bed form and the location of scour and deposition (Figure 6.4).

Changes in width, mean depth and mean velocity with discharge were analysed using hydraulic geometry diagrams (Figure 6.5). Trend lines were drawn in by eye. Equivalent plots for mean hydraulic characteristics are given in Figure 6.6 Froude numbers and Reynolds numbers were calculated using the mean transect depth and velocity.

Hydraulic biotopes were characterised using Froude numbers calculated from the point velocity and depth data. This enabled an analysis of the hydraulic variability within discrete channel form units. The distribution of data values for each discharge/transect combination was portrayed using box and whisker plots as given in Figure 6.8.

6.2.5 Results

The study site can be subdivided into three broad morphological units as indicated on Figure 6.2 - riffle, pool and sand wave. The results for the two pool transects (Transects 2 and 5) and the two riffle transects (Transects 3 and 4) showed broad similarities so that these two pairs of transects will be discussed together. The transects will be presented starting with the upstream site, Transect 1, as the progress of the sand wave moving through this section was found to have a significant influence on downstream sections.

Bed particle size distribution

Bed material particle size distribution for the five transects is shown in Figure 6.3. The two pools (Transects 5 and 2) and the sand wave (Transect 1) had very similar size distributions with over 85 % of the material being finer than 0.5 mm and a negligible amount being coarser than 1 mm. The relatively coarse nature of the two riffle sections is clear, with 9% and 17% of the material being in the gravel size category in Transects 3 and 4 respectively. Very little material exceeded 8 mm in diameter.

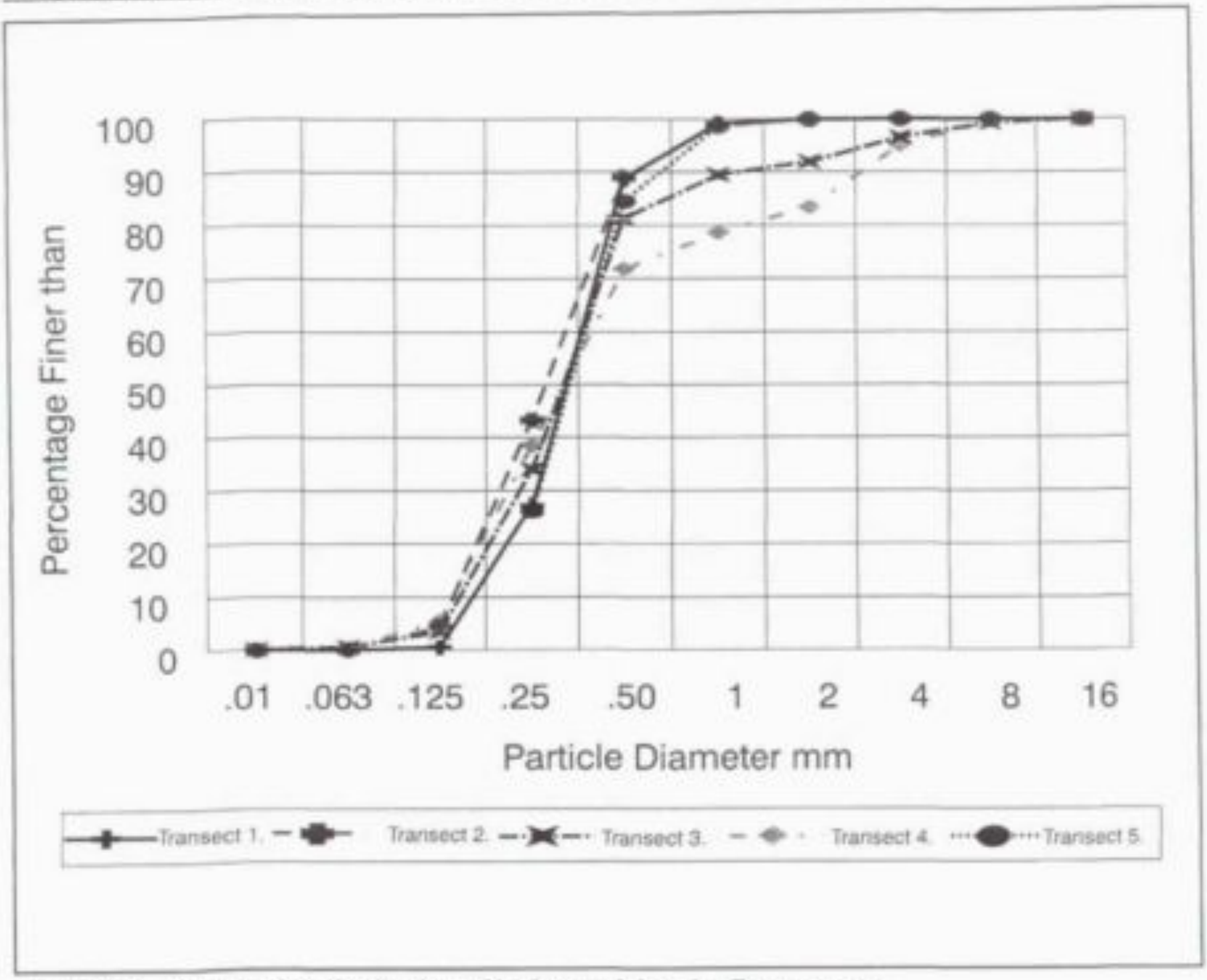


Figure 6.3 Particle size distribution of bed material at the five transects

Channel adjustment to discharge

Transect 1 Sand wave

Figure 6.4a shows that large changes occurred in the bed profile, but these did not appear to be discharge related. Scouring during the second release was quickly infilled by deposition during the final release. The channel at this transect was characterised by a highly mobile, unstable bed, of quicksand like material.

Transect 2 and 5. Pool.

Changes in bed profile in the upper pool indicated an accumulation of sediment throughout the three releases (Figure 6.4b). Aggradation increased particularly during the final release due to encroachment of the front of the sand wave from upstream. The lower pool demonstrated limited scour in the deepest section.

Transect 3 and 4. Riffle.

The cross-section of the riffle was very stable with little change in the bed profile as discharge increased (Figure 6.4c and d). The only observable change was the development of a small dune as material from upstream was deposited on top of the armoured layer. The site of deposition was upstream of an existing vegetated sand bar. Deposition of fine material supplied from the upstream transects was more pronounced at the top of the riffle section.

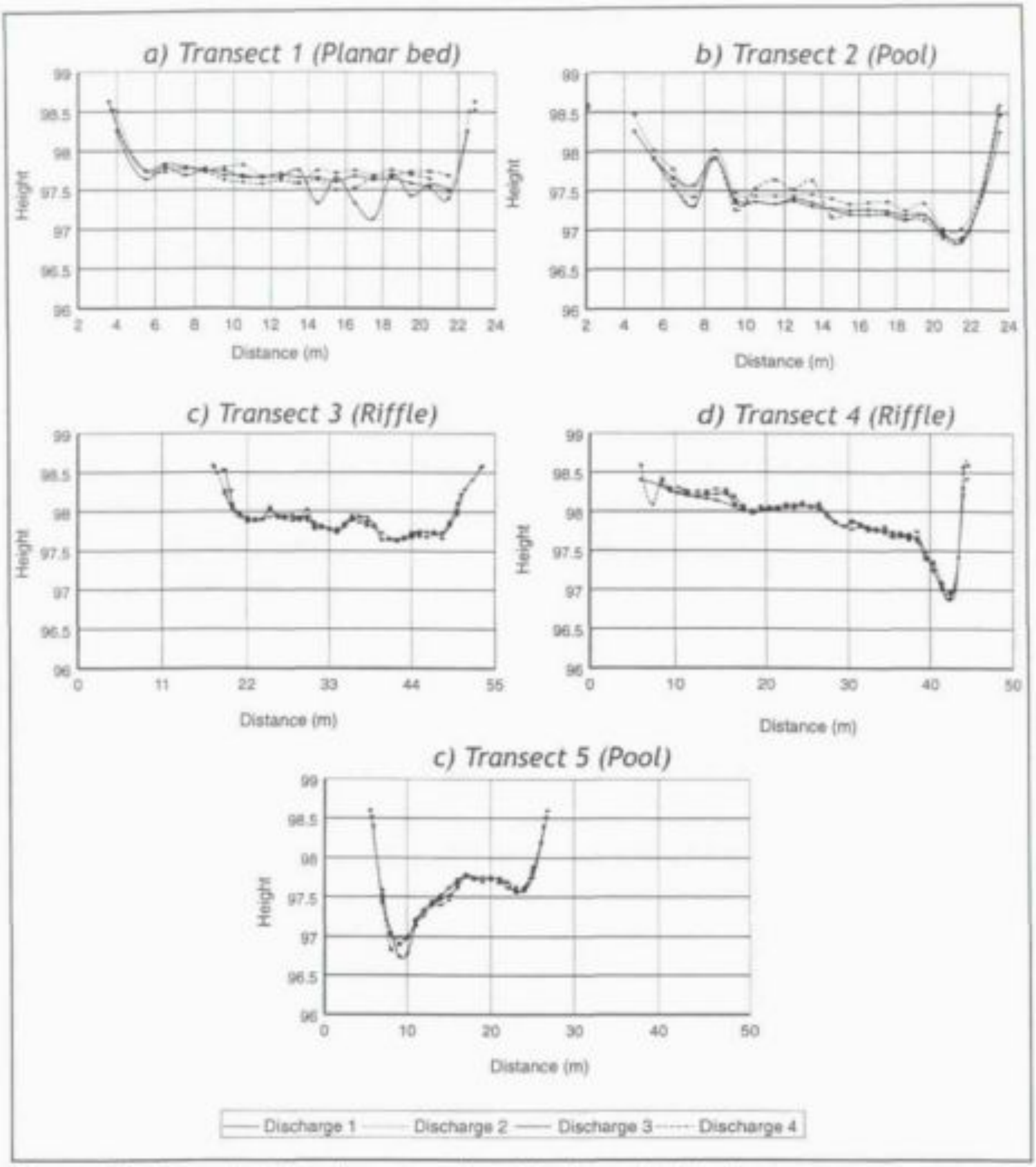


Figure 6.4 Changes in channel cross section with changes in discharge

Flow adjustment to discharge (hydraulic geometry)

Hydraulic geometry describes the adjustment of the flow variables width, depth and velocity to changes in discharge. Figure 6.5 shows the hydraulic geometry for the five transects surveyed in the Olifants river.

Transect 1 Sand wave

From Figure 6.5a it can be seen that an increase in discharge was accommodated largely by an increase in depth with a much smaller increase in velocity. Compared to the other four sections, velocity was relatively high at all discharges. Width increased slightly with discharge.

Transects 2 & 5. Pool.

Both depth and velocity increased with discharge, but the increase in depth was the greater. There was a small but perceptible increase in width.

Transect 3 & 4. Gravel bar.

It can be seen from Figure 6.5d (Transect 4) that adjustment to an increasing discharge over the gravel bar was through an increase in depth and width, but a reduction in velocity. These findings were unexpected as conventional hydraulic geometry suggests a significant increase in velocity as discharge increases. The reduction in velocity may have been the result of a reduced water surface slope as depth increased throughout the length of the channel. Transect 3 at the upper end of the gravel bar showed a response transitional between the gravel bar at Transect 4 and the pools at Transects 2 and 5. There was a marked increase in both width and depth, but velocity remained more or less constant.

Flow hydraulics and sediment transport

Variation in hydraulic variables and sediment transport are illustrated in Figure 6.6. The variation in the particle size distribution of the material transported as bed load can be seen from Figure 6.7. At all transects Reynolds numbers increased with discharge, approximately doubling over the range of discharges experienced. This was related to an increase in either depth, velocity or both.

The Froude number proved to be a conservative index, remaining more or less constant at the two pool transects and the sand wave. Over the gravel bar, Froude numbers decreased. This decrease was particularly pronounced at Transect 4 and is related to the reduction in velocity with discharge.

Transect 1. Sand wave.

The highest sediment transport rates were measured at Transect 1, over 0.38 $kg.s^{-1}$ during all flow conditions. This was related to the high mobility of the sand wave. Transport rates were not directly related to discharge or hydraulic variables, maximum rates being measured during the first release with an intermediate discharge. Transport rates for the sand wave are more likely to be dependent on the progression of mobile surface dunes through the channel. The particle size distribution at this transect

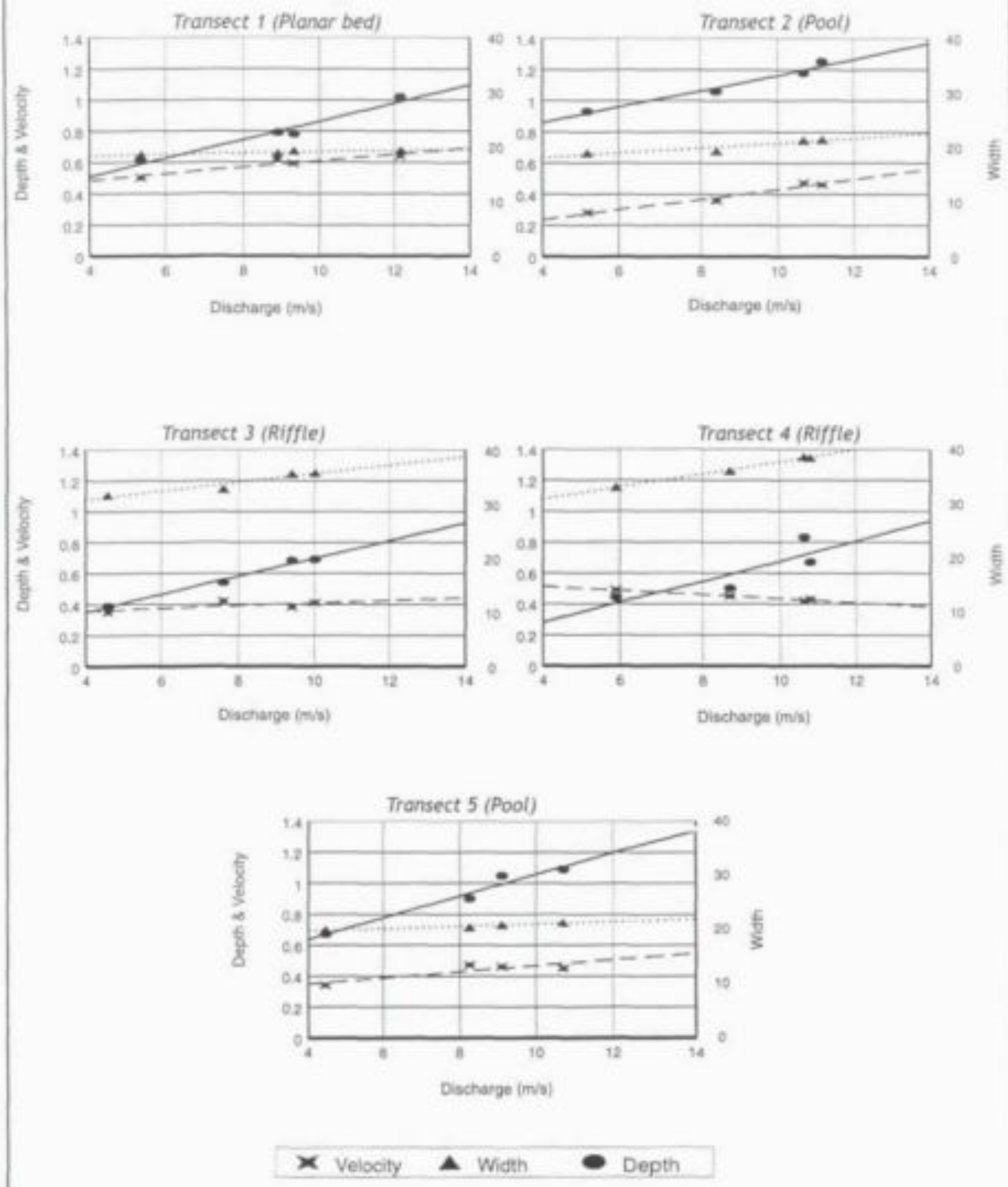


Figure 6.5 Hydraulic geometry, showing changes in width, depth and velocity with discharge

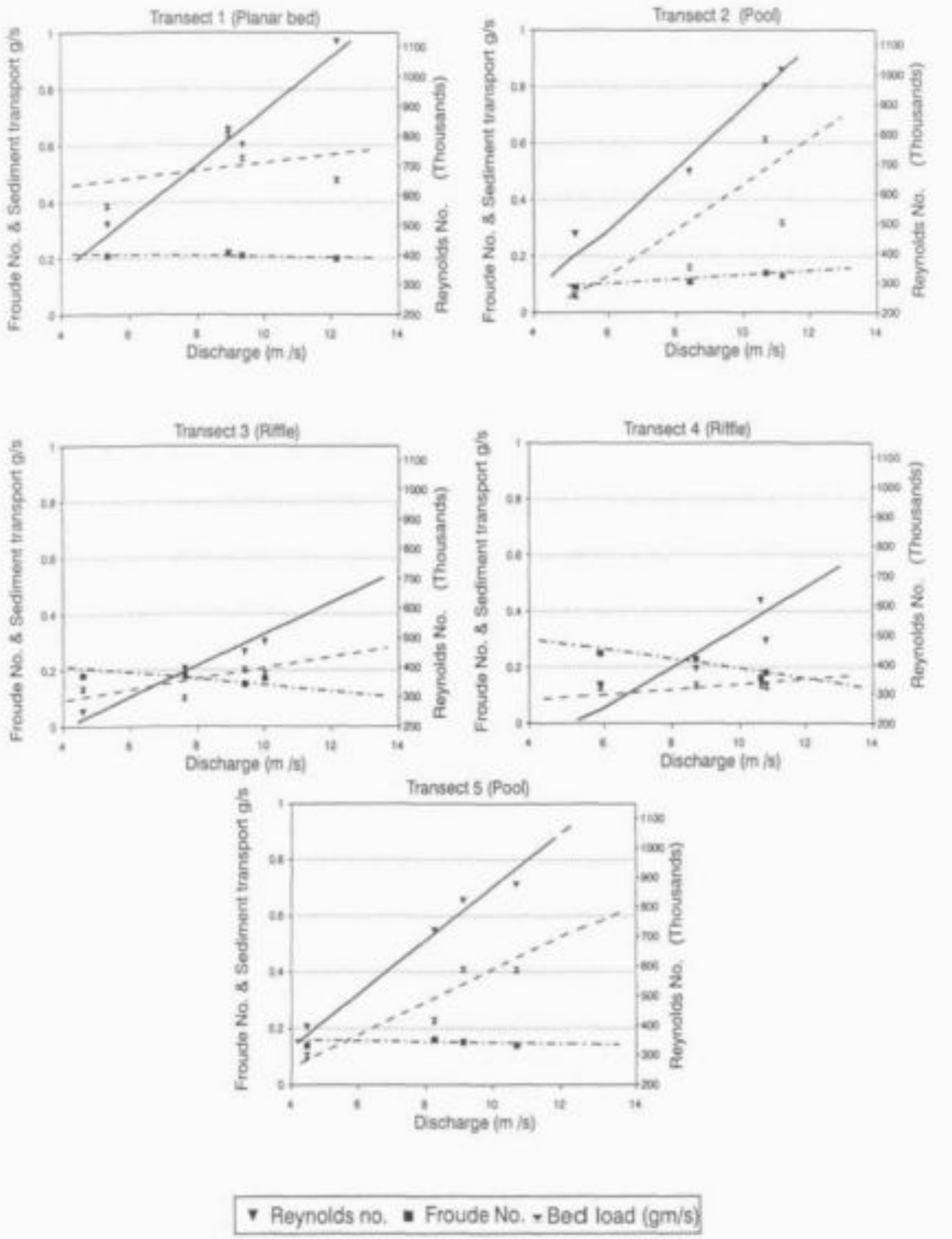


Figure 6.6 Changes in hydraulic indices and bedload transport with discharge

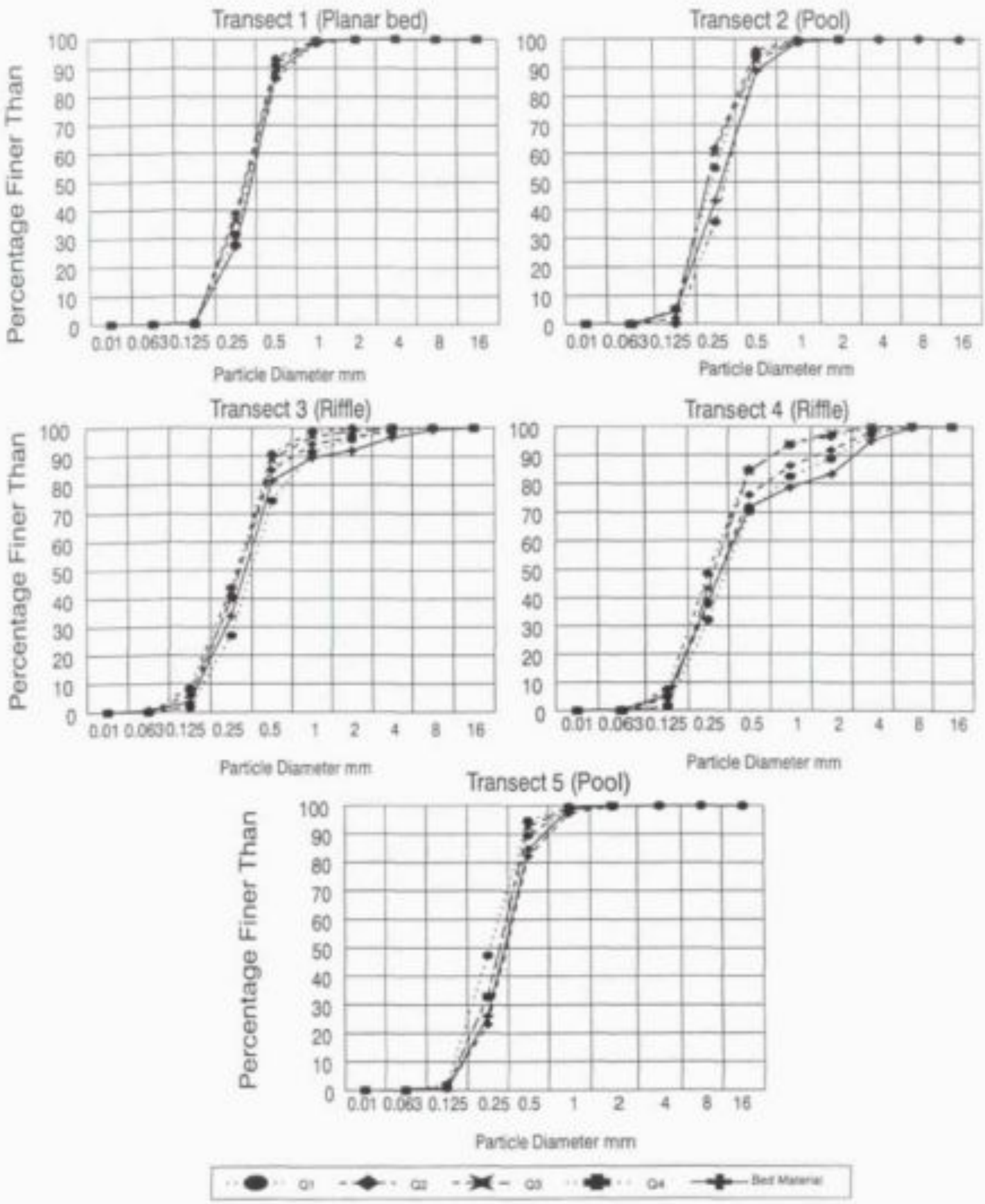


Figure 6.7 Particle size distribution of the bedload

Table 6.2 Sediment transport rates

Discharge ($m^3 s^{-1}$)	Sediment load (tonnes day^{-1})	Discharge ($m^3 s^{-1}$)	Sediment load (tonnes day^{-1})	Discharge ($m^3 s^{-1}$)	Sediment load (tonnes day^{-1})
Transect 1		Transect 2		Transect 3	
5.16	33.41	5.16	5.20	5.16	11.38
8.35	55.07	8.10	13.88	8.02	8.69
10.88	41.20	10.71	27.55	10.7	16.11
9.73	47.91	10.06	52.96	10.39	17.49
Transect 4		Transect 5			
5.16	10.85	5.16	8.95		
7.94	11.65	7.94	19.69		
10.55	11.33	10.22	35.33		
10.79	11.54	11.20	35.17		

(Figure 6.7a) varied little through time and was essentially the same as the bed material. Hence at this site the whole bed was in motion and there was no selective transport.

Transects 2 & 5. Pool.

Sediment transport rates at the pool transects (Transects 2 and 5) increased with discharge and the Reynolds number as can be seen from Figure 6.6b and 6.6e. From Figure 6.7b and 6.7e it can be seen that there was some selective transport of particles smaller than 0.5 mm, but generally there was little difference between the bed material and transported sediment. At Transect 2 an anomaly occurred during the third flow release (discharge 4) when sediment transport rates doubled despite a slight reduction in discharge. This was related to the arrival of the sand wave noted previously. At this time sediment transport rates approached those measured upstream at Transect 1. At the same time the transported sediment became coarser, resembling the bedload more closely.

Transects 3 & 4. Gravel bar.

Sediment transport rates over the gravel bar remained low through all discharges. This site had a high stability and few changes were observed over the range of discharges experienced. The two gravel bar sites showed increasingly selective transport through the series of events, with the finest material being carried during the highest discharges. This can be explained by the movement of sand from upstream onto the gravel bar where it formed small dune features over the armoured surface.

The gravel bar site remained stable at all flows whereas sediment transport in the pools responded to changes in discharge. Temporal variations were independent of discharge itself, but were related to the movement of pulses of sediment through the system. The same conclusions apply to the particle size distribution of the transported material.

Sediment transport rates as daily values are given in Table 6.2. From this table it can be seen that significant amounts of sediment are being moved through the channel even at these moderately low flows. Sediment transport rates during natural flood events will be considerably higher. These transport rates are surprising given that much sediment will be trapped in Clanwilliam Dam. A tributary entering the main channel below Clanwilliam Dam may be a source of much of this sediment.

Hydraulic biotope classification

Transect 1. Sand wave.

Field classification of hydraulic biotopes placed all cells in this transect as a run at all discharges. Froude numbers lay in the lower range of Jowett's (1993) classification of a run in a gravel bed stream. An interesting observation at this transect is the reduction in hydraulic variability as discharge increases.

Transect 2 & 5. Pool.

The field classification of these transects indicated a change from pool class to run class as discharge increased. This is borne out by the change in Froude numbers shown in Figure 6.8. This diagram indicates that pools and runs are not discrete units but form a continuum. There is good agreement with these results and the classification values of Jowett (1993) for gravel bed rivers. In contrast to the previous transect, variability increased at higher discharges.

Transect 3 & 4. Gravel bar.

Although the morphological unit at Transect 3 was classified as a gravel bar, the hydraulic biotopes were classified as runs at all discharges. The measured Froude numbers concurred with Jowett's (1993) classification for gravel bed streams. In contrast, at low discharges the hydraulic biotopes at Transect 4 were classified as riffle due to the presence of undular standing waves, but as discharge increased the hydraulic biotopes were classified as runs. As can be seen from the range of Froude numbers in Figure 6.8 there was great diversity between different cells across the transect at low flows, so that although the whole transect was classified by eye as a riffle, comparison to Jowett's classification showed that it contained pool, run and riffle elements. At this stage the hydraulic biotope matrix had not been developed; had a more rigorous classification technique been available, differentiation between hydraulic biotopes may have taken place.

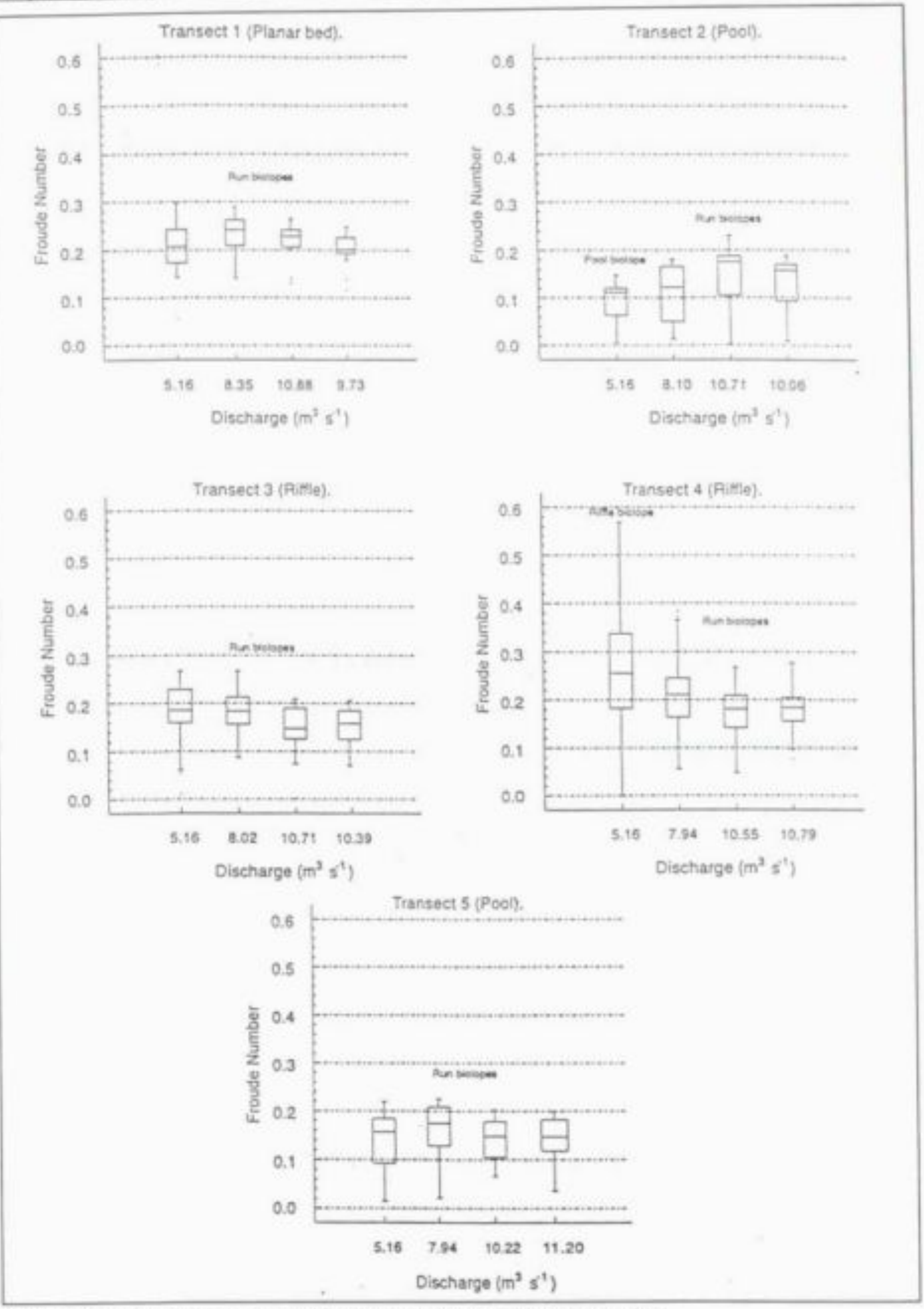


Figure 6.8 Hydraulic biotope classification based on cell Froude number

6.2.6 Hydraulic biotope characteristics: a synthesis

Hydraulic biotopes were defined earlier as spatially distinct in-stream flow environments characterised by specific hydraulic attributes. Hydraulic variables considered in this study include flow depth and velocity, Froude and Reynolds numbers and bed mobility. The combined effect of these variables will be assessed so as to examine the way in which discharge impacts on hydraulic biotope characteristics for each type of morphological unit: sand wave, pool and gravel bar.

Transect 1 - sand wave

This site was characterised by relatively high velocities and a highly mobile bed at all flows. An increase in discharge was accompanied by an increase in depth and Reynolds number and a reduction in the hydraulic variability measured in terms of Froude number. This feature consisted of run hydraulic biotopes at all discharges. The relatively conservative nature of velocity may have been due to increased bed roughness as the bed became deformed at higher flows. Conditions at this site would appear to be unfavourable for all biota over the range of discharges measured.

Transect 5 & 2 - Pool

The two pool morphological units offered relatively stable environments at low discharges, but as discharge increased so did velocity, Reynolds number and bed mobility. There is some indication that the increased sediment transport at higher discharges was due to an increased import of sediment from upstream, rather than localised scour of the bed itself. Hence organisms that burrowed into the bed to escape unfavourable hydraulic conditions would be relatively well protected. The hydraulic variability increased with discharge with pools being transformed into runs, an effect which may be beneficial if higher diversities and density of biota are related to a more variable hydraulic environment as has been suggested by some ecologists.

Transect 4 & 3 - Gravel bar

Increased flow over the gravel bars was accompanied by a gradual increase in Reynolds number and hence turbulence. Sediment transport rates remained low at all discharges, indicating a stable bed. This bed stability can be explained both by the presence of an armoured layer of fine gravels and an observed decrease in velocity as discharge increased. Observations in the field showed the deposition of finer material over a limited section of the armoured layer, upstream of a vegetated island. Away from this obstruction the velocity and turbulence experienced over the gravel bar were adequate to move the relatively fine material arriving from upstream and maintain the armoured nature of the bed. At low flows this feature contained pool, run and riffle hydraulic biotopes. Increased discharge produced a transformation from a riffle dominated feature to one dominated by runs.

The ecological importance of this area arises from the stability of the substratum, and the presence of coarse sands and fine and medium gravels. Gravel bars may provide an important refuge area for certain stream biota as discharge increases and velocity and turbulence becomes unfavourable elsewhere. This is particularly relevant in sand bed rivers where refuge sites are rare. The gravel bars also had the highest hydraulic variability, especially at low flows. Riffles are often selected as sampling sites by riverine ecologists because of the highly variable flow conditions which promote increased biotic diversity and density.

6.2.7 Hydraulic biotopes in the Olifants River: Conclusion

The Olifants study was initiated to carry out further research into the development of the hydraulic biotope concept. This study allowed an assessment of the cell by cell hydraulic response of various hydraulic biotopes to variations in discharge.

The hydraulic biotope concept has been found to hold true for sand bed rivers, although some clear differences can be noted between the results obtained for a sand bed and previous findings for gravel bed rivers. At low flows there were distinctions in hydraulic biotope classification between the different morphological units, but the differences were more subdued than those found previously in gravel bed rivers (Wadeson 1994, Jowett 1993). This is probably due to the relatively homogeneous nature of the substratum across hydraulic biotope classes. The high diversity in Froude numbers over the gravel bar is consistent with findings elsewhere (Wadeson, 1994). At higher flows there is convergence in hydraulic biotope classes between separate morphological units, a finding consistent with gravel bed streams.

One important feature which distinguished sand bed hydraulic biotopes from those found in gravel bed streams is the increased importance of bedload movement which is highly sensitive to discharge. The mobility of the bed will have a major impact on biological processes even at low discharges.

Significant changes in hydraulic biotope characteristics occurred over the range of discharges measured, with pools exhibiting the most changeable environment, gravel bars the least. Gravel bars tended to lose variability in their Froude numbers as flow increased, but maintained mean values, whereas in pools both the variability and the median Froude number increased. The bed of gravel bars was also remarkably stable, changes in sediment transport being related more to a throughput of sediment from upstream, rather than to disturbance of the bed itself. Sediment transport through pools increased significantly with discharge. The most unstable bed was found for the planar sand wave.

There is a limited understanding in South Africa as to how sand bed channels respond to changing geomorphological environments such as changed flow regimes or sediment inputs. An understanding of the influence these changes have on such aspects as flow hydraulics, channel form and hydraulic biotope characteristics is important for the successful management of our rivers. The Olifants River is considered to be of particular ecological importance in South Africa because of the presence of 10 indigenous fish species, 8 of which are endemic (Gaigher, 1981). This river, and its inhabitants, are likely to be placed under ever increasing threats from alien fish predation and from anthropogenic change.

6.3 THE BUFFALO RIVER, EASTERN CAPE

6.3.1 Introduction

The Buffalo River was selected for an in-depth study of the spatial and temporal variability of hydraulic biotope characteristics, with respect to both mean flow and near bed hydraulic variables. The Buffalo River is a perennial river which, in its upper reaches, provides a variety of channel types for which the relationship between morphological unit and hydraulic biotope could be tested.

The aims of this study were as follows:

① To test the use of hydraulic indices representing mean flow conditions as quantitative variables to characterise hydraulic biotopes.

② To test the use of hydraulic indices representing micro flow conditions as quantitative variables to characterise hydraulic biotopes.

③ To determine the influence of substratum, scale and discharge on the mean flow characteristics of hydraulic biotopes.

④ To determine the influence of substratum, scale and discharge on the near bed flow characteristics of hydraulic biotopes.

⑤ To assess the validity of using a hydraulic biotope matrix to classify ecologically significant hydraulic environments.

⑥ To determine the relationship between hydraulic biotope distribution and channel morphology within selected reaches of the Buffalo River.

⑦ To determine the pattern and direction of change of hydraulic biotope classification in response to changing discharge.

6.3.2 The Study Area

The Buffalo River is a relatively short and steep coastal river system, fairly typical of those draining the eastern escarpment of South Africa. It has its headwaters in the Amatola Mountain range between King Williams Town and Stutterheim at an altitude of 1300 metres (amsl) and flows in a south-easterly direction for a 125 km before discharging into the Indian Ocean at the river port of East London. The river catchment covers an area of 1276 km^2 of which approximately 900 km^2 falls within the borders of the former homeland, Ciskei. Figure 6.9 shows the situation of the catchment. Further details are given in Chapter 8.

The longitudinal profile of the Buffalo River and its tributaries are characteristically concave upwards with a relatively sharp break in slope between the mountain (mean gradient of 0.19) and piedmont zones (gradient range between 0 003 to 0.008) (Figure 6.10). Local steepening of channel gradient can be associated with geological outcrops of sandstone and dolerite. Within the lowland Plateau the river and tributaries have incised their valleys but in most reaches have developed a narrow or limited flood plain.

6.3.3 Site selection and sampling framework

The physical requirements for the development of the hydraulic biotope concept within the Buffalo River included the need for a diverse hydraulic environment so as to provide a sampling framework which encompasses as many hydraulic biotopes as possible. The more diverse hydraulic environments within the Buffalo River are to be found within the upper reaches where large substratum dominated the bed material and discharge was more consistent. These are also the reaches for which a perennial flow is unregulated by impoundments. There are a number of impoundments within the catchment as indicated on Figure 6.9. None of these dams are managed for downstream flow releases so that flow below the dam wall depends on natural spillage. Below Maden and Rooikrans dams, flows are augmented by significant tributary inputs, but downstream of Laing and Bridal Drift dams there is little such augmentation so that very low flows persist for much of the year.

In order to encompass a sufficient range of channel type and channel scale, three sites were selected above Maden Dam and two some way below Rooikrans Dam where additional inflows had taken place (Figure 6.9). These five sites represented a good range of reach types and morphological units. At each site between three to nine transects were set up to represent the characteristic morphological units. Fixed sampling points for data collection were located along the transects. Data collection took place under four different discharges ranging from a spate to drought flows. Details of data collection techniques are given in Section 6.3.5; the sites themselves are described below

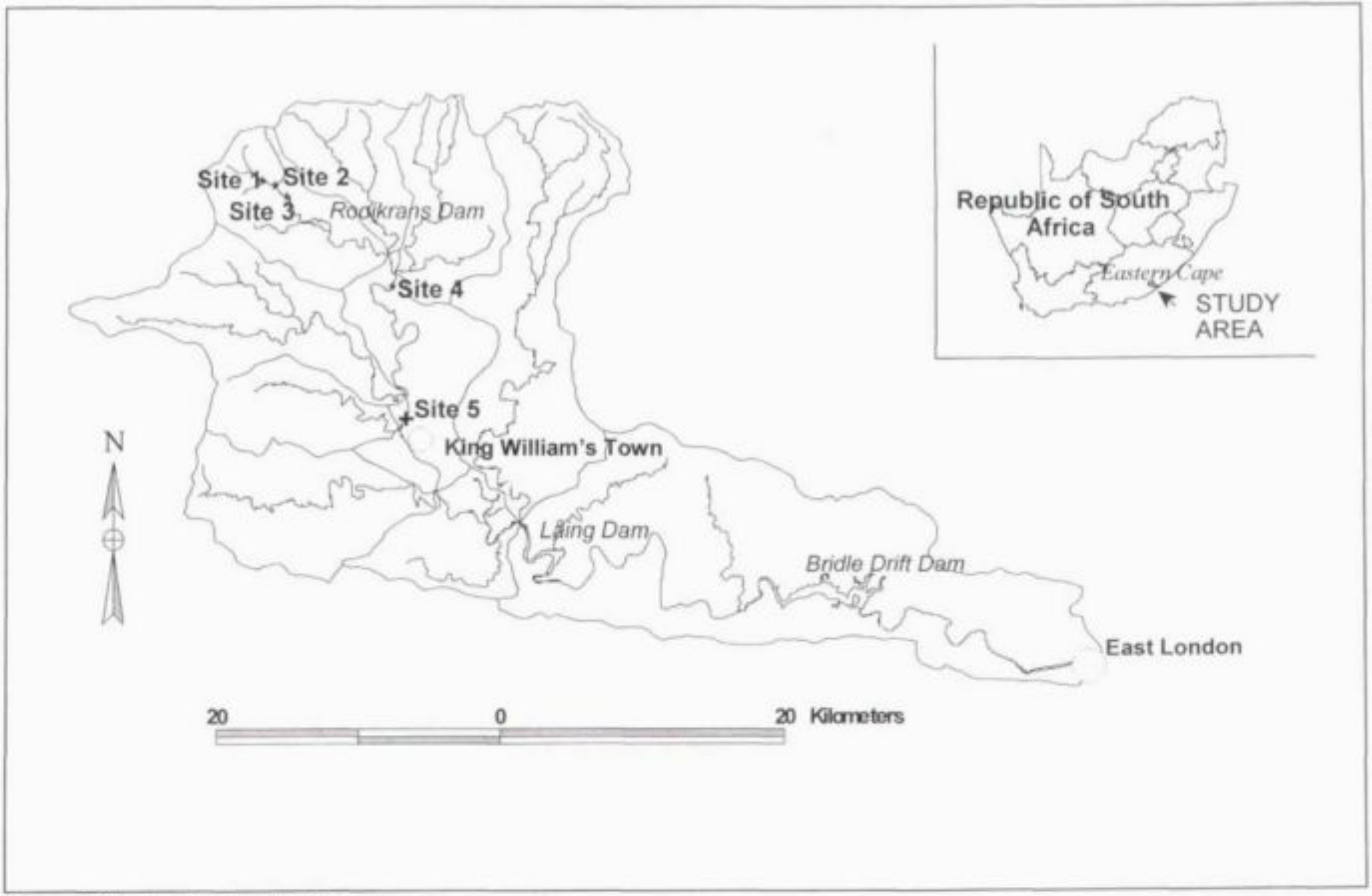


Figure 6.9 The Buffalo River Catchment

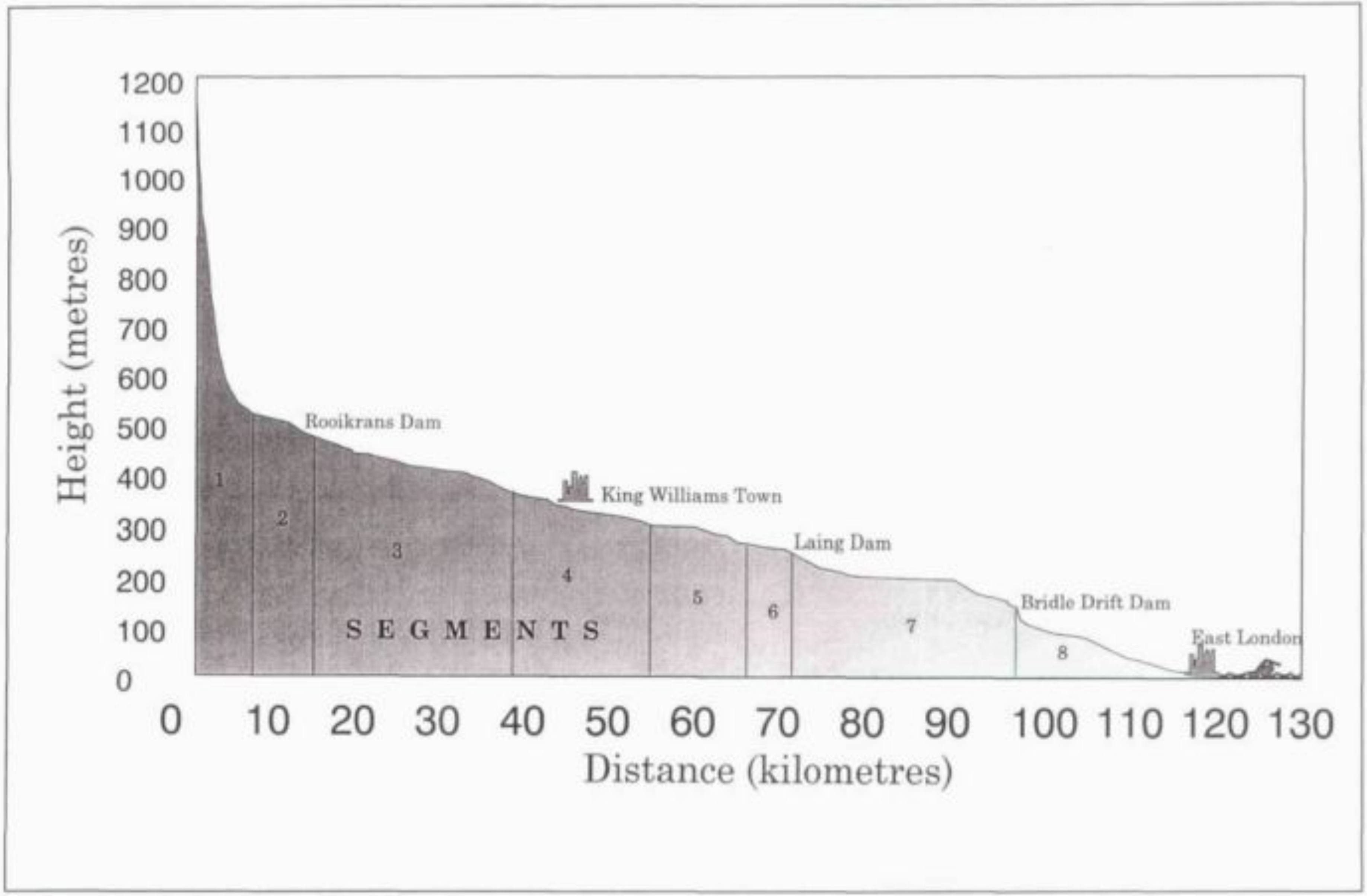


Figure 6.10 Longitudinal Profile of the Buffalo River

Sampling sites

Site 1. Trestle Bridge

The uppermost site is situated in the Amatola mountain foothills within state forest land. This area is dominated by the indigenous Yellowwood species (*Podocarpus latifolius*) . The channel is fairly steep with a 0.17 gradient and has a geology dominated by dolerite. The river channel is a 3rd order stream (Strahler, 1952) flowing within a laterally confined valley with steep, well vegetated slopes. There is no obvious floodplain in this reach but there are well defined terraces. Riparian vegetation consists of dense stands of mature indigenous trees which are situated on the toe, mid and top of the channel banks; these have a wide lateral extent. Indigenous reeds, grasses and shrubs tend to be more open than the trees but also have a wide lateral extent.

The local confinement of the river valley causes a straight, single thread, channel pattern. Reach morphology can be classified as step-pool. The channel is characterised by large clasts organised into discrete channel spanning accumulations that form series of steps separating pools containing finer material. Ashida *et al.* (1981) observed that step-pool morphologies are most strongly developed in regions characterised by high discharges and low relative sediment supplies and that they form on steep slopes (0.07). All these conditions apply to this reach. Specific morphological units associated with this type of reach include plunge pools and small waterfalls, bedrock pools and steps.

Thalweg bed material is dominated by large substratum in the range large cobble to very large boulder; this material forms the macro features of steps and pools. Finer material in the size range of sand, gravel and small cobble are found in pools. The shape of the bed material in this reach tends to be disk like and although loosely packed appears to be quite stable

The presence of a dense riparian zone and very large clasts in the reach produces a good overall channel bank condition. These conditions also meet the habitat requirements of a diverse stream biota by providing lots of cover, deep pool and areas of refuge between the substratum. Fortunately the step pool nature of the reach also provides a natural barrier from upstream migration of introduced exotic species of fish such as trout. Common hydraulic biotope classes include plunge pools, pools, backwaters, riffles, cascades, chutes, waterfalls and runs.

The presence of large clasts at this site produced an irregular channel with complex morphology and flow hydraulics. To account for the diversity of morphology and flow, nine cross sections were selected. The irregular pattern of flow within the channel did not allow the regular spacing of sampling points along each transect. Sampling points were subjectively selected so as to encompass the full range of likely flow conditions. Plate 6.1a and b illustrate the within site variability of flow hydraulics and the complexity of the channel morphology. A plan view of the research site is given in Figure 6.11 while cross sections of surveyed transects, together with sampling points, are given in Appendix A.

Plate 6.1a Photograph of site 1 (Trestle Bridge), looking upstream.

Plate 6.1b Photograph of site 1 (Trestle Bridge), looking downstream.

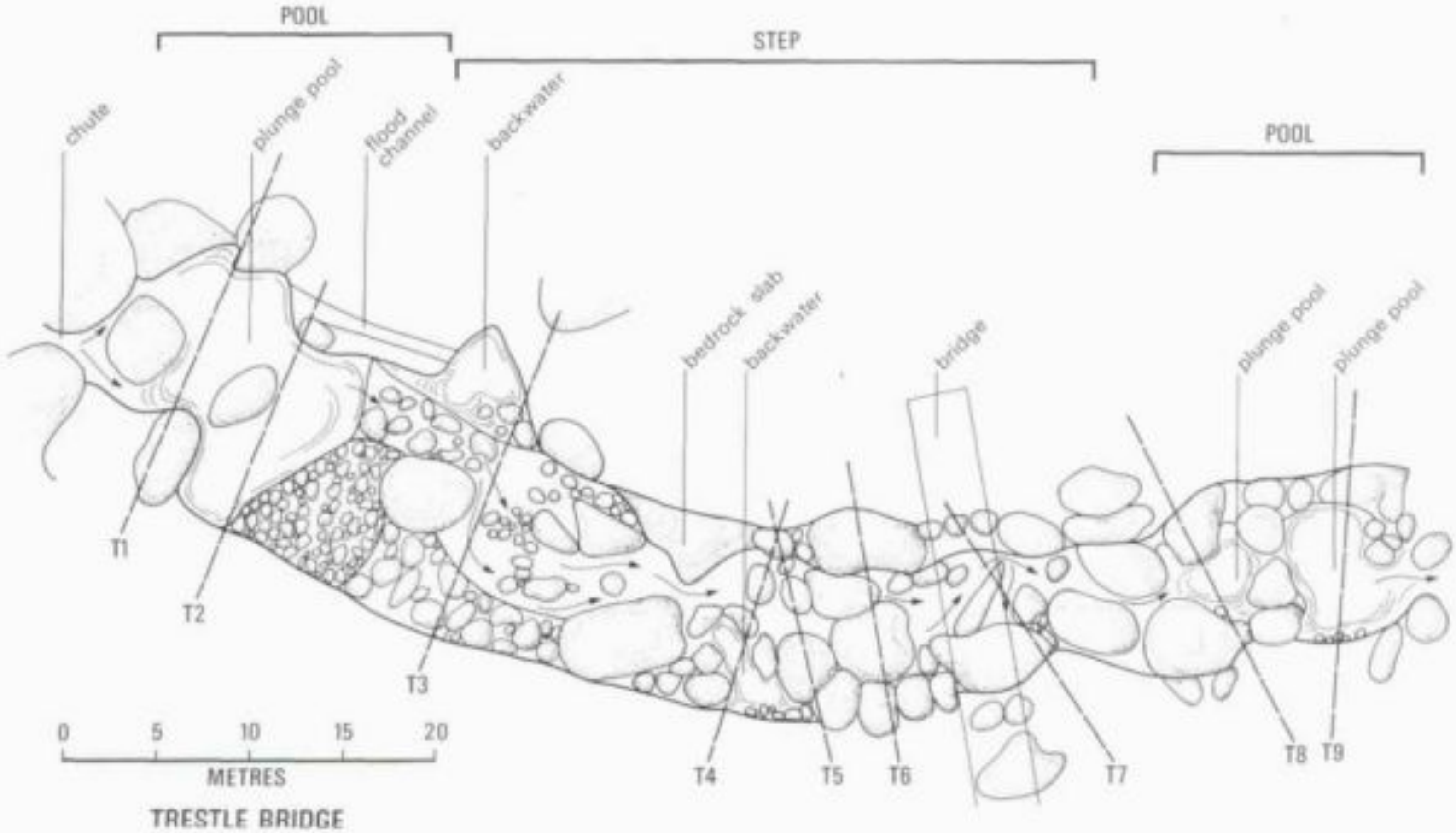


Figure 6.11 Plan view of site 1 (Trestle Bridge)

Site 2. Causeway

This reach is also situated in the Amatola forest reserve and represents a transition between mountain stream and foothill stream. The average channel gradient for this reach is 0.11. The local geology consists of Beaufort group shales and sandstone. The river at this point is still a 3rd order channel, but flows within a wider valley which has low channel banks and a well developed flood terrace. As with the previous reach, riparian vegetation is dominated by dense stands of trees which occupy all positions on the banks. Shrubs, reeds and grasses tend to be more open and situated on the top of banks. All riparian vegetation has a wide lateral extent because of the pristine condition of the catchment in this area.

Channel pattern is more sinuous in this reach as the valley side walls are less imposing. Following the ideas of Montgomery and Buffington (1993), this reach can be characterised as having a plane-bed morphology. The channel lacks well defined bedforms and is characterised by long stretches of relatively planar channel bed that is punctuated by occasional channel spanning bedrock rapids. Flow within this reach is around particles that are large relative to the flow depth. Specific morphological units found within this reach include a plane bed characterised by a series of cascades and shallow pools. The introduction of local flow obstructions such as large woody debris and bedrock outcrops produces local pool and bar formations.

Thalweg substratum was dominated by large cobbles and boulders which were interspersed with finer material in the lee areas. Particle shape was disk like and the larger material tended to be relatively well packed giving rise to a stable bed. Well vegetated channel banks and the lack of incision meant that the channel boundary appeared to be very stable. The aquatic habitat was very diverse with good cover being provided by depth, vegetation and substratum. Common hydraulic biotope classes include pools, backwater pools, riffles, cascades, chutes and runs.

To include the full diversity of channel morphology and flow hydraulics at this site, eight transects were regularly spaced. Along each transect sampling points were subjectively identified, these were marked at a relatively high flow to incorporate the full range of observed flow conditions. Plate 6.2a & 6.2b illustrates the channel morphology at this site. A plan view of the research site is given in Figure 6.13 while cross sections of surveyed transects, together with sampling points, are given in Appendix A.

Plate 6.2a Photographic overview of site 2 (Causeway), looking upstream.

Plate 6.2b Photographic overview of site 2 (Causeway), looking downstream.

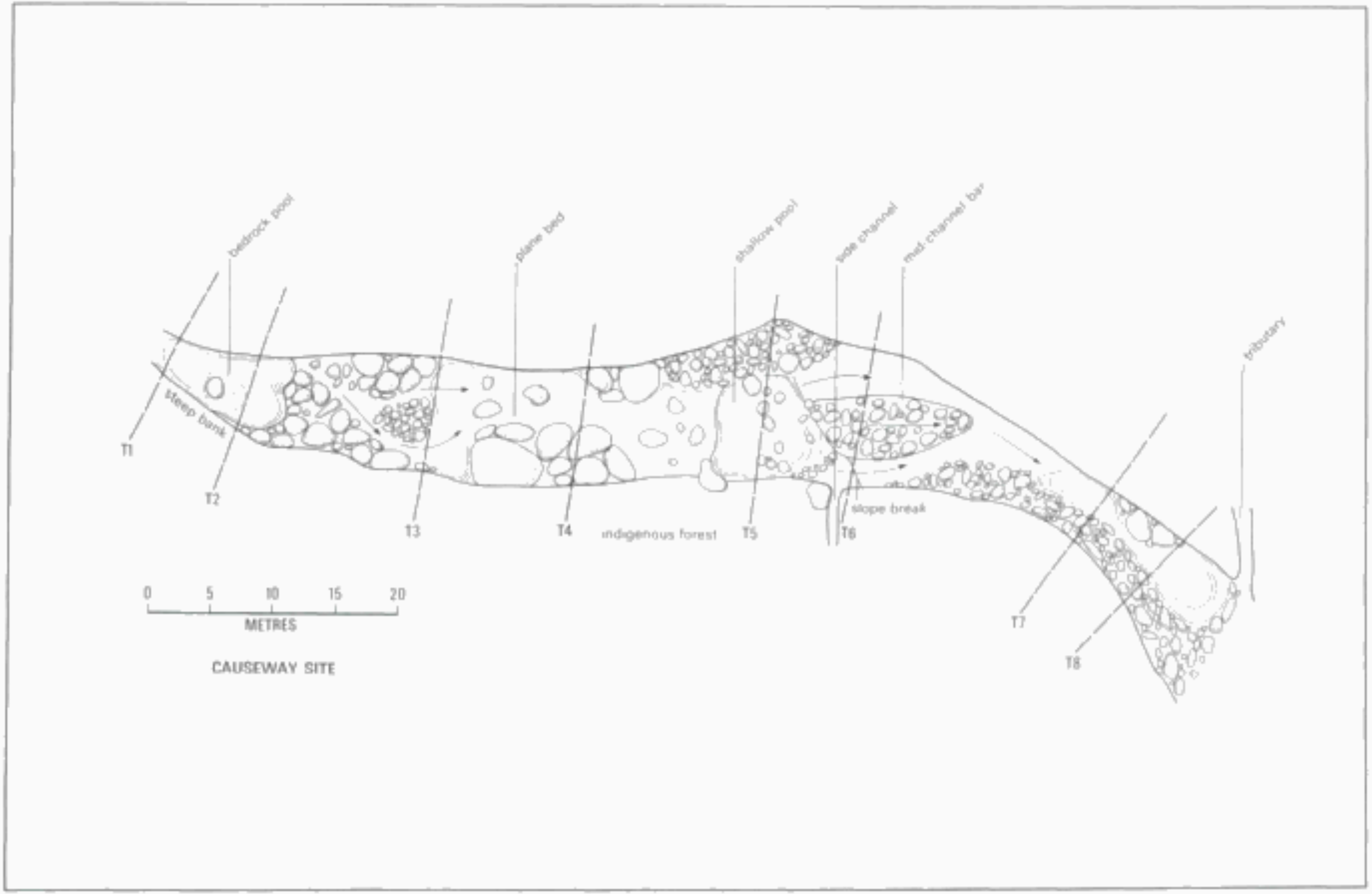


Figure 6.12 Plan view of site 2 (Causeway)

Site 3. Trout pools

This reach is situated on the margins of the Amatola state forest approximately 1 km upstream of Maden Dam. The slope of the channel here has decreased further to approximately 0.0087 and the geology of the reach is dominated by shales and sandstones of the Beaufort group. The channel is a 4th order stream within this reach and contributing runoff area has approximately doubled. Although there is little confinement in terms of the valley side slopes, the channel within this reach is deeply incised with the top of the right hand bank being 3 - 4 metres above the channel bed and being actively undercut in places. Flood waters are free to inundate the left hand bank and there is clear evidence of flood terraces on this side of the channel. Wadeson (1989) estimates a 1.2 year recurrence interval for floodplain inundation within this reach at a discharge of approximately 6 $m^3.sec^{-1}$. Riparian vegetation is dominated by trees and shrubs with little grass being present. The steep and unstable channel banks means that all riparian vegetation is found on the top of these banks.

Channel pattern in this reach tends to be irregular meanders which have an associated reach morphology of riffles and pools. Specific morphological units associated with this reach type are lee bars, lateral bars, alluvial pools and riffles. The reach is dominated by smaller substratum than that found upstream, that is small cobbles and coarse gravels which are interspersed with boulders. Pools of this reach have beds dominated by similar size material which has been covered by a thin layer of fine material (silt and mud). Substratum shape is still disk like and is well packed to create a stable bed; this would explain the tendency for lateral migration of the banks. The undercutting of the channel banks has provided local sediment sources to the channel. This situation is exacerbated by the presence of dense vegetation on the top of these banks which leads to slumping. Despite the areas of local instability this reach provides diverse aquatic habitat for the stream biota. Observations at this site have indicated common use of the pool features by trout. Common hydraulic biotope classes include alluvial pools, backwater pools, riffles, runs, chutes and cascades.

Eight transects were selected at this site, two each for the succession of pools and riffles. Sample points were taken at regular spaced intervals across the pools, but were subjectively selected within the more chaotic flow of the riffles. Photographs depicting the general characteristics of this site are given in Plates 6.3a and b. A plan view of the research site is given in Figure 6.13 while cross sections of surveyed transects, together with sampling points, are given in Appendix A.

Plate 6.3a Photograph of site 3 (Trout Pools), looking upstream

Plate 6.3b Photograph of site 3 (Trout Pools), looking downstream

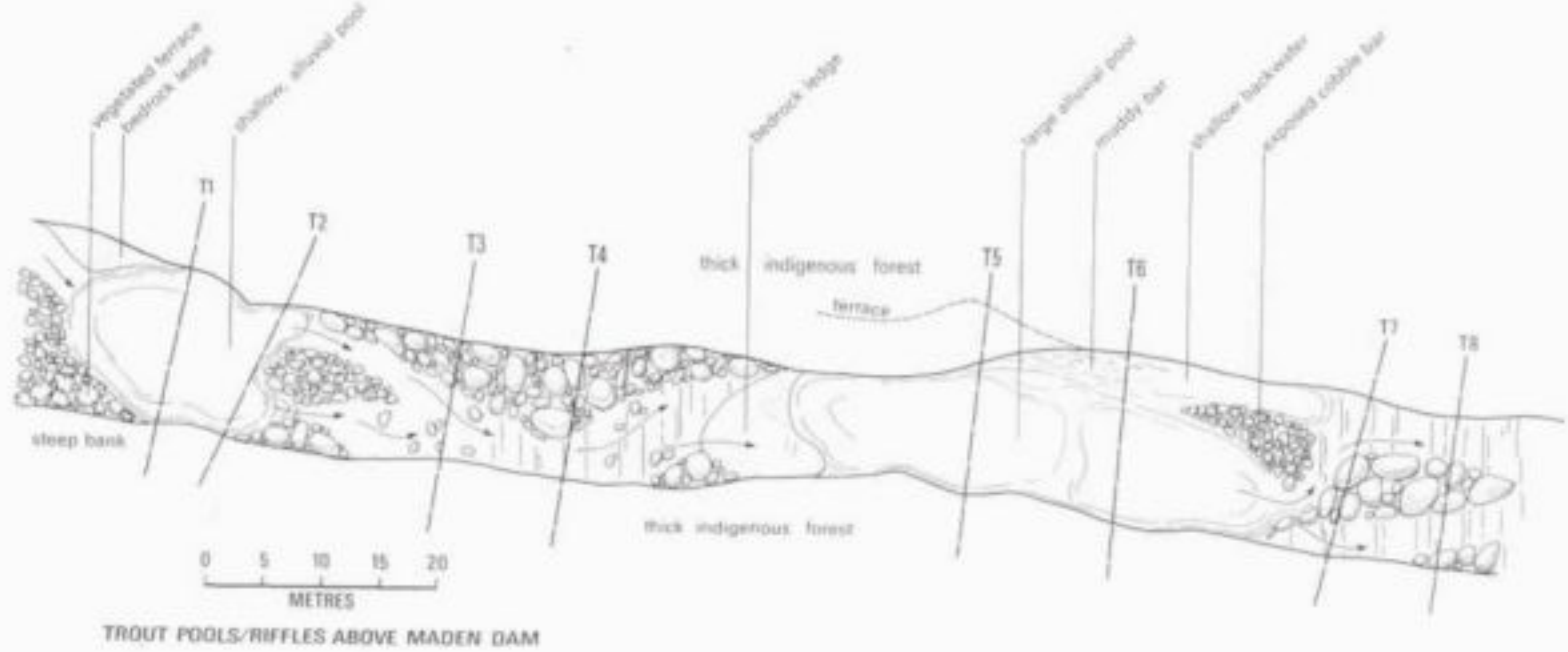


Figure 6.13 Plan view of site 3 (Trout pools)

Site 4. Braunschweig

This reach is situated in the drier lowland areas of the catchment approximately 10km downstream of Rooikrans Dam. Catchment landuse includes local irrigation of farmlands bordering the river and subsistence agriculture and grazing further from the channel. River gradient has flattened considerably within this reach with a gradient of approximately 0.0028 and geology is dominated by shales and sandstone. The river here is a 6th order stream but has a greatly reduced baseflow because of the influence of upstream impoundments (Maden Dam and Rooikrans Dam). The operating rules of these dams do not allow for downstream releases (except for very small quantities of water to the Pirie trout hatchery immediately downstream of Roikrans Dam). River flow in this reach is reliant on tributary inputs and the occasional dam spills. The reach is unconfined with respect to local valley side slopes but the channel is incised. The presence of dolerite on the channel bed would indicate that incision has occurred in the past into fluvial and/or colluvial sediments. Floodplain inundation is likely to occur at an approximately 3 year recurrence interval with a discharge of approximately $40m^3.sec^{-1}$ (Wadeson, 1989).

Woody riparian vegetation occurs as a fairly narrow strip within this reach and is dominated by alien species such as Black Wattle (*Acacia mearnsii*). Evidence of slumping within the incised channel can be seen throughout the reach. Many of these slumps are densely vegetated by growths of small trees and shrubs on the active channel margin. Within the channel there is evidence of vegetation encroachment by reeds in small pockets of sediments on top of small bedrock core bars. The development of these features within this reach of the Buffalo River has been encouraged by river impoundment plus high sediment loads from densely settled areas of the catchment. Grass is the dominant vegetation type as one moves further from the channel, and is encouraged by the removal of trees for firewood.

The channel pattern of this reach is irregular meanders which have formed in response to local controls such as resistant geology. The reach morphology has been described as planar bedrock (Table 3.4). This is characterised by the dominance of fractured bedrock on the bed and the absence of large amounts of alluvial material. Some alluvial material is present but is only temporarily stored in scour holes or behind flow obstructions (a fallen tree in the case of this site). There is also an absence of significant falls or rapids which one might associate with steeper bedrock reaches. The morphological units most commonly associated with this reach are rapids, bedrock pools and bedrock pavement with the occasional alluvial bars and alluvial pools.

The thalweg substratum is dominated by resistant bedrock which has local pockets of coarse sand and gravel either deposited in pools or behind flow obstructions. The smooth nature of the bed means that a small increase in discharge produces velocities necessary to move this material. The bed is very stable but provides a poor habitat for riverine biota. Common hydraulic biotopes associated with this reach include backwaters, pools and chutes.

Because of the regular nature of this channel only three transects were selected. Sampling points along each transect were chosen to incorporate the full diversity of flow conditions observed at a high discharge. A photographic overview of the reach is given in Plate 6.4 and a plan view of the research site is given in Figure 6.14. Cross sections of surveyed transects, together with sampling points are given in Appendix A.

Plate 6.4 Photographic overview of site 4 (**Braunschweig**)

Site 5. King William's Town

The final reach selected for this study is situated on the lowland piedmont zone immediately upstream of the urban centre of King William's Town This area of the catchment receives little rainfall but has a relatively high runoff coefficient due to roads, roofs and paving etc. The land adjacent to the river has been extensively used either for residential settlement or for the irrigation and cultivation of market gardens. This reach can be considered as having a high disturbance.

The gradient of the channel is approximately 0.0056 and geology is dominated by shales and sandstone. A narrow dolerite dike crosses the channel reach immediately upstream of King William's Town. As with the previous reach the channel is a 6th order stream, impacted by upstream impoundments. The influence of these impoundments is not as marked in this reach because of the contribution of tributaries.

The reach is locally confined by valley side slopes. Flood terrace inundation occurs approximately once a year at a discharge of approximately $45m^3.sec^{-1}$ (Wadeson, 1989) and there is evidence of overbank deposition of fines in the size range of sands and silt. The water is often turbid within this reach as a

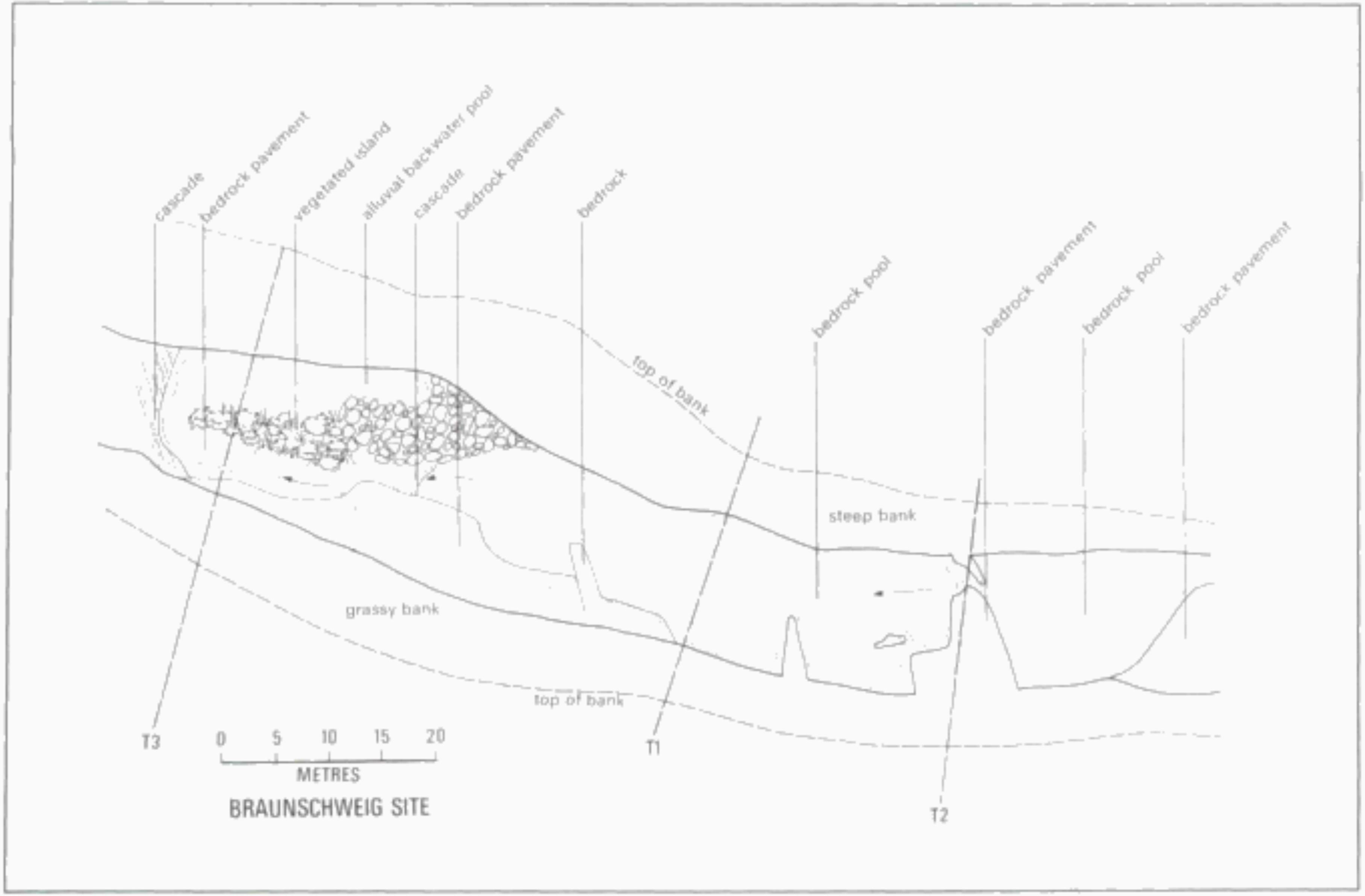


Figure 6.14 Plan view of site 4 (Braunschweig)

result of land use impacts while algal blooms indicate high nutrient contents as a result of irrigation return flows, sewerage inputs etc. The riparian vegetation of this reach is dominated by reeds, grasses, shrubs and trees, all of which show a mixture of indigenous and alien species. The lateral extent of the riparian vegetation is narrow except for the grasses. Trees, shrubs and reeds are present only on the toe and mid bank.

The channel pattern for the upper sections of this reach is anabranching as evidenced by well vegetated islands within numerous channels. Reach morphology is similar to the previous site with a dominance of planar bedrock. As the influence of the dolerite dike is reduced further down the reach, the active channel becomes single thread flowing within a series of alluvial flood channels. These flood channels become active during higher flows when the upstream bedrock controls redirect flow. The morphological units in this reach include waterfall, rapids, plunge pools and bedrock pools. Channel stability is high due to the bedrock perimeter (Plate 6.5). Alluvial material downstream of the dolerite dike is infrequently mobilised by high flows. The aquatic habitat of this reach is poor because of the anthropogenic disturbance and homogenous bed conditions. Common hydraulic biotopes include bedrock pools, backwaters, rapids, cascades, chutes and runs. Due to the homogeneity of the bed it was deemed necessary to select only three transects at this site. Sampling points were selected using the same criteria as the previous sites. A plan view of the research site is given in Figure 6.15, while cross sections of survey transects, together with sampling points, are given in Appendix A.

Plate 6.5 Photograph of site 5 (King William's Town), looking upstream

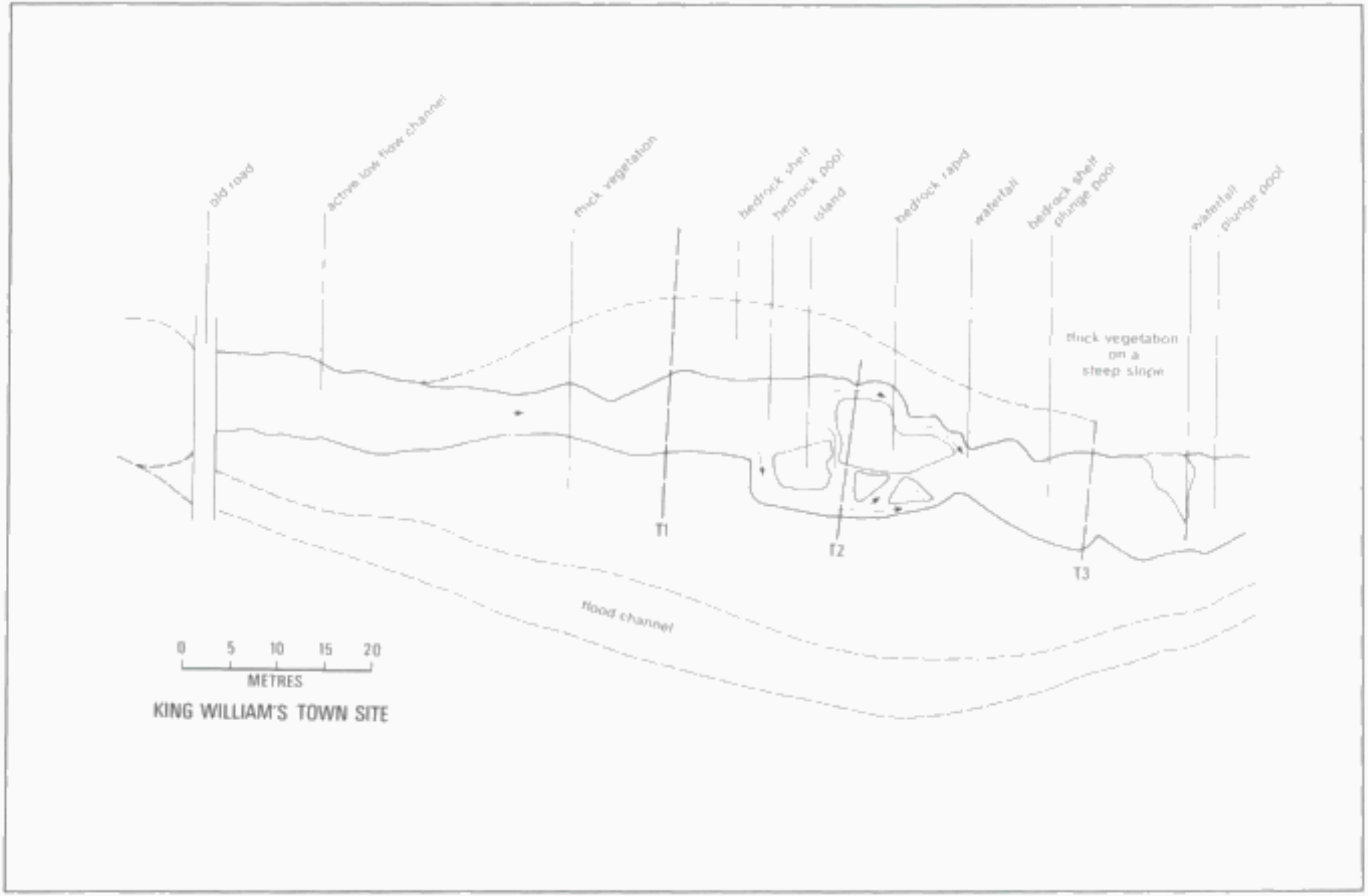


Figure 6.15 Plan view of site 5 (King William's Town)

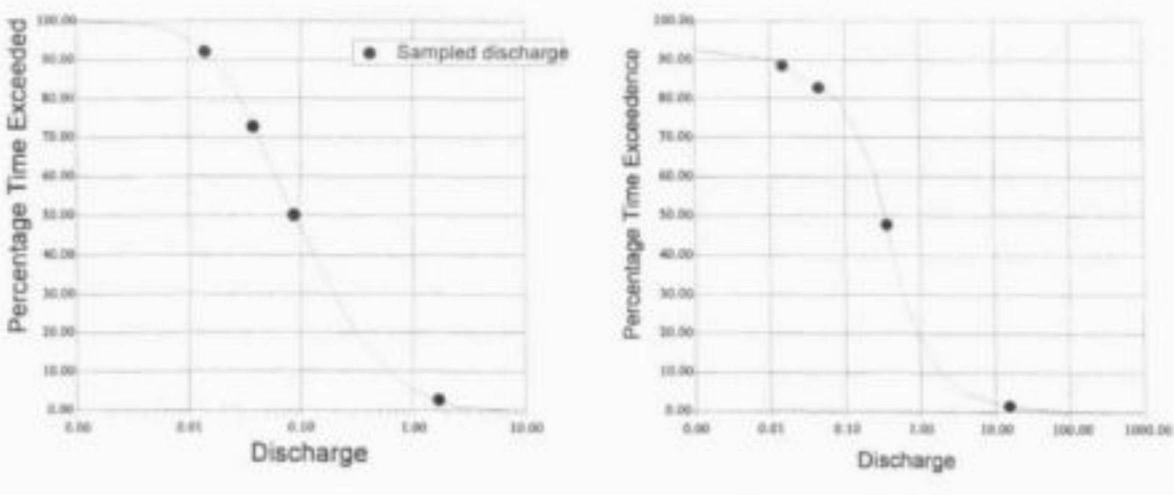
Summary of spatial sampling framework

The number of transects set out at each site was determined by hydraulic variability, both between and within morphological units at a site. A total of 31 transects were laid out and surveyed; 9 at the Trestle Bridge (site 1), 8 each at the Causeway (site 2), and the Trout Pools (site 3), and 3 each at Braunschweig (sites 4), and King William's Town (site 5). At each site transects were positioned so as to incorporate the full range of morphological units (and their associated hydraulic biotopes) recognised within the reach. Along each transect approximately 12 sampling points were selected. Data from approximately 1600 data points was collected for analysis.

A requirement for this study was the collection of data at fixed points at different discharges. The location of sampling points along the transects was such as to incorporate as many different hydraulic biotopes as possible over the probable range of discharges to be sampled. Because of the irregular nature of the channel bed at many of the sites, points were purposefully selected rather than at random or in a systematic manner across the transect. The transects and sampling points are given in Appendix A.

Sampling frequency

Sampling was carried out over four different discharges ranging from a drought base flow to spate. The discharge at the time of sampling was related to flow duration curves constructed from DWAF data available for gauges immediately downstream of Site 3 (R2H001) and Site 5 (R2H005). It was assumed that these gauges would also represents sites 1 and 2 and site 4 respectively. The two flow duration curves are presented in Figure 6.16. The four sampling discharges are indicated on these figures. These were estimated from stage readings taken at the time of each survey, converted to discharge using the relevant discharge tables provided by the DWAF.



Site R2H001 (48 years of data) Site R2H005 (23 years data)

Figure 6.16 Daily flow duration curves

To assess the distribution of discharges sampled in the sites situated some way from the established gauging weirs, stage Plates were fixed in the channel at sites 1, 2 and 4. Regression analysis was carried out to determine the relationships between temporary stage plates and the closest established one. Coefficients of determination (r^2) were calculated as follows: 0.99 between site 1 and site 3; 0.94 between site 2 and site 3 and 0.87 between site 4 and site 5. All of these values indicate a strong positive relationship and suggest the distribution of sampling points within the natural flow regime would probably look quite similar to those shown for the gauged sites.

6.3.4 Data collection

Hydraulic indices

Measurements of depth, velocity, bed profile and water temperature were collected at each point at four different discharges. Data for all sites was collected during the same flow event. As discussed in Chapter Five these variables are the essential components of hydraulic equations to calculate the velocity-depth ratio, roughness height and relative roughness, Froude number (Equation 5.2), Reynolds number (Equation 5.1), shear velocity (Equation 5.6), shear stress and the 'roughness' Reynolds number (Equation 5.9). These indices are used to characterise conditions of flow both near the bed and within the water column of the various hydraulic biotope classes.

Velocity

Flow velocities were measured at the selected points across the channel at 0.6 depth from the water surface. As outlined in Chapter Five the collection of a number of velocity readings within the water column would have been preferable to the six-tenths depth method. Unfortunately limited depth at many points (less than 0.75m) together with numerous sub-surface flow obstructions did not allow the collection of velocity profiles. To standardise the data collection technique a single velocity reading was taken at each point.

Water temperature

Temperature was collected at each sampling site and at each discharge so as to allow the inclusion of a value for kinematic viscosity in the calculation of hydraulic indices.

Bed Roughness

Roughness height and spacing was measured using the profiler described in Chapter 5 (Figure 5.6). Roughness heights were calculated for all points at the separate sites by analysing the bed profiles that had been transferred onto water proof paper in the field. This technique is described in Chapter 5. These measurements are essential components for the calculation of relative roughness, shear velocity and 'roughness' Reynolds number. The data was also used for the classification of boundary roughness after Morris (1955) as discussed in Chapter 5. A further use of this data was to determine potential differences in substratum between sample sites, this data is presented in Table 6.3.

Table 6.3 Roughness height of substratum at five sites in the Buffalo River

SITE	MEDIAN (cn)	10 PERCENTILE (cm)	90 PERCENTILE (cm)
1	10	4	20
2	6	3	12
3	7	2	12
4	3	1	10
5	5	1.5	12

Discharge

Discharges were estimated using the velocity area method (Gordon *et al.*, 1992) and are given in Table 6.4, in all instances discharges were below bankfull. Stage was monitored in the channel at each site using a stage plate.

Table 6.4 Flow discharges measured at the research sites.

	DISCHARGE (m^3 sec^{-1})				
	Site 1	Site 2	Site 3	Site 4	Site 5
1	.015	.015	.015	.033	.015
2	.037	.04	.04	.05	.047
3	.045	.075	.084	.12	.32
4	.93	.97	1.87	.38	15.2

Hydraulic biotopes

Hydraulic biotopes were classified in the field using the concepts and ideas which are formalised in Figure 4.1. At each new discharge, the hydraulic biotopes along each transect were reclassified. The use of photographic evidence for the classification/re-classification of hydraulic biotopes, and as a historic record was considered for this research, but was found to be impractical due to poor light conditions under the forest canopy.

Hydraulic biotopes were characterised using Froude number, Reynolds number, width/depth ratios, the 'roughness' Reynolds number, and flow type (described by Davis & Barmuta, 1989). This enabled an analysis of the hydraulic variability within and between hydraulic biotope features.

6.3.6 Data analysis

Statistical analysis

The PC software programme *Statgraphics 6.0* was used to carry out all statistical analyses. This programme has some limitations as to the amount of data it can process, but was considered adequate for the analysis required in this research. The following statistical procedures were used for various aspects of the data analysis.

Box and Whisker plots

This is a useful technique for exploratory data analysis as it provides a visual display of data distribution and outliers and allows a quick analysis of symmetry (Tukey, 1971).

Analysis of variance - ANOVA

Analysis of variance techniques are used for a set of statistical problems in which one is interested in the effect of one or more variables on a single dependent variable, also called a response variable. The underlying concept of an ANOVA is that sample values almost invariably differ and the question is whether the differences among the samples signify genuine population differences or whether they merely represent chance variations such as are to be expected among several random samples from the source population (Milliken & Johnson, 1984). ANOVA is a statistical test that considers all sample values or groups together.

Multiple Range Analysis

A multiple range analysis is a subroutine within ANOVA, this technique allows comparison between the means for the different levels of each factor. This test calculates whether differences between all possible pairs of means are significantly different or not (Box *et al.* 1978). The test groups those levels that are not significantly different.

Discriminant Analysis

This test derives linear combinations of variables called discriminant functions, independent of each other. The technique may be used to classify new samples with unknown membership into one of the *a priori* groups. The discriminant function is a multivariate technique for sampling the extent to which different populations overlap one another or diverge from one another (Bolch & Huang, 1974). The main use of discriminant analysis in this research was to determine to what extent hydraulic biotope classes could be considered as being correctly classified, and to what extent overlap of data occurred between classes.

Data management

Statistical analysis was initially carried treating the entire data set together, that is hydraulic biotope characteristics were analysed for all sights and all discharges lumped together (aggregated data). A second analysis was carried out so as to compare the five sites and four discharges (disaggregated data).

6.4 AGGREGATED DATA

6.4.1 Introduction

A preliminary analysis was carried out on all data (aggregate analysis) in order to determine which hydraulic indices best quantify hydraulic biotope classes. Two approaches were taken, firstly an exploratory data analysis using box and whisker plots to examine the variability of selected hydraulic indices and, secondly, a multiple range analysis to determine if there were significant differences between the values of hydraulic indices characterising the different hydraulic biotope classes.

Exploratory data analysis was carried out using box and whisker plots to show the variability of hydraulic indices within the various hydraulic biotopes. The initial analysis was carried out by grouping 1600 data points from five sites and four discharges. Summary statistics for these points are given in Appendix B. Initially all hydraulic variables were considered in order to ascertain which indices may best represent hydraulic biotope characteristics. These variables included Reynolds number, Froude number, velocity-depth ratio, 'roughness' Reynolds number, shear velocity, shear stress, relative roughness and roughness height.

Five hydraulic indices were shown to represent some pattern of hydraulic variability across the hydraulic biotope classes, these were the Froude number, Reynolds number, velocity-depth ratio, 'roughness' Reynolds number and shear velocity (Figures 6.17a, b, c, d and e). These variables were used for a more detailed analysis of hydraulic biotope characteristics. The variables shear stress, relative roughness and roughness height showed no pattern of variability between hydraulic biotopes and were therefore excluded from further analysis.

Before any statistical analysis was carried out on the selected variables, distribution curves were created to determine if the variables approximated normal distributions. It was discovered that all variables were positively skewed and therefore needed to be transformed. The most widely used transformation for positively skewed distributions is that in which numbers are replaced by their logarithms. Table 6.5 illustrates the skewness and kurtosis of the selected variables before and after transformation. The idealised normal distribution curve has values of 0 for both skewness and kurtosis.

Table 6.5 Tests for normality of data distribution

Variable	Re	**log Re**	Fr	**log Fr**	Shear Vel	**log SV**	Re*	**log Re***	V/D	**log V/D**
Skewness	5.1	**-0.66**	2.6	**-0.67**	3.2	**-0.67**	8.1	**-0.62**	3.3	**-0.65**
Kurtosis	42.2	**-0.61**	8.8	**-0.89**	15.1	**-0.89**	108	**-0.76**	15.5	**-0.72**

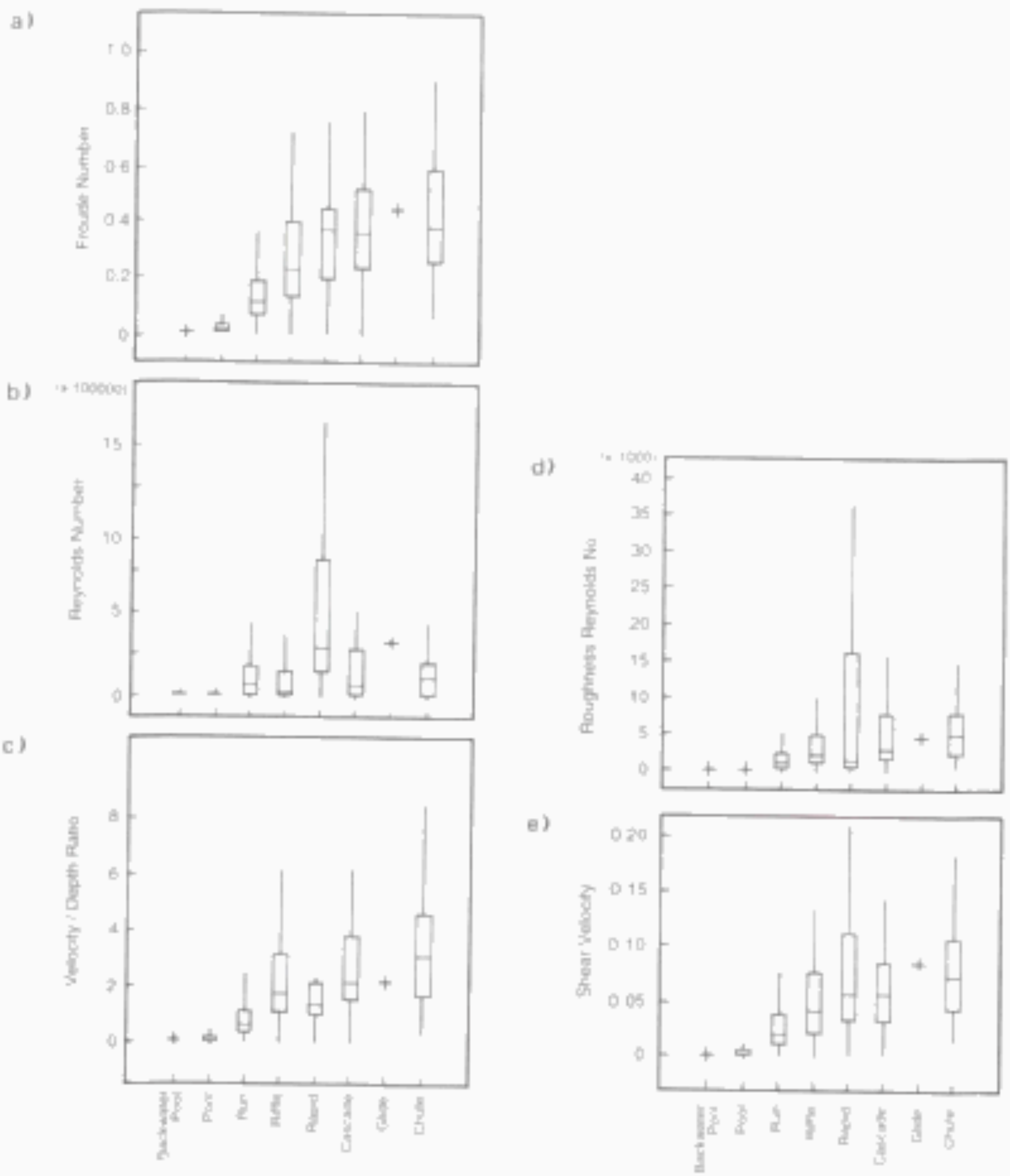


Figure 6.17 Box and whisker plots of selected hydraulic indices for hydraulic biotope classes observed in the Buffalo River

A multiple range analysis routine was performed within an ANOVA statistic (95 % confidence interval) on the transformed data. The least significance test was used, a procedure that allows one to make specific comparisons between hydraulic biotopes when the F-ratio is significant (significance level = 0). The multiple range test calculates intervals for differences between all possible pairs of means, where there is no significant difference between levels the test groups them. The technique provides a useful starting point for the comparison of hydraulic biotope classes.

Results for this analysis are given in Table 6.6, homogeneous groups can be identified by identifying shaded blocks that are common to the various hydraulic biotope codes. For example, in the case of the Froude number all hydraulic biotopes can be considered as significantly different from each other with the exception of the grouping of riffles (4) and rapids (5) and the grouping of rapids (5) and cascades (6). These results are discussed separately for the relevant hydraulic indices.

Table 6.6 Homogeneous groups identified using multiple range analysis (n =1581, confidence level = 99.5, significance level = 0). Where hydraulic biotopes fall within the same column there is no significant difference between them.

Hydraulic biotope	Froude No	Vel/Depth	Reynolds No	Shear Vel	Roughness Re No
backwater					
pool					
run					
riffle					
rapid					
cascade					
glide					
chute					

6.4.2 Froude number

A visual analysis of the box plots in Figure 6.17a shows that the pattern of variability of Froude numbers within the various hydraulic biotopes appear to be different for all classes except riffles, rapids and cascades which have similar variability. These results are similar to those found in previous studies and suggest that certain hydraulic biotopes can be considered as being hydraulically distinct from others in terms of their mean flow characteristics. Summary statistics for data before transformation are given in

Table 6.7. A clear progression can be seen in both mean and median values from one hydraulic biotope class to the next.

Table 6.7 Froude number : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater	317	0.002	0.00	0.004
Pool	619	0.02	0.01	0.02
Run	287	0.12	0.10	0.07
Riffle	146	0.21	0.18	0.14
Rapid	51	0.23	0.19	0.16
Cascade	79	0.25	0.23	0.18
Glide	54	0.49	0.42	0.23
Chute	28	0.41	0.41	0.25

Results of the multiple range analysis in Table 6.6 indicate that in terms of the mean flow characteristics represented by the Froude number, there are significant differences between virtually all hydraulic biotope classes. Classes which have overlap are the riffle, rapid and cascade which have similar mean values.

Consistent with previous studies, the Froude number appears to be a good quantitative index to characterise the mean flow conditions being experienced within separate hydraulic biotope classes. Results from grouped data clearly show that separate hydraulic biotope classes can be recognised but that mean flow characteristics are likely to be quite similar between some classes (riffles, rapids and cascades). It is important to consider, however, that even if mean flow conditions are similar, these hydraulic biotope classes are likely to provide significantly different refuge conditions for organisms living on or near the bed due to different substrate conditions. This initial analysis of grouped data serves to illustrate the potential use of the Froude number as an index to quantify hydraulic biotope characteristics. The role of scale and discharge still needs to be explored.

If we consider the traditional use of the Froude number as an index to determine areas of subcritical ($Fr < 1$), critical ($Fr = 1$) and supercritical flow ($Fr > 1$), it is obvious that none of the hydraulic biotopes sampled fall within the rapid or supercritical flow. Gordon *et al.* (1992) provide an explanation for this by stressing that when point measurements are taken rather than cross sectional averages, critical flow is no longer necessarily defined by $Fr=1$.

6.4.3 Velocity Depth Ratio

The velocity depth ratio is a very similar index to the Froude number, the principle difference being that in the case of the Froude number the affect of depth relative to velocity is reduced through a square root function. Visual analysis of the box plots in Figure 6.17b show a different pattern of variability from that demonstrated using the Froude number. A particularly point of interest is the way in which the rapid class is now clearly distinguishable from riffles and cascades. In terms of a hydraulic biotope progression using the velocity-depth ratio, the rapid should now be positioned between runs and riffles. Summary statistics are given in Table 6.8.

Results from the multiple range analysis given in Table 6.6 indicate that six homogenous groups can be recognised with only one overlap between groups, that between riffles and cascades.

As with the Froude number, the use of velocity-depth ratio appears to be a useful index to quantify mean flow characteristics of different hydraulic biotope classes. It appears to be particularly useful to distinguish rapids from the group riffles and cascades. Unfortunately this index does not distinguish between riffles and cascades.

Table 6.8 Velocity/Depth Ratio : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater	317	0.01	0.00	0.03
Pool	619	0.13	0.07	0.26
Run	287	0.82	0.64	0.72
Riffle	146	1.93	1.28	1.88
Rapid	51	1.27	1.00	1.24
Cascade	79	1.84	1.47	1.59
Glide	54	2.83	2.13	1.76
Chute	28	3.61	2.94	2.47

6.4.4 Reynolds number

Although pilot studies have indicated that, on its own, the Reynolds number is not a good hydraulic biotope descriptor (Wadeson, 1994), the box plots in Figure 6.17c indicates that for the Buffalo River sites it may be more useful. Although this index does not follow the same pattern of progression for hydraulic biotope classes as the previous two indices, there do appear to be clear distinctions between the variability of data between hydraulic biotopes. Summary statistics for this index are given in Table 6.9.

Results from the multiple range analysis (Table 6.6) indicated that six hydraulic biotope classes can be recognised. Relatively clear distinctions are made between the lower energy environments (pools, runs and riffles) but the pattern is considerably more confused when cascades and chutes are included. Although the variability of data is quite distinct in the box and whisker plots, the means of many of the hydraulic biotope classes are similar, hence the confusion in the multiple range analysis.

Results from this study indicate that the Reynolds number appears to be a much better descriptor than had been found in previous studies. The Reynolds number is traditionally used to define laminar flow (<500), transitional flow (500 -2000) and turbulent flow (>2000). Summary statistics from Table 6.9 indicate that in terms of the mean, all hydraulic biotopes experience turbulent condition with the exception of backwater pools which may be transitional. In contrast the median value indicates that more than half the points measured in backwater pools can be considered as being composed of laminar flow (probably almost stationary flow). Results from the range analysis suggest that the Reynolds number is most useful in determining turbulence differences between hydraulic biotope classes in lower energy environments.

Table 6.9 Reynolds number: Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater	317	1754	38	3868
Pool	619	17247	3402	50874
Run	287	88031	40747	101115
Riffle	146	60881	19224	78398
Rapid	51	221550	117595	322425
Cascade	79	112459	73894	116455
Glide	54	319199	255748	246842
Chute	28	92459	36088	130146

6.4.5 'roughness' Reynolds number

An analysis of the box and whisker plots in Figure 6.17d indicate that the patterns of data variability across hydraulic biotope classes for the 'roughness' Reynolds number (a hydraulic index describing near bed flow characteristics) closely approximates the patterns demonstrated by the Froude number (describing mean flow conditions). The range of values for the different hydraulic biotope classes indicates that a certain degree of overlap occurs between hydraulic biotopes. Extreme values produce a skewed data distribution. This can be observed if one compares the mean and median values of the different hydraulic biotope classes. Summary statistics for this index are given in Table 6.10.

Table 6.10 'roughness' Reynolds number: Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater Pool	317	29	1	78
Pool	619	256	97	529
Run	287	1673	1088	1740
Riffle	146	2524	1815	2518
Rapid	51	4782	1714	8257
Cascade	79	4196	2341	6099
Glide	54	8021	6171	6206
Chute	28	7460	4562	12729

An analysis of the box plots indicates that the 'roughness' Reynolds number is a useful index to quantify hydraulic biotopes in terms of their micro flow environments and that in terms of variability, hydraulic biotope classes can probably all be considered separately. Although the box plots indicate clear differences between many of the hydraulic biotopes, the use of range analysis (differences between the means) does not always demonstrate this.

Results from the multiple range analysis (Table 6.6) indicate that five hydraulic biotope classes can be recognised. Three classes are paired in this analysis to form individual groups: backwater pools are recognised together with pools; rapids are combined with cascades and chutes and glides are combined. It does not seem unreasonable, however, to consider pools and backwater pools together in terms of their micro flow environment as it is fairly well recognised that hydraulic mixing is very limited in these environments. Furthermore the combining of cascades with rapids and glides with chutes in terms of their near bed flow characteristics may be a reasonable premise when one considers the harsh environments these hydraulic biotope classes are likely to present to organisms attempting to live on or near their beds.

6.4.6 Shear Velocity

Shear velocity is a measure of the shear stress experienced over an area but expressed in velocity units. As with the 'roughness' Reynolds number, this index represents flow conditions close to the bed and has special significance for bottom dwelling organisms (Davies, 1994). Box and whisker plots in Figure 6.17e show similar trends to those in Figure 6.17d ('roughness' Reynolds number), this is not surprising when one considers that shear velocity is an important component for the calculation of 'roughness' Reynolds number. As with the 'roughness' Reynolds number, this index shows clear differences in the variability between all hydraulic biotopes, but similarities in the mean values for rapids and cascades. Summary statistics are given in Table 6.10.

Table 6.10 Shear Velocity : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater	317	0.0004	0.0001	0.0006
Pool	619	0.004	0.002	0.005
Run	287	0.025	0.019	0.016
Riffle	146	0.035	0.029	0.024
Rapid	51	0.048	0.033	0.045
Cascade	79	0.046	0.035	0.032
Glide	54	0.091	0.083	0.054
Chute	28	0.079	0.063	0.062

The results of a multiple range analysis (Table 6.6) indicate that seven hydraulic biotope classes may be recognised with only two classes being combined; rapids and cascades. Glides and chutes also show some similarity (Table 6.10).

Shear velocity appears to be a very useful index for the quantification of the near bed hydraulic characteristics of different hydraulic biotope classes. The index shows clear differences in its variability between hydraulic biotope classes (as demonstrated in the box and whisker plots of Figure 6.17e) and statistically significant differences between the mean values of most classes (with the exception of rapids and cascades). For grouped data, shear velocity provides better results than those for the 'roughness' Reynolds number by separating glides and chutes.

6.4.6 Discussion

An analysis of box and whisker plots shows that patterns of hydraulic variability within and between hydraulic biotopes recognised in the Buffalo River closely approximate those findings from other studies carried out in South Africa. A similar pattern of progression appears to exist between those studies which have hydraulic biotope classes in common:

backwater pools - pools - run - riffle - *rapid* - *cascade* - chute - *glide*

Unfortunately rapids, cascades and glides were either not present or not recognised in many of the earlier studies so their position in this progression is uncertain. Furthermore there is a need to assess the hydraulic characteristics of such features as boils to see where they might fit within a theoretical progression of hydraulic biotope classes.

An interesting comparison may be made between the median values for aggregate data in this study (***bold***) and published data of Jowett (1993). Jowett used discriminant analysis to separate pools riffles and runs according to the values of velocity-depth ratio and Froude number. The following classificatory values were identified:

	Velocity-Depth Ratio		Froude number	
Pool	< 1.24	***0.07***	< 0.18	***0.01***
Run	1.24 - 3.20	***0.64***	0.18 - 0.41	***0.10***
Riffle	> 3.20	***1.28***	> 0.41	***0.18***

It can be seen from this very simplistic comparison that the results differ markedly between the two studies with the values for the Buffalo River study being considerably lower in all classes. Many possible explanations need to be considered; the New Zealand study did not take into account the influence of changing discharge on hydraulic biotope classification. The study also only considered three classes suggesting a large degree of lumping for those additional classes identified in the Buffalo River study. Perhaps the most important difference that needs to be recognised is the differences in substratum. The New Zealand study was carried out in a gravel bed river while the Buffalo River includes both coarse alluvium and bedrock reaches.

If we use the classification values presented by Jowett (1993) to categorise the hydraulic biotopes recognised in the Buffalo River study we see that according to Froude number, pools, runs and riffles would all be considered as pools while rapids and cascades classify as runs and glides and chutes as riffles. A similar pattern exists using the velocity-depth ratio. It is clear from this example that problems of objective hydraulic biotope recognition need to be addressed, perhaps by the further development and testing of the hydraulic biotope matrix (Figure 4.1).

The analysis of grouped data for all sites and at all discharges serves as a useful means to determine which hydraulic indices best quantify hydraulic biotope characteristics. Although a number of hydraulic indices appear to be useful in the quantification and classification of hydraulic biotope classes, it is inefficient to use them all. The results from this aggregate data analysis agree with previous findings whereby the Froude number, 'roughness' Reynolds number and shear velocity appear to be the most useful variables for both exploratory and statistical data analysis. Together, these indices can be used to characterise both the near bed and the mean water column components of the flow. The remainder of the data analysis carried out in this chapter focuses on these indices.

6.5 DISAGGREGATED DATA

To assess the influence of substratum, scale and discharge on the hydraulic characteristics of the various hydraulic biotope classes, data will be disaggregated to the smallest workable unit, namely the hydraulic biotope. The large number of different combinations of hydraulic biotope classes, discharges and sites for the analysis of different hydraulic variables requires a logical approach to data analysis. The following section attempts to: determine differences between the hydraulic indices describing hydraulic biotope classes at different sites and to determine differences between hydraulic indices describing hydraulic biotope classes at different discharges.

6.5.1 The influence of scale on hydraulic biotope characteristics

Multiple range analysis is used to determine if significant differences exist between the hydraulic indices describing specific hydraulic biotope classes found within five different reaches of the Buffalo River. For the multiple range analysis carried out at this level, a confidence level of 99.7 was selected, this helps to remove "noise" from the data by highlighting the most significant differences. Table 6.11 illustrates the results of a multiple range analysis carried out for all hydraulic biotope classes separately. Not all hydraulic biotope classes were found at all sites. It is also important to note that when determining either homogenous groups or significant differences between sites, this should only be done within individual hydraulic biotope classes. Comparisons cannot be made across classes because of the way in which the multiple range analysis was carried out. All hydraulic biotope classes are displayed together simply to allow ease of comparison between the results for each class.

The trends will be analysed for each hydraulic index in turn.

Froude number

This hydraulic index consistently recognises no significant difference from one site to another for each hydraulic biotope class. The only class which shows any variation in this theme is the riffle where three possible groups may be recognised; all sites together; sites 1 and 2 together; site 3 alone.

Table 6.11 Multiple range analysis by **site** for all hydraulic biotope classes (n = 1581, confidence level = 99.7, significance level = 0). Where sites fall within the same column there is no significant difference between sites falling within the same hydraulic biotope.

Hydraulic biotope class	Site	Froude number	Shear Velocity	Roughness Re No
BACKWATER	1			
	2			
	3			
	4			
	5			
POOL	1			
	2			
	3			
	4			
	5			
RUN	1			
	2			
	3			
	4			
	5			
RIFFLE	1			
	2			
	3			
RAPID	1			
	4			
CASCADE	1			
	2			
	3			
GLIDE	4			
	5			
CHUTE	1			
	2			
	3			
	5			

Shear velocity

As with the Froude number, there is no significant difference in this flow index from one site to another for virtually every hydraulic biotope class, the only exception being the pool class. For this class two groups are recognised: sites 2, 3, 4 and 5 and sites 1,3,4 and 5. For all intents and purposes, the overlap between groups should allow all sites to be considered together. It is possible that differences between sites may be a result of mis-classification of pools in the higher energy environments which dominate sites 1 and 2. The only other hydraulic biotope class showing more than one grouping is the riffle which, although all sites are grouped together at one level, at a second level sites 1 and 2 are grouped together but separated from site 3. This mirrors the pattern shown by the Froude number.

'roughness' Reynolds number

As expected there is a similar variation in the grouping of sites using this index as for the other two hydraulic indices. Hydraulic biotope classes which show significant differences between sites include pool and riffle. All other classes can be considered as not being significantly different from one site to another.

The pool class is considered as two homogenous groups: sites 2, 4 and 5 on the one hand and sites 1, 3, 4 and 5 on the other. As with shear velocity, the overlap allows for grouping of all sites together. The riffle class can be grouped into sites 1, 2, 4 and 5 as one group and sites 1, 3, 4 and 5 as another. As with the pool class all sites are considered the same. Chutes are considered as three groups in this analysis; all sites together, sites 2 and 3 as a group and site 1 as a group on it's own.

Discussion

As evidenced from Table 6.11 the Froude number continues to show good results for the quantification of hydraulic biotope classes across different spatial scales. In the case of every hydraulic biotope class no clear differences are recognised from one site to another. This suggests that not only is the Froude number a good scale independent hydraulic descriptor for hydraulic biotope recognition, but also that the hydraulic biotope matrix (Figure 4.1) would appear to have tremendous potential as a quick technique to accurately identify different hydraulic biotope classes from one site to the next. This partly addresses the question as to how successful is the hydraulic biotope matrix as a tool for hydraulic biotope recognition.

In general terms the hydraulic indices which describe the micro flow environment are also remarkably consistent within hydraulic biotope classes from different sites. Two classes which show some degree of variability from site to site are the pool and riffle. Variability across pools may be explained by the need for the recognition of another class within pools, probably recognised by the dominant substratum type. In terms of channel morphology, alluvial pools are separated from bedrock or plunge pools, this differentiation is not made for hydraulic biotope classes as it was assumed that differences would be picked up using the hydraulic biotope matrix, that is by classifying a point either as a pool or run hydraulic biotope. It would appear that pools defined in the higher energy environments of sites 1 and 2 are different from those found in the other sites and as such may need a separate class of their own.

Variations in the riffle hydraulic biotope class are only significant for the 'roughness' Reynolds number; it is possible that these variations are a result of differences in roughness height. One important point which needs to be considered is the possibility of mis-classification of hydraulic biotopes in the field. It is sometimes difficult to determine accurately the flow type and substrate for a specific point of measurement; rather one often makes generalisations for a patch of flow. Inaccuracies will be greatest in high energy environments which are dominated by large clasts creating highly variable flow conditions across the channel.

6.5.2 The influence of discharge on hydraulic biotope hydraulics

The same method of statistical analysis was carried out to determine what influence discharge had on selected hydraulic characteristics of hydraulic biotope classes. A multiple range analysis within the ANOVA procedure at a 99.7 confidence level was used. The results from this procedure are presented in Table 6.12 and, as with the analysis of results for the influence of site (Table 6.11), homogenous groups cannot be considered across classes, only within a class across discharges.

One observation that can be made from the results presented in Table 6.12 is that the backwater hydraulic biotope was not observed at discharge 4 while rapid and glide hydraulic biotopes were not observed at discharge 1. The degree of complexity in the grouping of discharges within hydraulic biotope classes is higher in the lower energy environments (backwater, pool and run) than the high energy environments of riffle, rapid, cascade, glide and chute. Analysis of results considers each hydraulic biotope class separately, but across all three hydraulic indices.

Backwater

For all three hydraulic indices, the same groupings of discharge are recognised: discharge 1 and 3 and discharge 2 and 3. In other words, there are significant difference between the mean and micro flow conditions of backwaters at discharges 1 and 2.

One explanation for this is that the very low velocities which characterise backwaters and pools are difficult to detect and categorise using the flow conditions observed at the surface as defined by the hydraulic biotope matrix (Figure 4.1).

Another explanation is the possibility that although backwaters may be sub-divided into different units statistically, as is apparent from Tables 6.7, 6.8 and 6.10, they may, or may not, all fall within a limited range of hydraulic conditions which may have little or no influence on the distribution of stream biota. This would mean that it is unnecessary to differentiate between them.

Table 6.12 Multiple range analysis by **discharge** for all hydraulic biotope classes (n = 1581, confidence level = 99.7, significance level = 0). Where discharges fall within the same column, there is no significant difference in the given variable between discharges for that hydraulic biotope.

Hydraulic biotope class	Discharge	Froude number	Shear Velocity	'roughness ' Reynolds No
BACKWATER POOL	1			
	2			
	3			
POOL	1			
	2			
	3			
	4			
RUN	1			
	2			
	3			
	4			
RIFFLE	1			
	2			
	3			
	4			
RAPID	3			
	4			
CASCADE	1			
	2			
	3			
	4			
GLIDE	2			
	3			
	4			
CHUTE	2			
	3			
	4			

Previous evidence from the pilot studies, and a visual analysis of the box and whisker plots (Figure 6.18 a, b, and c) indicate that it is very difficult, if not impossible, to assign a single value to a hydraulic biotope class as the multiple range analysis does. Hydraulic biotope classes are defined by a range of values which appear to increase as discharge increases. The range of values which characterises different hydraulic biotope classes show a progressive increase in variability as one moves from one hydraulic biotope class to the next. The variability of hydraulic indices means that there are areas of overlap between hydraulic biotope classes and suggests that hydraulic biotope classes exist as a continuum with areas of transition from one class to the next. All of these factors could account for statistically significant differences between backwaters recognised at different discharges.

One final point which needs to be considered is the issue of measurement error. Velocity was measured using rotating cups which are not sensitive to the very low velocities that characterise backwaters.

Pool

Ignoring the slight variation in discharge groupings for the 'roughness' Reynolds number, all three hydraulic indices show consistent groupings. Three groups of pools can be recognised within the four discharges; pools of discharge 1, those of discharge 2 and 3 together and finally those of discharge 4. These results are very similar to those observed in the backwater class.

The explanations given for variation of flow hydraulics for different discharges in the backwater class are likely to hold true for this class and are demonstrated in Figures 6.18 a, b, and c.

Run

The pattern of discharge groupings for the run class is consistent across all three hydraulic indices. Only two groups are recognised within this class: discharges 1, 2 and 3 together and discharge 4 on its own.

The run represents a higher energy environment than pools and appears to be less sensitive to smaller changes in discharge (discharge 1, 2 and 3). Using the earlier argument for hydraulic biotope progression, it would seem feasible that runs classified at discharge 4 represent a hydraulic environment close to the theoretical outer ranges and probably overlap with the next hydraulic biotope class making their identification problematic, according to the hydraulic biotope matrix they could be runs (top end of the range) or riffles (lower end of the range). A distinction between slow and fast runs within the hydraulic biotope matrix may be useful, particularly if a relationship is found to exist between these two types of runs and their associated biota.

Riffle

This hydraulic biotope classes shows that the hydraulic conditions describing both the mean and near bed hydraulic environment can be considered to be the same or similar from one discharge to the next. The only variation on this theme is the shear velocity which demonstrates a significant difference between discharges 3 and 4.

Rapid Cascade Glide and Chute

These two hydraulic biotope classes show the same pattern of discharge groupings for all hydraulic indices, that is there is no significant difference between the class recognised at discharge 2, 3 or 4. It must be mentioned that these features were not recognised as being present at discharge 1. Possible suggestions for this are that as discharge increased, runs or riffles either became rapids or glides depending on the appearance of the water surface and the bed material. It must also be realised that as discharge increases so too does the wetted perimeter, creating new hydraulic biotope classes.

Discussion

The analysis presented in this section addressed the question of whether the classification or identification of hydraulic biotopes is discharge dependent?

Results from the multiple range analysis in Table 6.12 indicate that the hydraulic indices of Froude number, shear velocity and 'roughness' Reynolds number are generally useful for the quantification of hydraulic biotope classes at any discharge. Each class appears to be relatively consistent in terms of the selected flow hydraulics, despite changes in discharge.

An interesting result is the apparent increased accuracy of recognition of hydraulic biotope classes across discharge as one moves from a low energy environment (backwater and pool) towards a moderate energy environment (run) to the high energy environments of riffle, rapid, cascade, glide and chute. It would seem as though the hydraulic biotope matrix allows for consistent classification of hydraulic biotopes common in higher energy environments, but may be less accurate in low energy environments. One reason for this may be that the high energy environments are less sensitive to small changes in discharge. For example a standing wave at discharge 1 and a standing wave at discharge 4 are likely to represent similar hydraulics and therefore have a fairly narrow range of values (riffle or rapid). In contrast a faint

small ranges in values for the pool and backwater classes. Although statistically significant differences may occur between discharges, it is questionable whether these have ecological significance.

A relatively high degree of hydraulic variability exists within each hydraulic biotope class with a certain amount of overlap to be expected between classes. It appears that a progression of hydraulic values exist from one hydraulic biotope class to the next. Box plots of variability with discharge (Figures 6.18 a, b and c) are presented to substantiate the theory of overlap and progression. A reasonably clear pattern of progression can be distinguished. It can also be seen that as higher energy environments are encountered, hydraulic variability and overlap between classes increases.

6.5.3 Discriminant Analysis

An analysis of the results for site and discharge differences between selected indices of hydraulic biotope classes indicates that it is reasonable to lump the data for all sites together, but that data could be segregated into three discharge groups; discharge 1, discharges 2 and 3 together, and discharge 4. This grouping can be justified on the basis of the results for the multiple range analysis (Table 6.12) which recognises differences between the hydraulics of the classes of backwater, pool and run.

Discriminant analysis was used to select the variables, or set of variables, which best distinguished between the different hydraulic biotope classes. Nine hydraulic variables were originally considered, four of which were finally selected from their discriminant functions. Table 6.13 presents the results for the three different discharge groups.

Discharge 1 shows poor classification success for the hydraulic biotope classes of pool, riffle and chute. The riffle class improves slightly when three or four classification functions are used. At this discharge, backwaters, runs and cascades are adequately classified and have an improved success with increasing function. Discharge 2 and 3 together show a limited success in the classification of riffle, rapid and cascade, and where more functions are used, chute. A similar pattern is evident for discharge 4. A possible reason for poor classification success is the high degree of variability, and therefore overlap, within these hydraulic biotopes at higher discharges.

The average success for the various discriminant functions is between 39% and 45% for the use of Froude number alone, between 42% and 52% for the use of Froude number with velocity-depth ratio, between 43% and 57% for the use of Froude number, shear velocity and velocity-depth ratio, and finally between 40% and 58% for the use of Froude number, Reynolds number, shear velocity and velocity-depth ratio.

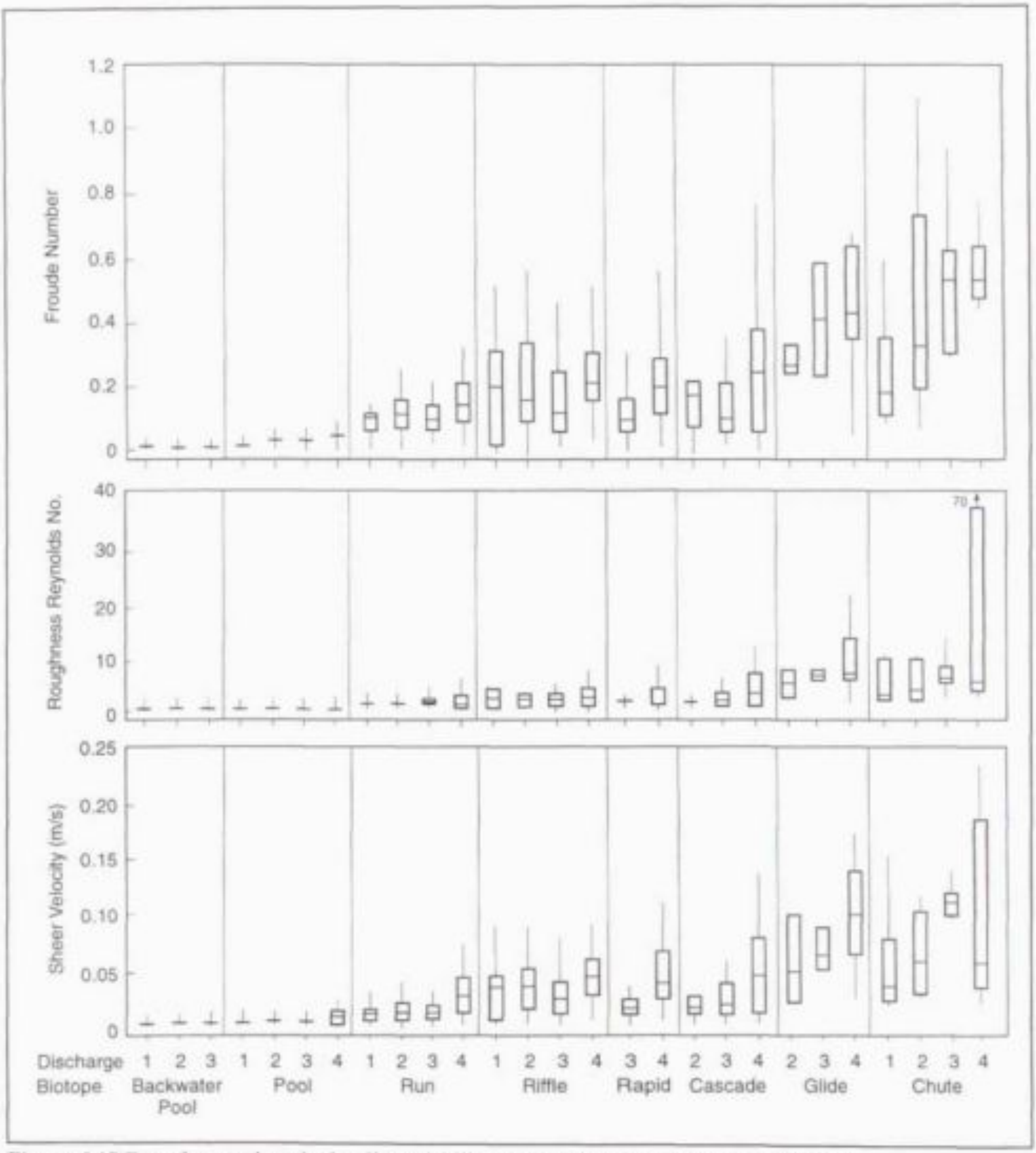


Figure 6.18 Box plots to show hydraulic variability as a response to increasing discharge.

ripple on the surface probably represents considerably different hydraulics from a clearly defined ripple which is almost but not quite a standing wave, and yet they are both classified within the run class. It may be necessary to make a subdivision into fast and slow runs. A second point to bear in mind are the

Table 6.13 Classification success (%) of discriminant analysis using combinations of Froude number, Reynolds number , Velocity-Depth Ratio and Shear Velocity. (Poor classification success is indicated by shaded blocks).

Classification functions ➤	Froude No			Froude & Vel/depth			Froude No, Shear Vel & Vel/depth			Froude No, Reynolds No, Shear Vel & Vel/depth		
Discharge Group	1	2+3	4	1	2+3	4	1	2+3	4	1	2+3	4
Backwater	83	94	-	80	93	-	81	93	-	89	78	-
Pool	38	44	100	38	49	94	39	49	94	34	40	94
Run	66	44	44	69	45	41	63	45	39	63	46	42
Riffle	23	7	16	31	10	18	46	10	22	46	16	32
Rapid		21	8		43	22		29	21		21	27
Cascade	60	15	15	80	4	15	80	0	13	80	0	19
Glide		40	29		80	49		80	53		80	47
Chute	0	46	67	16	38	56	33	38	56	33	39	56
AVERAGE	**45**	**39**	**40**	**52**	**45**	**42**	**57**	**43**	**43**	**58**	**40**	**45**

Discussion

The results from this section indicate a variable degree of success in the use of one or more hydraulic indices to classify hydraulic biotopes. A general pattern emerges which suggests that as a single classificatory index for hydraulic biotope classes the Froude number may be extremely useful. For no extra effort in data collection, an improved classification result can be obtained by combining the Froude number with the velocity-depth ratio. The classification results can be improved slightly by adding a third component, shear velocity. This requires considerable more effort in the collection of data as it requires the measurement of either the velocity profile (if a log linear relationship exists), the water surface slope or the roughness height of substrate elements. The addition of a fourth component, the Reynolds number, makes a minor contribution to the improvement of classification.

The poor classification success for riffle, rapid and cascade classes using any number of variables could be attributed to a number of different things. Firstly the high degree of variability of hydraulic indices, and hence overlap between them, may make it difficult to distinguish between separate classes. The second factor is one that dominates throughout this report, the possibility of mis-classifying hydraulic biotope classes.

The hydraulic biotope matrix was developed late in the overall research programme and was therefore not explicitly used for much of the data collection. The matrix provides a more rigorous and objective approach to hydraulic biotope classification than the subjective classification originally used. It is felt that if this matrix had been available at the start of the research programme, results may have been more conclusive.

6.5.4 Summary

Section 6.5 disaggregates data collected at five different sites and at four different discharges to determine the influence of these two variables on the classification of hydraulic biotopes. Although differences are clearly shown in the frequency distributions of roughness height for each site, statistical analysis indicates that there is no significant difference between selected hydraulic characteristics of the hydraulic biotope classes from site to site. Statistical analysis comparing hydraulic biotope classes across different discharges indicates that there are no significant differences for the higher energy hydraulic biotope classes (riffle, rapid, cascade, glide and chute). Differences were noted for the hydraulic biotope classes of backwaters, pools and runs between discharges; it is not known whether these differences have any ecological significance.

Discriminant analysis indicates that the use of hydraulic indices to distinguish between hydraulic biotope classes is more successful for backwaters, pools, runs and glides than they are for riffles, rapids, cascades and chutes. Average values for successful classification of hydraulic biotope classes range between 39% and 58% depending on the number of discriminant functions used. Easily collected and useful hydraulic variables to quantify differences between hydraulic biotope classes are the Froude number and the velocity-depth ratio.

Results from this section indicate that the hydraulic biotope matrix has potential as a useful tool for the identification of different hydraulic biotope classes in the field. It is suggested that the matrix may need further refinement by the addition of hydraulic biotope classes in the lower energy environments (backwater, pool and run). This refinement, however, may not be necessary if the distribution of aquatic organism does not show a corresponding response to the hydraulic variations within these hydraulic biotope classes.

It would appear that the hydraulic indices of Froude number, velocity-depth ratio, 'roughness' Reynolds number and shear velocity are useful quantitative measures to characterise the mean and near bed flow characteristics of various hydraulic biotope classes. It is envisaged that general classification values for these indices can be obtained using selected percentile values as given in Table 6.14.

Table 6.14 Percentile values for hydraulic indices characterising hydraulic biotopes

Hydraulic Biotope	Percentile	Reynolds Number	Froude Number	Velocity-Depth Ratio	Shear Velocity	'roughness' Reynolds Number
Backwater	25	12	.00005	0.0003	.000009	0.36
	50	38	.00008	0.0007	.00001	1
	75	1695	.004	0.010	.0007	26
Pool	25	61	.0003	0.009	.00007	7
	50	3402	.011	0.064	.001	97
	75	9268	.028	0.153	.005	294
Run	25	7157	.066	0.366	.010	491
	50	40747	.108	0.644	.019	1088
	75	154705	.161	1.07	.030	2284
Riffle	25	9543	.108	0.718	.017	939
	50	19224	.180	1.280	.029	1815
	75	103464	.312	2.28	.049	2941
Rapid	25	39092	.102	0.49	.020	922
	50	117595	.190	1.0	.335	1714
	75	248236	.306	1.33	.055	3677
Cascade	25	14943	.097	0.639	.018	1092
	50	73897	.236	1.472	.036	2341
	75	150224	.392	2.238	.068	4695
Glide	25	162790	.330	1.646	.058	3893
	50	255748	.420	2.135	.086	6171
	75	440727	.635	3.744	.123	11590
Chute	25	13954	.189	1.779	.028	1648
	50	36088	.412	2.947	.066	4562
	75	122759	.581	5.00	.098	8961

6.6 HYDRAULIC BIOTOPES AND ROUGHNESS FLOW CLASS

As discussed in Chapter 5, Davis and Barmuta (1989) classified flow over rough surfaces into four categories based on the roughness height and spacing of elements protruding from the channel bed:

- Isolated roughness flow - when the roughness elements are far apart and the vortices in the wake behind each roughness element are completely dissipated before the next element is reached (Figure 5.5a).
- Wake interference flow - when the roughness elements are closer together and the eddies from these elements interact causing intense turbulence (Figure 5.5b).
- Skimming flow - when roughness elements are so close together that flow skims across the crests and the spaces between the roughness elements are filled with much slower water containing stable eddies (Figure 5.5c).
- Chaotic flow - when roughness elements protrude through the water surface and flow conditions become very complex as water flows over and around these large obstacles (Figure5.5d).

Results are presented to demonstrate associations between flow classes as determined by bed roughness and hydraulic biotopes classified in terms of surface flow conditions. Following the research findings presented earlier in this chapter, indices characterising different hydraulic biotope classes were combined for all sites and all discharges. The distribution of flow classes are illustrated in Figure 6.19 and are summarised in Table 6.15. The presence of many different types of flow class within each hydraulic biotope illustrate the high degree of hydraulic variability which characterises these instream flow environments.

Table 6.15 Distribution of roughness flow classes by hydraulic biotope (Values in brackets indicates percentage of cases falling within that categories)

Hydraulic biotope	Dominant flow class	Second most frequent flow class	Third most frequent flow class
Backwater	Smooth (70)	Skimming (14)	Chaotic (8)
Pool	Skimming (33)	Smooth (27)	Chaotic (28)
Rapid	Skimming (53)	Chaotic (27)	Isolated (18)
Glide	Skimming (45)	Chaotic (34)	Isolated (15)
Run	Chaotic (44)	Skimming (36)	Isolated (14)
Cascade	Chaotic (53)	Skimming (31)	Isolated (9)
Riffle	Chaotic (65)	Skimming (26)	Isolated (5)
Chute	Chaotic (75)	Skimming (18)	Isolated (7)

Backwaters and pools separate out as one group, being dominated by a combination of smooth and skimming flow. Surprisingly, chaotic flow comes out as the third most frequent class. This may be a reflection of the shallow nature of some pool biotopes, with large cobbles and boulders protruding through the surface. All other hydraulic biotopes were dominated by skimming and chaotic flow, with isolated roughness flow as a less frequent third class. Table 6.15 shows a progressive increase in chaotic flow from rapids, glides, runs, cascades, riffles to chutes. It can be seen from this table and from Figure 6.19 that rapids and glides are very similar, as are runs and cascades and riffles and chutes.

These groupings are noticeably different from those identified earlier for mean and near-bed conditions. As expected the two pool classes are clearly different from the rest, but the grouping of glides with rapids and runs with cascades is a departure from earlier findings. These groupings relate more closely to substrate conditions than to the bulk flow and provide a useful secondary level of classification and strengthen the validity of the hydraulic biotope classification. For example, whilst riffles and rapids are similar in their bulk and near bed flow characteristics (Table 6.14), they are quite different with respect to roughness flow class. This, together with a clear difference in the potential mobility of the substratum, fully justifies their classification as different flow environments. The same argument can be applied to glides and chutes which also have similar mean and near-bed flow characteristics, but differ significantly in terms of flow roughness class.

Figure 6.19 Distribution of roughness flow classes by hydraulic biotope

6.7 CHANNEL MORPHOLOGY, HYDRAULIC BIOTOPE DISTRIBUTION AND THE INFLUENCE OF DISCHARGE.

6.7.1 Introduction

It has been established through the research described in this chapter that a hydraulic biotope classification based on visual observations of surface flow characteristics and substrate can be used to identify hydraulically distinct instream flow environments. Hydraulic biotope terminology has been developed in relation to that of morphological units and it is generally believed that there is a strong association between the two. It is anticipated that for a particular morphological unit there is a discharge dependent assemblage of morphological units. If such an association does exist it could provide the basis of a cost effective method of assessing discharge related changes in available habitat such as is required for example in assessment of Instream Flow Requirements. The relationship between hydraulic biotopes and their host morphological units is examined in this section.

Table 6.16 Morphological Units recognised within five research sites of the Buffalo River.

MORPHOLOGICAL UNIT	Site 1.	Site 2.	Site 3.	Site 4.	Site 5.
Alluvial Backwater Pool				★	
Alluvial Pool			★		
Bedrock Pool		★		★	★
Plunge Pool	★				★
Bedrock Pavement				★	
Plane Bed		★			
Step	★				
Riffle		★	★		
Rapid					★

Table 6.16 presents the distribution of morphological units per site. For the purpose of analysis morphological units were subdivided into two groups: pools and hydraulic controls. Pools are scour or erosional features with relatively high depths relative to width and within which the macro-scale flow hydraulics are controlled by a downstream hydraulic control. The hydraulic controls are usually aggradational or erosionally resistant features, such as steps, plane-beds, riffles or rapids, with relatively low depth relative to width and within which the macro-scale flow hydraulics are not controlled by downstream hydraulic features. Shallow flows and large bed material calibre leads to micro-scale hydraulic controls at low flows so that these features tend to be hydraulically complex.

Sites in the Buffalo River were also divided into two groups, the three upstream sites and the two located in the middle reaches. The upstream sites are all located in reaches characterised by coarse alluvium whereas the downstream sites are bedrock controlled. The two groups can also be distinguished in terms of sampled events with respect to their flow duration curves. Although the two sets of flow duration figures are not greatly different (Table 6.17), the flow duration curve for the downstream site was constructed from flows which have been impacted by upstream impoundments. The low flows in particular are well below their natural levels.

Table 6.17: Flow exceedence for the two groups of sites

Flow exceedence (%)	
Upstream sites	**Downstream sites**
92	88
73	82
50	48
3	1

6.7.2 Data analysis

Each site was divided into clearly recognisable morphological units and stacked bar graphs plotted to represent the abundance of different hydraulic biotope classes for each of these units at each discharge (Figures 6.20, 6.21, 6.22, 6.23). The graphs give a good visual indication of both the diversity of hydraulic biotopes and the dominant hydraulic biotope at each discharge. The analysis was kept at a subjective level as the lack of replication of morphological units did not justify a more objective statistical analysis.

6.7.3 Upstream sites (Sites 1-3)

Pool Morphological Units

The three types of pools, alluvial pool, bedrock pool and plunge pool, all showed a similar response, with backwater and pool dominating at the three lowest discharges and a significant increase in run biotopes at the highest discharge (Figure 6.20). The inclusion of some riffle flow at high discharges may have been due to the lateral extension of the water into shallow margins with high relative roughness. Hydraulic biotope diversity was low for all pools at all discharges, with hydraulic biotopes concentrated in one or two classes. The bedrock pool at the causeway site is particularly consistent. Maximum diversity occurred at discharges with flow exceedence between 73 percent and 50 percent. Some diversity was lost at spate discharges as runs came to dominate the pools.

It is clear that at discharges with flow exceedence between 92 percent to 50 percent there was little change in the type of hydraulic habitat available whereas a major change took place when the river was in spate. Unfortunately no intermediate discharges were sampled so that it is not possible from the available data to pinpoint the discharge exceedence at which major changes started to take place.

Hydraulic Control Morphological Units

In the case of hydraulic controls - the step, plane bed and riffle - greater differences can be observed between the three morphological units. It is clear that at all discharges there was a far greater diversity of hydraulic biotopes. The step morphological unit showed a general increase in diversity from discharge 1 to discharge 4, with both a greater number of hydraulic biotopes present and a more uniform distribution amongst the different biotopes (Figure 6.21). Low energy biotopes such as backwater and pool gave way to high energy biotopes such as chutes, cascades and rapids. Run and riffle biotopes were maintained at all discharges.

At low discharges the plane bed had a relatively high diversity, dominated by pool and backwater. Runs, riffles and cascades were also present. As discharge increased backwaters were lost and pools were largely replaced by runs. Riffles and cascades were maintained. This pattern continued through the higher discharges, with increases in runs at the expense of pool and replacement of cascades by chutes at the highest discharge. Diversity was lowest at the highest discharge.

Perhaps surprisingly, riffle biotopes only came to dominate the riffle morphological units at discharge 3 when maximum diversity was observed. At low discharges the riffle was dominated by pool biotopes, with run and riffle being more or less evenly represented. At the highest discharge, increasing flow depth over the coarse cobble substrate caused riffle biotopes to give way to runs; pool biotopes disappeared and chutes and cascades also became significant as water began to flow over the largest cobbles.

With the exception of the plane bed, all morphological features showed a significant increase in hydraulic biotope diversity as discharge increased from 92 percent flow exceedence to 73 percent exceedence. Little change in overall diversity occurred as flow increased to the 50 percent exceedence level, but diversity tended to fall significantly at the highest discharge. It would therefore seem that a discharge lying between the 70 percent and 50 percent exceedence level would be the most favourable in maintaining the greater diversity of habitat.

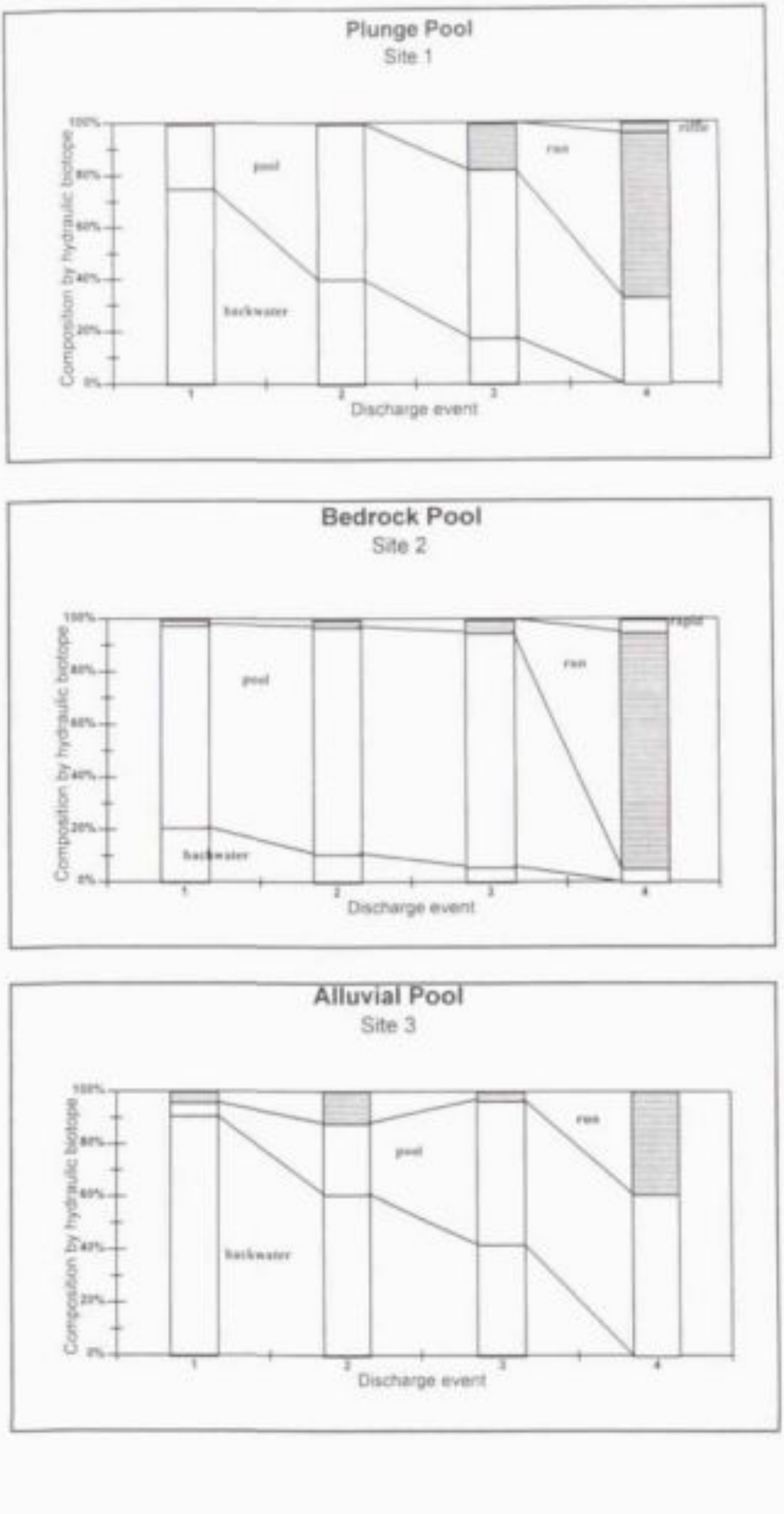


Figure 6.20 Variation in the distribution of hydraulic biotopes with discharge for pool morphological units in the upstream sites.

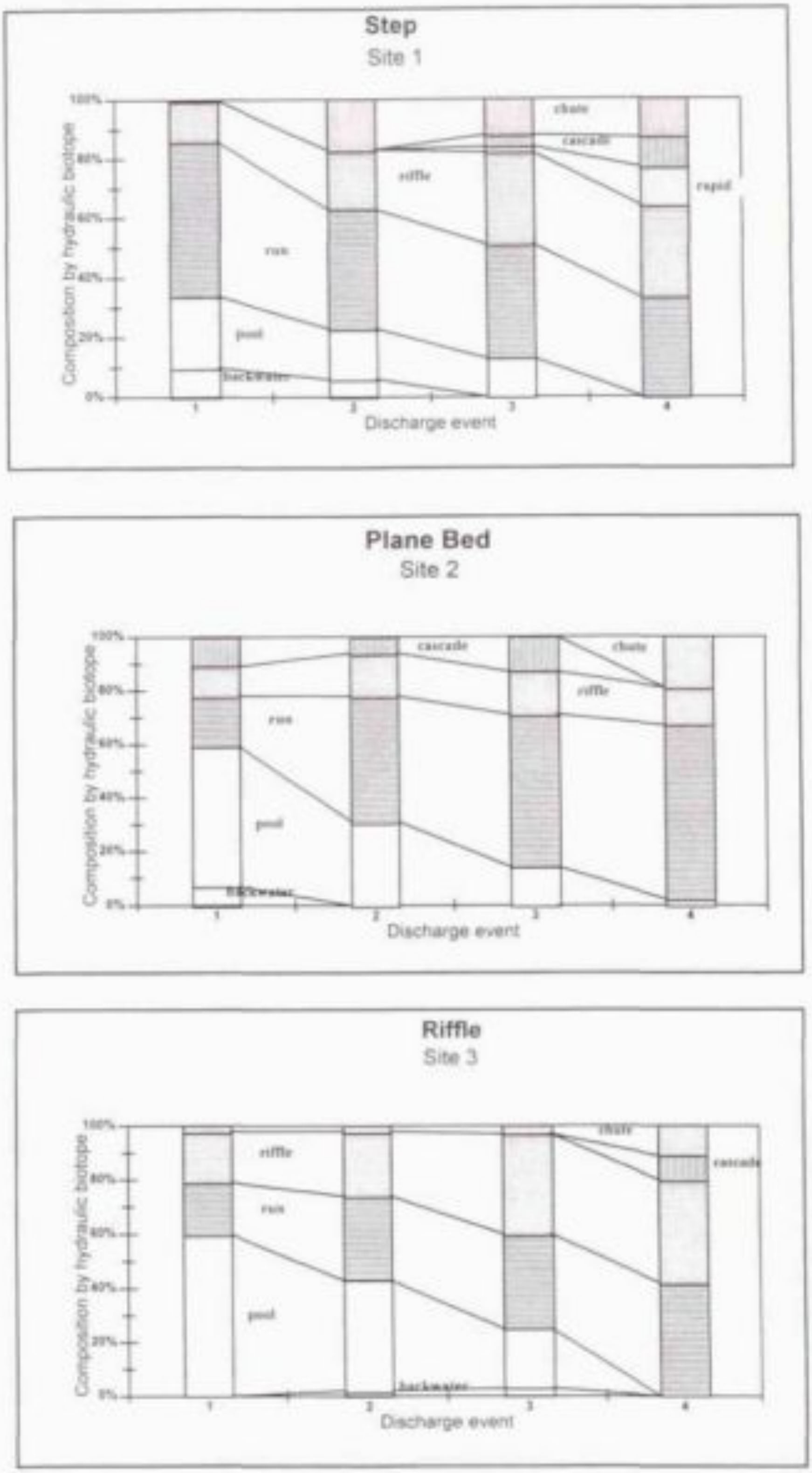


Figure 6.21 Variation in the distribution of hydraulic biotopes with discharge for hydraulic control morphological units in the upstream sites.

6.7.4 Downstream sites (sites 4 & 5)

Pool Morphological Units

Three pool types were studied in the lower reaches: bedrock pool, plunge pool and alluvial backwater (Figure 6.22). As in the upper sites, backwater and pool hydraulic biotopes dominated at the lower discharges. In the alluvial backwater the backwater hydraulic biotope persisted as the only biotope except at the highest discharge when the backwater channel became connected to the main channel and the hydraulic biotope classification changes to pool. The plunge pool lost the backwater class more quickly than did bedrock pools, but maintained a significant proportion of pool even at the highest discharge. This may have been due to the more irregular morphology of this feature. The main difference between pools at the bedrock controlled sites compared to those at the alluvial sites upstream was the presence of the glide hydraulic biotope at the highest flows in place of chutes, riffles or cascades. This is a result of a relatively fast flow over a smooth bed.

Hydraulic Control Morphological Units

The two morphological units classified as hydraulic controls found in the bedrock controlled sites were a bedrock pavement and a rapid . As with their counterparts upstream a much greater diversity was associated with these morphological units (Figure 6.23).

The bedrock pavement exhibited a relatively diverse assemblage of hydraulic biotopes at all discharges. Backwater, run and pool were all present at the lowest discharge; as discharge increased glides appeared, followed by rapid which replaced much of the run hydraulic biotope at the highest discharge. The highest discharge was also associated with the re-appearance of the pool hydraulic biotope due to the extension of the wetted area towards the channel margins and incorporation of new channel areas into the flow.

Rapids had the highest diversity at discharge 3 (48% exceedence) with chute, glide, run, pool and backwater hydraulic biotopes being present. At the highest discharge (1% exceedence) both pool classes were lost, whilst at lower discharges (>82% exceedence) pool became more extensive and chute was lost, followed by glide hydraulic biotopes. At the lowest discharge (88% exceedence) the only hydraulic biotope was backwater. It is interesting to note that at no discharge was the rapid hydraulic biotope recorded.

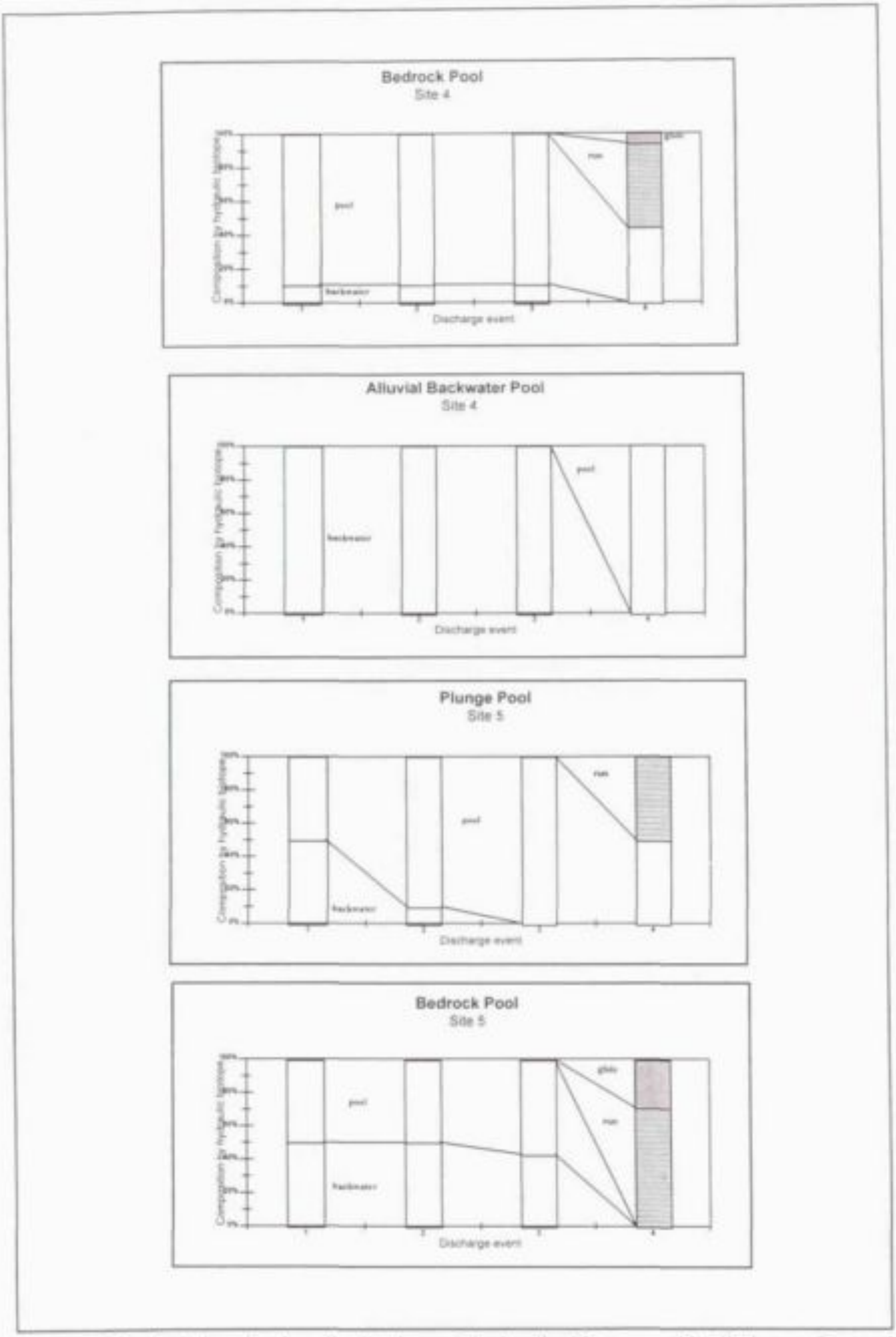
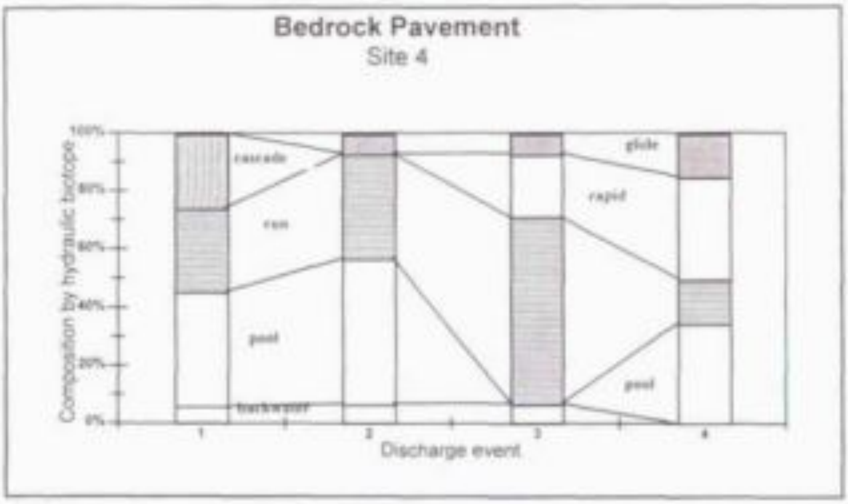


Figure 6.22 Variation in the distribution of hydraulic biotopes with discharge for pool morphological units in the downstream sites.



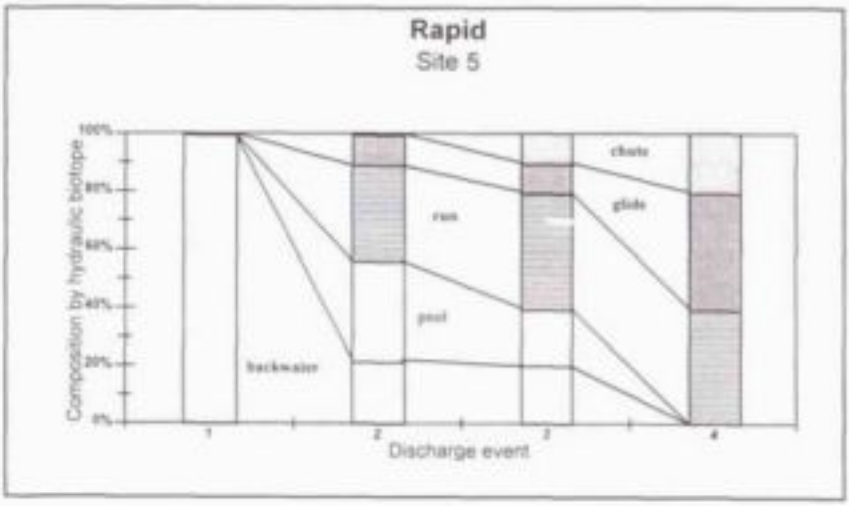


Figure 6.23 Variation in the distribution of hydraulic biotopes with discharge for hydraulic control morphological units in the downstream sites.

6.7.5 Summary and discussion

For selected morphological units in the upper and middle reaches of the Buffalo river it has been shown that available habitat described in terms of hydraulic biotope classes varies both between morphological units and with discharge. Not surprisingly, the pool morphological units showed the least diversity of hydraulic biotope classes whilst hydraulic controls, due to their high relative roughness and shallow depth, provide far greater habitat diversity at all measured discharges. The next challenge is to extend the research to a wider range of morphological units and river environments to see if general relationships can be found.

Backwater, pool and run were the three hydraulic biotope classes which were not associated exclusively with specific morphological units: they were equally as common in all channel morphology. Glides were associated with smooth beds consisting of unfractured bedrock which provided little frictional resistance to fast shallow flow and resulted in a smooth water surface. Rapids were commonly associated with fractured bedrock or large well imbedded boulders, the substratum which makes up bedrock pavement, bedrock pools and plane bed morphologies. At the sampled discharges the roughness height projection of this material was enough to create standing waves on the water surface. Cascades, chutes and riffles were associated with the larger alluvial material which may be periodically moved by large floods. This material made up the plane bed, step and riffle morphologies of the research areas. The substratum creates a high roughness influence on the flow which is evidenced by undular standing waves in riffles. In these morphological units the flow is often laterally confined or funnelled between large clasts to create chutes. If discharge is high enough to overtop these large clasts, small falls or cascades occur.

In all morphological units examined, a clear progression appeared to exist from the dominance of one hydraulic biotope class to another as discharge increased. This pattern of progression was dependent upon the association between morphological units and hydraulic biotope classes. For example a riffle morphology may be dominated by the following hydraulic biotopes at low discharges: backwater, pool, run, riffle and chute. At high discharges the pattern changes to run, riffle, cascade and chute. A bedrock pavement has different associations; at low discharges backwater, pool and run are common hydraulic biotopes. At higher discharges this assemblage changes to pool, run, rapid and glide.

The diversity of hydraulic biotopes tends to be greatest at intermediate discharges, those with an exceedence between 70 percent to 50 percent providing the most diverse habitat. Within this discharge range there tends to be a favourable distribution between pool/backwater, run and higher energy hydraulic biotopes. At the lowest discharges pool becomes dominant to the exclusion of most other hydraulic biotopes whilst at high discharges pool tends to be lost completely.

6.8 CONCLUSIONS

Analysis of results in this chapter suggest that we can define the hydraulic biotope as an instream flow environment which has specific mean and near bed variability of flow. Useful hydraulic indices to describe these flow conditions are the Froude number and velocity-depth ratio (mean), 'roughness' Reynolds number and shear velocity (near bed).

The hydraulic biotope matrix as a tool for the identification of different hydraulic biotope classes appears to be extremely useful as it has been shown to be valid at a number of different spatial and temporal scales. Statistical analysis of results supported the hypothesis that hydraulic biotope classes recognised at different sites and at different discharges do not show significant difference in their hydraulic characteristics as defined by the Froude number, 'roughness' Reynolds number and shear velocity.

Specific associations appear to exist between channel morphology and hydraulic biotope class distribution. Various patterns of class progression occur as a dynamic responses to changes in discharge. Both the greatest diversity of hydraulic habitat and the optimum combination of different flow types was observed at intermediate discharges. Very low discharges resulted in extensive pool hydraulic biotope in all morphological units, with little diversity, whereas at the highest discharge hydraulic biotope diversity was also lost as local hydraulic controls were drowned out.

The relationships described here are for a localised selection of morphological units in one river system. The next challenge is to extend this research to a wider range of morphological units and river environments to see if general relationships can be found. This would provide an important step forward in formulating models which predict available habitat from channel geomorphology and could prove invaluable to future instream flow assessments.

CHAPTER SEVEN

A HIERARCHICAL FRAMEWORK FOR CATEGORISING RIVER GEOMORPHOLOGY: METHODOLOGY

7.1 INTRODUCTION

For a classification system to be successful it must be based on valid process-form relationships, objectively defined units, clear identification procedures and readily accessible data. These features of the model are described in this chapter.

This chapter describes the methods or techniques used to derive and analyse data and classify features at each level of the hierarchy. This chapter therefore, could serve as the basis of a handbook. Many of the recommended techniques and classifications presented in this chapter have been described previously in Chapter 3. For convenience to the user, they are summarised here in sufficient detail to be self explanatory.

Each method is described in relation to its application to one of the research catchments, namely the Buffalo River, Eastern Cape. This river was selected as all levels of the hierarchy had been researched in detail for this river. It must be borne in mind, however, that the methods were developed using experience from a number of different catchments where the authors have had the opportunity to put these methods into practice in IFRs and other management applications.

The methods described below are based on a combination of desk study and field surveys. The desk studies as described here are based largely on the use of the WR90 hydrological data base - Surface Water Resources of South Africa 1990, Midgley *et al* (1994). This data base was derived using ARC/INFO and is readily accessible through ARCVIEW. It gives a complete cover for the whole of South Africa. Data was captured from a variety of maps at scales ranging from 1: 50 000 (e.g catchment boundaries) to 1: 1 000 000 (e.g. Geology). Rivers and sediment yield data were both captured from 1: 500 000 scale maps. Much of the data is therefore at a fairly coarse resolution, but provides a uniform data base for comparison of catchments.

The finest scale of resolution of catchments is the quaternary catchment. This therefore determines the finest scale at which the geomorphological model can be readily applied. To work at finer scales of resolution requires further investment in data capture. The quaternary catchment is used in this report.

Although the WR90 data base is recommended as the basis for this classification, the method can be applied to other data bases as these become available. For big water development projects basin studies are often available; where appropriate this data base can be utilised to generate appropriate maps of runoff and sediment yield. For analyses of the channel long profile, necessary for definition of segments and reaches, the appropriate 1: 50 000 maps are needed.

Users of this classification model require a working understanding of ARC/INFO, ARCVIEW and QUATTRO PRO as these three programmes are all used in deriving data. Interpretation of the desk study results requires expert judgement as does field classifications. The user therefore should have a basic training in geomorphology.

7.1.1 Working with WR90

Preparing the data base

Before new covers can be created it is necessary to create a working folder on the hard drive into which the complete COVERAGE folder is copied from the WR90 CD rom. The new directory will now contain all relevant covers plus associated files which are necessary to access attribute tables in ARCVIEW.

The covers need to be converted from Read Only files. In **Windows, My Computer**, open the directory for each cover required in the analysis.

In **Edit**,

Select <u>All</u>.
File
Properties
turn off **Read Only.**

7.1.2 Creating a Long Profile

Before any manipulation of data takes place it is necessary to produce a long profile of the river being studied. This provides input to various levels of the hierarchy including: the calculation of catchment morphometry, the demarcation of reach breaks, and for delimiting segments.

Data capture is carried out as follows. Note that ARC/INFO **features** are indicated in **bold** type, *actions* or procedures are given in *italics*. The course of the river is identified from the map and all contour intersections are marked. It is also useful to make a note of major tributary junctions. An example is given in Figure 7.1. The length of the river course is then digitised, marking each contour intersection with a **node**. The length of channel between two nodes is designated as an **arc**. The programme automatically *labels* each individual arc in numeric order in the direction in which they are digitised, usually from source to mouth. In the case of tributary junctions which are not coincident with contour intersections, it is necessary to adjust the arc labelling using the appropriate command in ARC/INFO so that the two contiguous arcs have the same number, signifying that they fall between one contour interval. This exercise produces a '**cover**' which contains all the relevant spatial information derived from digitising.

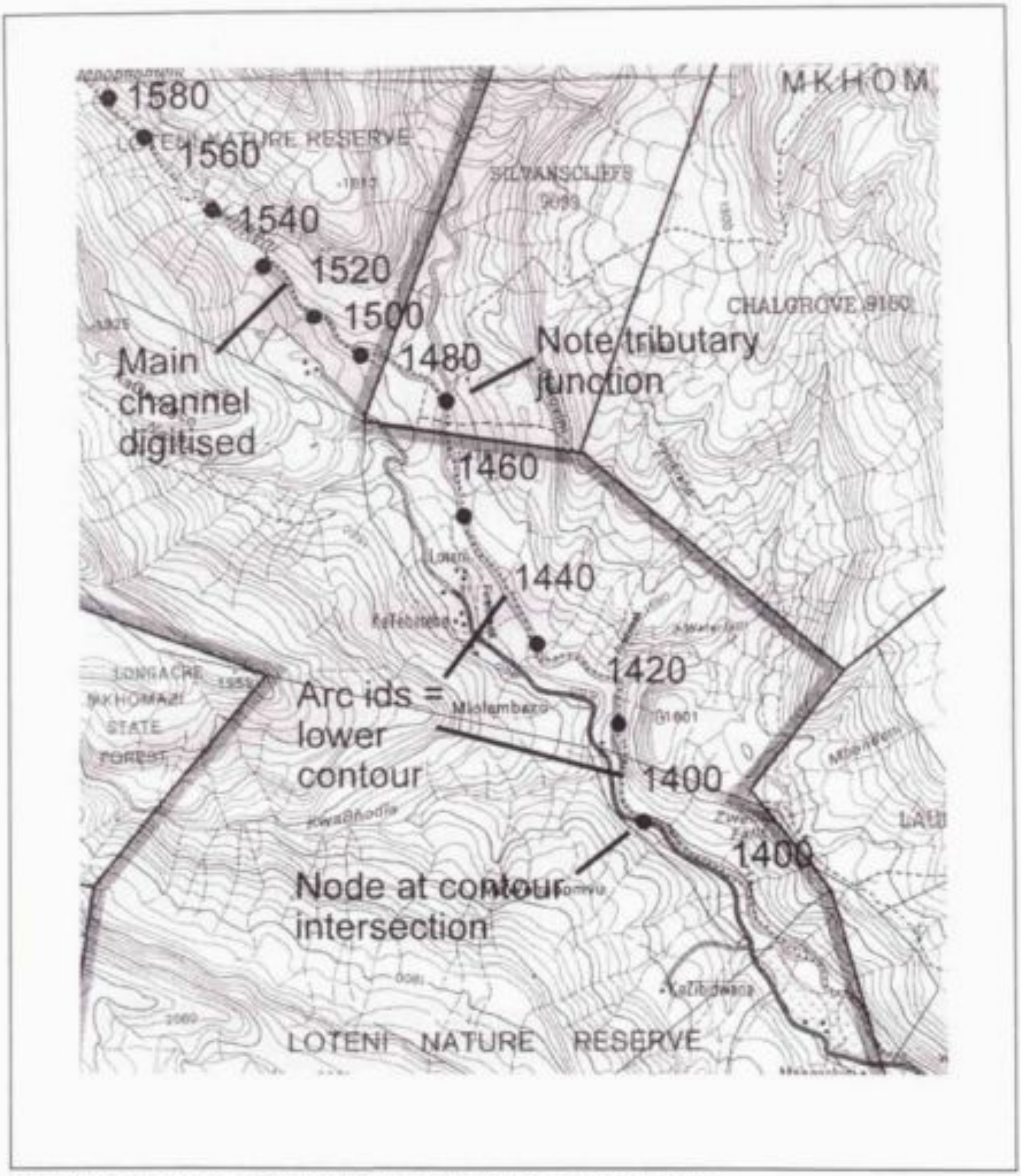


Figure 7.1 Example of a river course and contour intersections

After *editing* and *cleaning*, the cover must be *built* using the command *BUILD LINE*. This produces an **arc attribute table (.AAT file**)which lists each individual arc, label ID and length in digitising units. To convert the length of arcs to metres the cover must be *transformed* into Lat-Long co-ordinates and *projected*. It is recommended that an equal areas projection such as Albers is used. Full details of these procedures are given in the ARC/INFO manuals.

Once the projected cover has been produced, it can be exported to a spread sheet programme such as Quattro Pro for further analysis. In the sub programme 'Tables' the .AAT file is *selected* and *dumped* as a **.prn delimited** file which can then be imported directly into Quattro Pro. An alternative is to create a

Quattro Pro Data Base

Arc length (m)	Distance (km)	Height (m)	Arc length (m)	Distance (km)	Height (m)
	0.000	1160	433.5	3.58	580
39.7	0.04	1140	545.5	4.13	560
15.3	0.06	1120	831.2	4.96	540
32.6	0.09	1100	1593.9	6.55	520
40.7	0.13	1080	4305.2	10.86	500
43.8	0.17	1060	1697.5	12.55	480
37.8	0.21	1040	3025.9	15.58	460
37.8	0.25	1020	4108.6	19.69	440
101	0.35	1000	5785.7	25.48	420
64	0.41	980	6122.8	31.60	400
53	0.47	960	3500.8	35.10	380
104.2	0.57	940	3630.7	38.73	360
76.6	0.65	920	5116.8	43.85	340
157.4	0.80	900	5973.2	49.82	320
128.3	0.93	880	11682.2	61.50	300
112.1	1.04	860	61.5	61.56	280
161.9	1.21	840	1626.6	63.19	260
134.3	1.34	820	4366.4	67.56	240
115	1.46	800	4443.5	72.00	220
83.1	1.54	780	5876.7	77.88	200
107.7	1.65	760	4797.4	82.67	180
188.9	1.84	740	3642	86.32	160
138.7	1.97	720	15272	101.59	140
200.3	2.17	700	1940	103.53	120
171.6	2.35	680	890.1	104.42	100
109.7	2.46	660	1527.5	105.95	80
192.6	2.65	640	1805.7	107.75	60
191.4	2.84	620	3521.8	111.27	40
308.6	3.15	600	5800	117.07	20
			8500	125.57	0

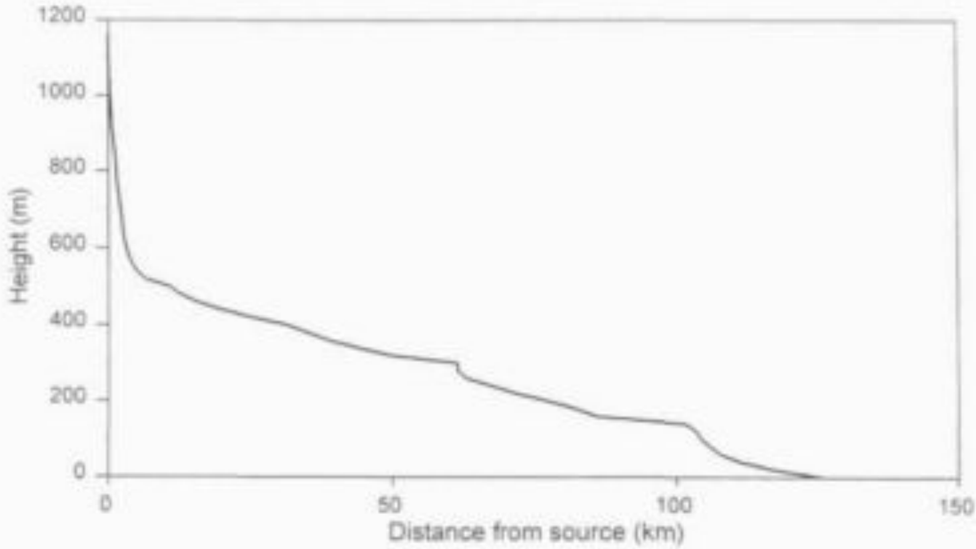


Figure 7.2 Creating a long profile from the Quattro Pro data base

.dbf file. In Quattro Pro view the imported **.dbf** or **.prn delimited** file with the long profile information. It will be found to contain a number of columns of which only two are of interest: the length of the individual arcs and their identification numbers (label_id). It is then necessary to add in the contour heights of the top of each arc (upstream point) and to create a column which gives the cumulative distance from the origin. This data can now be plotted to create a longitudinal profile (Figure 7.2).

7.2 THE CATCHMENT

The catchment is the land surface which contributes water and sediment to any given stream network. Classification of whole catchments allows comparison between systems and an assessment of the extent to which relationships established for one catchment can be extrapolated to another. Simple classification indices include topographic descriptors such as the relief ratio, catchment shape and bifurcation ratio (channel network shape)

Data requirements for classifying at this level should be based on nationally available data networks at a manageable scale, say 1:250 000 or smaller. The compilation and use of a national geographical information system (GIS) data base is especially relevant here. The example given here is based on the WR90 hydrological data base (Midgley *et al.*, 1994).

7.2.1 Creating the Catchment Cover

The cover for the specified catchment must be extracted from the national data base using ARCINFO. The overlay command **Reselect** is used to select the catchment area from the WR90 cover ***CATCH***. In the example the new cover ***BUFFCAT*** is created by selecting the Tertiary catchment R20 (Buffalo River).

In **ARC**

  RESELECT *CATCH BUFFCAT*

Logical expression:

  RESELECT TERTIARY CN 'R20'

Use **BUILD** to create an Arc attribute table (.AAT)

  BUILD *BUFFCAT* **LINE**

This new cover retains the information base from the original cover as it relates to the new area. For example, the Polygon Attribute Table (PAT file) includes the following quaternary information: area, catchment perimeter, MAR, CMAP as well as a number of other hydrological indices. The new cover needs to be projected in ARCVIEW (Albers equal area) so as to be able to obtain distance and area values in metric units.

The Relief Ratio requires values for the elevation difference between the top and bottom of the catchment (h) and the maximum length of the catchment (L). The value for h can be obtained either from the long profile data or directly from the 1:50 000 map series. The length of the catchment can be obtained from the projected cover in ARCVIEW using the measure tool.

The Elongation Ratio requires values for the catchment area and the maximum length. These values are readily obtained from the projected cover in ARCVIEW. The Bifurcation Ratio is based on stream ordering and requires a more significant data base. This value can be calculated from a map depicting the stream network (in the WR90 Report).

To calculate drainage density a new cover has to be produced by clipping the Buffalo catchment cover (**BUFFCAT**) with the national cover of rivers (**RIV**). This new cover needs to be projected so as to be able to calculate the total stream length of the catchment. A total stream length can be obtained in ARCVIEW by going to TABLES and selecting the column representing stream length and looking at the statistics.

The three catchments , the Sabie, Buffalo and Olifants are compared in Table 7.1. The reader is referred to Chapter 3 for full definitions and equations. Catchment area can be extracted directly from the WR90 Report.

Table 7.1 Morphometric catchment indices

Catchment Index	Formula	Reference	Sabie	Buffalo	Olifants
Relief Ratio	$R_r = h / L$	Schumm (1956)	**0.010**	**0.017**	**0.003**
Elongation Ratio	$R_e = D_c / L$	Schumm (1956)	**0.614**	**0.51**	**0.26**
Bifurcation Ratio	R_b = number of streams of one order / number of streams of next highest order	Horton (1932)	**4.96**	**4.66**	**5.39**
Drainage density	$R_D = \sum L / A$ km.km^{-2}	Horton (1932)	**1.9**	**1.72**	**1.91**

L = the maximum length of the catchment. h = the difference in elevation between the mouth of the catchment and the highest point on the catchment boundary. $\mathbf{D_c}$ = the diameter of a circle with the same area as that of the catchment. $\sum$**L** = the total stream length of the catchment. **A**= the catchment area.

Table 7.1 shows that despite differences in total catchment area, the Sabie and Buffalo River's are seen to be similar in their catchment relief, shape and drainage network characteristics. The Olifants River however represents quite a different river. It has a gentler relief, is more elongate and has a higher bifurcation ratio.

7.3 THE RESPONSE ZONE

Within higher order catchments there is much heterogeneity with respect to topography, climate, geology, vegetation cover, soils and land use so that subdivision into zones is necessary for classification purposes. Zones are defined as areas within a catchment which can be considered as homogenous with respect to flood runoff and sediment production. The geomorphological response of these zones should be manifested through drainage network characteristics such as drainage density.

For the large catchments commonly considered for water resource development purposes, it is necessary that data inputs into the model at the zone level are readily accessible from published sources, can be uniformly applied throughout the country and do not require detailed field mapping. A GIS is well suited to manipulating separate covers to produce zones. Data inputs at this level include rainfall and/or runoff, slope gradient, geology, soils, natural vegetation cover and land use. The recommended data base is that available form WR90 which includes mean annual rainfall, pan evaporation, mean annual runoff per quaternary catchment, land cover (indigenous forest, wattle, pine, eucalyptus, sugar cane, urban areas), geology (1: 1 000 000), soils, erodibility and vegetation. Erodibility and vegetation cover are the key to potential sediment source areas under natural conditions. Land use is an important factor determining present day source areas. Erodibility is based on a combination of soil type, slope and rainfall characteristics. Runoff is the key variable determining stream flow and sediment transport capacity and is used to determine sediment routing in this exercise. Ideally some index of flooding should be incorporated as it is the flood flows which are responsible for most geomorphological work. No such index is available form WR90; the only runoff variable is mean annual runoff.

7.3.1 Creating Zone Covers

It is important to note that the finest resolution of data should be used wherever possible. The model described in this report allows data of any resolution to be used, but focusses on the WR90 information which is available nationally and therefore provides a minimum standard. It is useful when carrying out this exercise to familiarise oneself with all of the mapped catchment variables as these provides a broad overview of the catchment and quickly allow a subjective assessment of zone maps produced.

Runoff Zones

Because of the lack of a flood index, the cover for mean annual runoff is used from WR90. The polygon attribute table of the catchment cover ***(BUFFCAT)*** contains sufficient hydrological data (MAR) to create a runoff zone map as shown in Figure 7.3.

Sediment Zones

Potential sediment contributing zones can be produced by overlaying the different covers relating to catchment variables and undergoing some sort of modelling exercise. This was the basis for the potential sediment production maps produced for the Sabie River (Rowntree and Wadeson, 1997). In this report the recommended method is to use the sediment yield cover provided in the WR90 data set.

The polygon attribute table of the catchment cover ***(BUFFCAT)*** does not contain sediment yield data. It is necessary therefore to create a sediment yield map for the catchment. This is done using the overlay command CLIP in ARC. The catchment cover (***BUFFCAT***) is used to clip out the catchment area from the national sediment yield cover ***YLD***.

In **ARC**

CLIP YLD *BUFFCAT BUFFYLDc*

This new cover ***BUFFYLDc*** must now be combined with the catchment cover to give sediment yield for each catchment area. This is done using **IDENTITY**.

In **ARC**

IDENTITY *BUFFLYDc BUFFCAT BUFFYLDi*

Depending on the routine followed, a large number of very small sliver polygons may be created along boundaries. These can be eliminated as follows. First, in **TABLES** check the size of the 'true' quaternaries relative to the sliver polygons. Use **ELIMINATE** to get rid of the sliver polygons.

In **ARC**

ELIMINAT *BUFFYLDi BUFFYLDe*

logical expression:

RESELECT AREA LT (specified size)

Rename the final cover ***BUFFYLD***

in **ARC**

RENAMCOV *BUFFYLDe BUFFLYD*

Because the cover ***BUFFYLD*** has been combined with ***BUFFCAT***, it contains all the information from ***BUFFCAT***. The PAT file now contains the following relevant data:

Quaternary catchment number (Quaternary)

Quaternary catchment area in geographic units (Area)

Mean annual runoff in mm (MAR)

Sediment yield in '000 tons per annum (Sum_Yield)

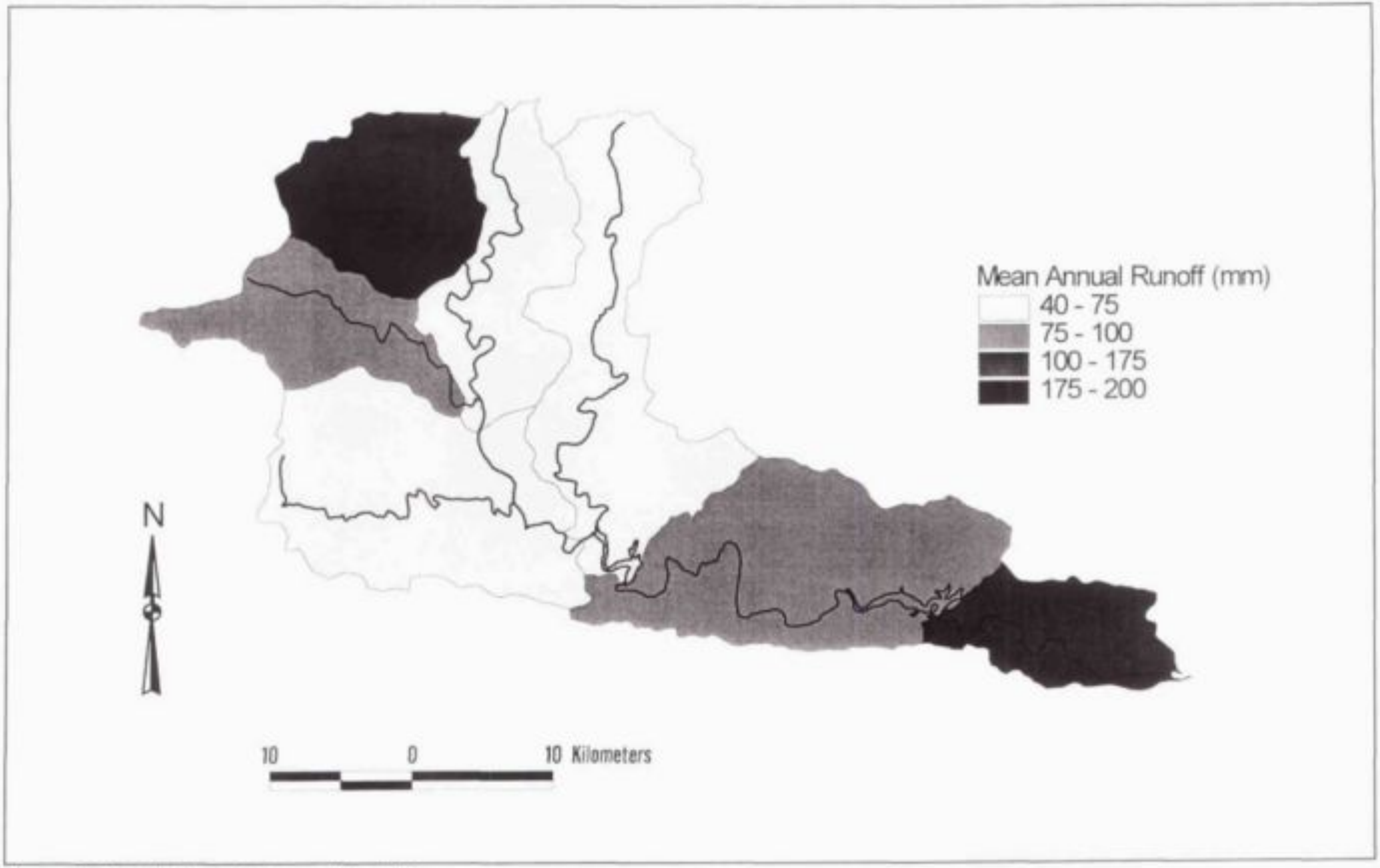


Figure 7.3 Buffalo River Catchment Runoff Zones

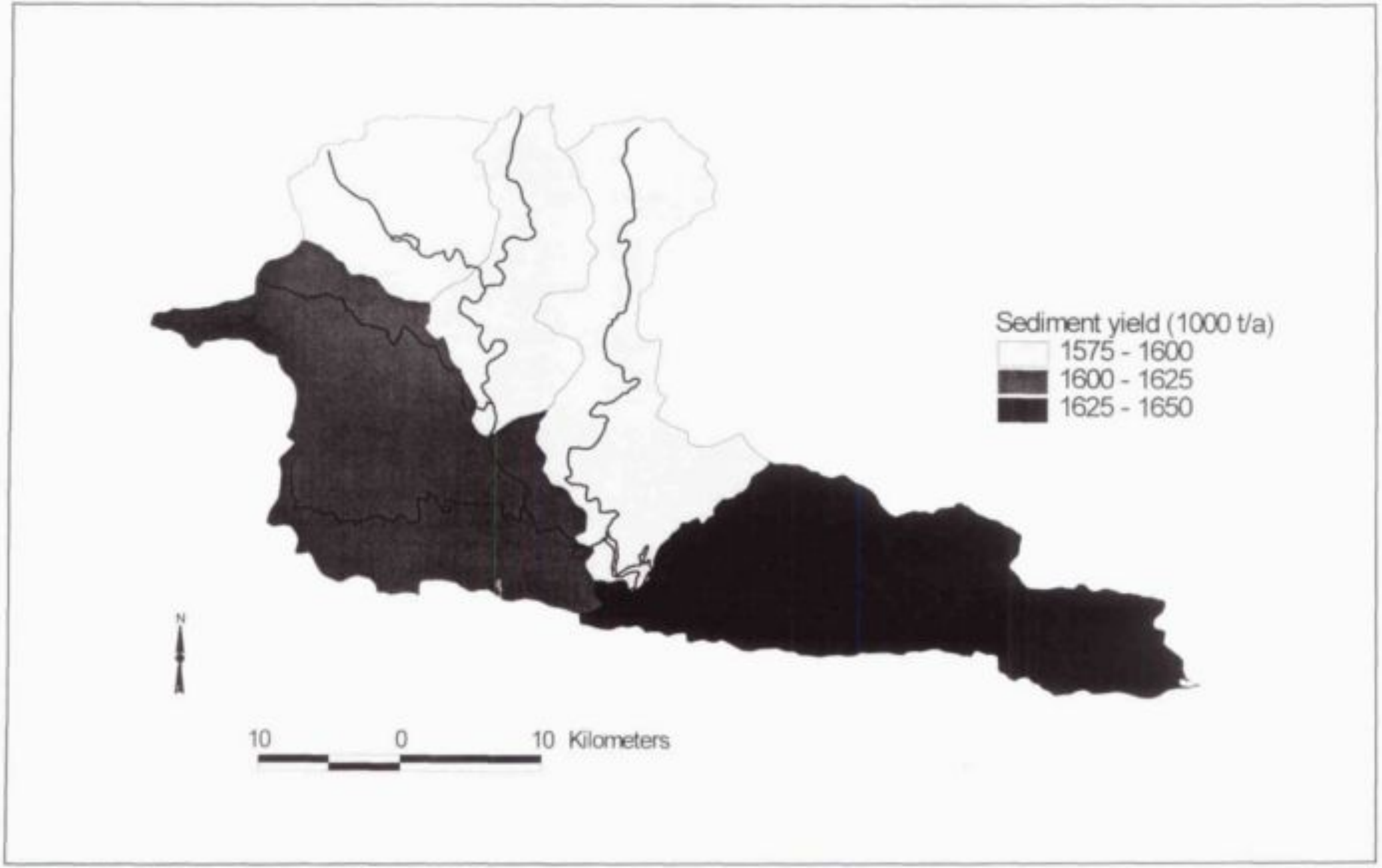


Figure 7.4 Buffalo River Catchment Sediment Yield Zones

This data can be readily manipulated in **ARCVIEW**

In **ARCVIEW**

Open **NewView** and add the theme ***BUFFYLD***

Open the table icon.

Start edit

Add field

Areakm (area in km^2)

Disch (flow discharge in '000 m^3 per annum)

Sed/disch (index of sediment concentration)

Unless the covers are projected in ARC, the linear and aerial units in ARCVIEW will be geographic (i.e related to lat long co-ordinates). The values can be manipulated in tables to give true distance and area if the tertiary catchment area (catarea) is known. Alternatively, areas can be entered using the values given in the relevant WR90 Appendix.

To calculate areas:

In **Edit**

Select all

On the table, select the theme **Area**

In **Field**

Statistics

sum (sum of areas = totarea)

In

Calculate

Areakm = area * catarea/totarea

Calculate

disch = mar * area

Calculate

sed/disch = sum-yield / disch

Maps of quaternary catchment sediment yield can now be created in ARCVIEW as shown in Figure 7.4.

The data base needs to be transferred to Quattro Pro for further manipulation into river segments.

In **Edit**

Select all

File export (as a .dbf file)

The recommendation given here above is to use the available sediment yield cover as a best estimate of catchment sediment yield. Users can create their own potential sediment source maps from composites of geology, vegetation, land use etc. Catchment maps for each variables can be produced using the **IDENTITY** command as outlined above. For example, to produce a geology map of the Buffalo sub-catchments **CLIP** the geology map with ***BUFFCAT***, then use **IDENTITY** to combine ***BUFFCAT*** and the clipped geology map

7.4 THE SEGMENT

A segment is defined as a length of channel along which there is no significant change in the imposed flow discharge or sediment load. Segments can be delineated by overlaying the zone maps with the channel network so as to identify major changes in runoff and/or sediment along the length of the channel. Segment boundaries will tend to be co-incident with major tributary junctions and/or a change in stream order.

In order to delimit segments the extent of the runoff and sediment zones produced for the catchment need to be routed through the linear network of the drainage system. River segments are produced in the following way.

In **QUATTRO PRO**

Open the .dbf file. Delete columns that will not be needed in the following analysis to retain the following variables:

Quaternary
sum-yield
MAR
areakm
disch
sed/disch

Select the entire block (not headings) and **sort** (in **tools**) on Quaternary. Check that the resulting order reflects the routing of water and sediment through the catchment. If not, the quaternaries will have to be renumbered appropriately.

The flow discharge and sediment are routed through the stream network by carrying out a cumulative calculation as indicated in Table 7.2. The cumulative sediment- discharge ratio is calculated as cumulative sediment/cumulative discharge. Indicate on the spread sheet The altitude of the catchment outlet, the point at which the main channel crosses the quaternary catchment boundaries, should be indicated on the spread sheet. Altitudes can be extracted form the relevant 1: 50 000 topographic map. Results for the Buffalo River are given in Table 7.3.

The data in Table 7.3 must now be plotted on the longitudinal profile of the river. The data should be copied into the data base of the long profile, matching up each set of quaternary catchment data with the appropriate altitude on the long profile.

Table 7.2 Spread sheet calculations for cumulating sediment yield

Catchment	D	E (calculation)	E (result)
1	sum_yield	cumulative sediment	cumulative sediment
2	250	+ D2	250
3	300	+ E2 + D3	550
4	400	+ E3 + D4	950
5	150	+ E4 + D5	1100

Table 7.3 Cumulative discharge, sediment yield and sediment discharge ratio for the Buffalo River quaternary catchments.

Quaternary catchment	Height [1] (m)	Area km^2	MAR mm	Discharge $10^6 m^3/a$	Sediment yield 10^3 t/a	Cumulative discharge $10^6 m^3/a$	Cumulative sediment yield 10^3 t/a	Sediment discharge ratio
R20A	560	137.9	179	24.7	25.8	24.7	25.8	1.04
R20B	380	154.1	65	10.0	28.6	34.7	54.4	1.57
R20C	360	121.0	95	11.5	22.4	46.2	76.8	1.66
R20D	300	254.4	40	10.1	47.8	56.2	124.6	2.22
R20E	280	247.6	62	15.2	46.2	71.5	170.7	2.39
R20F	120	259.2	84	21.8	48.3	93.3	219.0	2.35
R20G	0	101.9	142	14.5	19.1	108.0	238.1	2.21

[1] Height of catchment in metres above mean sea level.

Defining Segments

A composite diagram showing the channel long profile and cumulative discharge, sediment yield and sediment/discharge ratio is created as follows.

Create an XY chart using the following series:

distance	x
altitude	y1
cum. Discharge	y2
cum Sediment yield	y3
sed/disch	y4 (secondary axis)

If necessary the discharge and sediment yield variable can be adjusted by e.g dividing by 100 so that the data range is similar to that of the altitudinal range. This allows plotting all three variables against one axis.

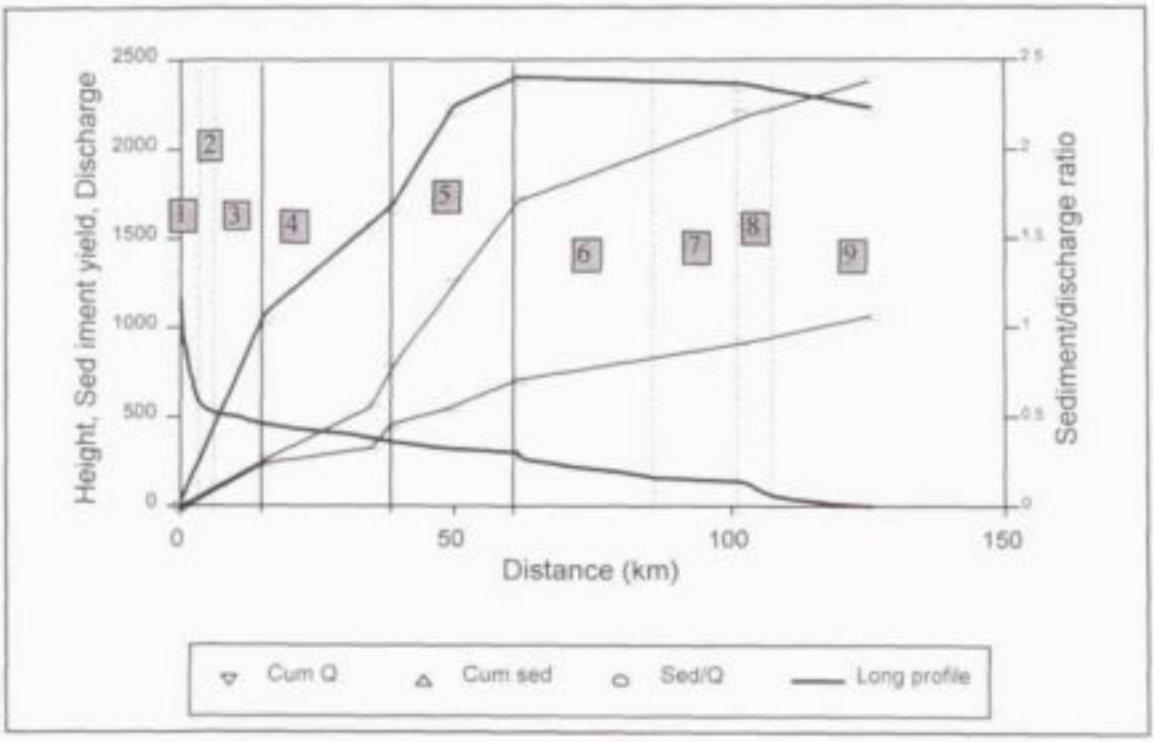


Figure 7.5 Plot showing discharge and sediment yield data in the Buffalo River for the demarcation of river segments. Height in meters a.m.s.l., sediment yield in ' 00 tonnes per annum and discharge in 10^5. cubic metres per annum

The resulting chart will show the long profile as a continuos line, but the discharge and sediment values appear as single points plotted at the catchment boundaries. A curve can be drawn in by hand using the **Insert** option. (**Insert, shape, polyline**).

Segment breaks can be identified where the lines show a sharp break in gradient. The most significant line for defining segments is the sediment/discharge ratio. Further refinement of the segments is carried out by referring to the zonal classifications based on gradient. Vertical lines indicating the segment

Table 7.4 The nine segments recognised in the Buffalo River

Segment number	Contour range	Quaternary catchment	Catchment features - dams and tributaries	Sediment - discharge relationships	Sed/Q ratio	Zone characteristics
1	source - 560	R20A		Moderate sediment yield, high runoff	1.04	headwater streams
2	560 - 520	R20A	Maden Dam			mountain stream
3	520 - 450	R20A	Roikrans Dam, Qcwenkwe			mixed
4	450 - 360	R20B & R20C	Mgquakwbe	Moderate sediment yield, moderate runoff	1.57 - 1.66	foothills gravel bed & cobble bed
5	360 - 300	R20D & R20E	Ngxwalane, Yellowwoods' Laing Dam	High sediment yield, low runoff	2.22 - 2.39	foothills gravel bed
6	300 - 160	R20 F		High sediment yield, moderate runoff	2.35	foothills gravel bed/ lowland river
7	160 - 120	R20 F	Bridledrift Dam			foothills gravel bed
8	120 - 60	R20G			2.21	Rejuvenated cascades
9	60 - mouth	R20G				foothills gravel bed

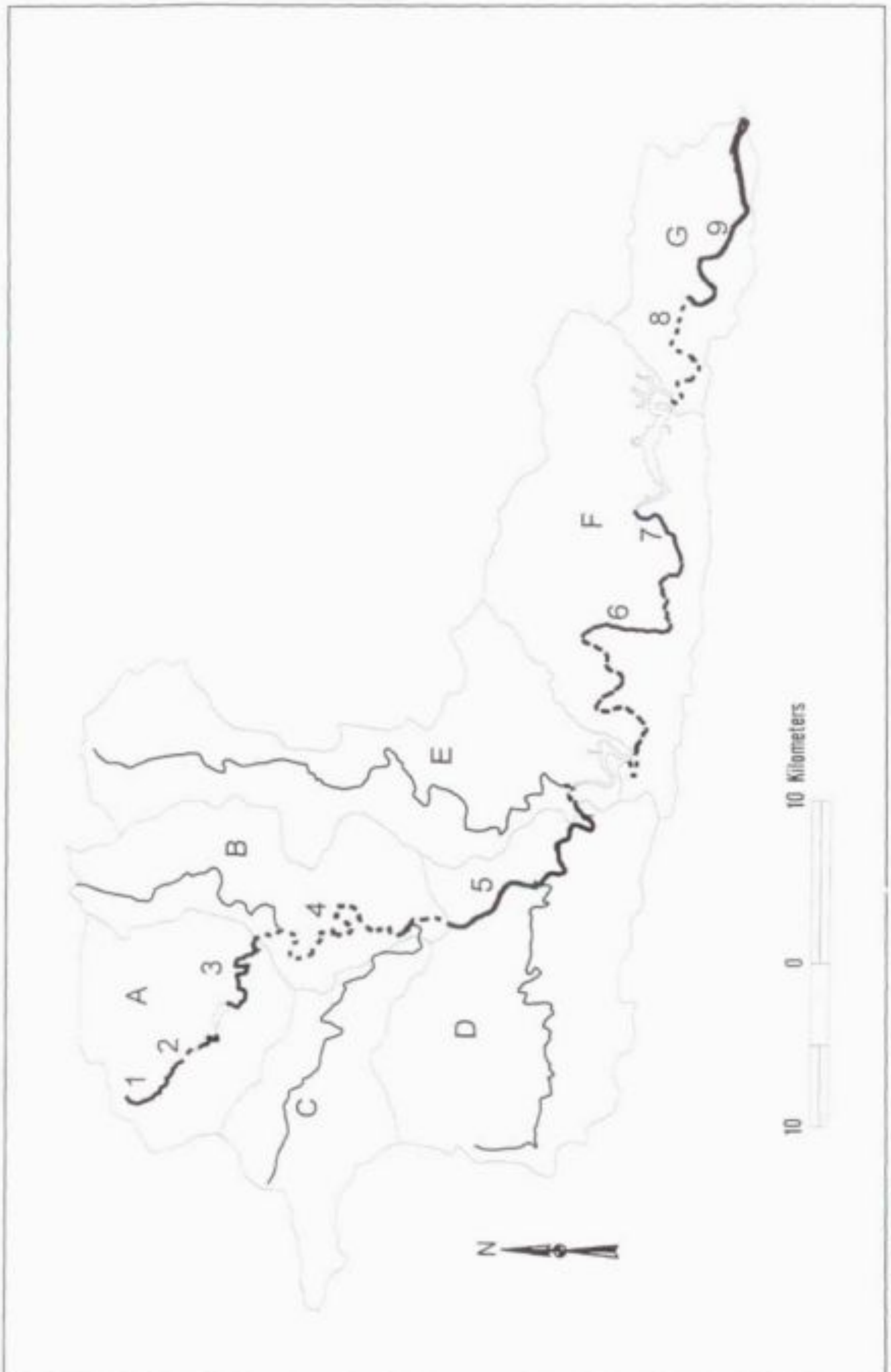


Figure 7.6 Buffalo River Catchment River Segment Map.

breaks zones according to both the discharge and sediment and the zonal classes (gradient) can be inserted on the diagram as shown in Figure 7.5. Nine segments were identified on the basis of quaternary catchment sediment yield, mean annual streamflow, the sediment-discharge ratio (Sed/Q), and slope gradient. These nine segments are described in Table 7.4. and are shown on the catchment map in Figure 7.6.

Four segments were identified on the basis of stream flow, sediment yield and the sediment discharge ratio. These are from the source to the Cwengcwe tributary, from the Cwengcwe to the Mgqakwebe tributary, from the Mgqakwebe to the Yellowwoods tributary and finally downstream from the Yellowwoods to the river mouth. The sediment yield from quaternary catchments R20A and R20B is similar, resulting in a steady increase in sediment load along the stream network. Runoff form R20B is lower than R20A so that the sediment/discharge ratio increases significantly after the Cwengcwe tributary junction. Further downstream the Mgqakwebe River provides a further injection of sediment; runoff from this catchment is also moderately high. The Ngxwalane and Yellowods catchments both have significantly higher sediment yields, but reduced runoff. Runoff from the Ngxwalane is especially low. As a result the sediment/discharge ratio reaches a maximum downstream of the Yellowoods River. The ratio declines slightly in the lower catchment due to higher runoff from the coastal strip.

A further five segments were identified on the basis of gradient and zone classes. Zone boundaries are often coincident with the segments defined above. The upper reaches fall within the mountain headwater zone which is followed by a short mountain stream zone which extends as far as Maden Dam. From Maden Dam to the Cwengcwe tributary there is no clear zone class as the river consists of an assemblage of mixed gradient reaches. A foothills gravel bed zone extends as far as the 160 m contour below Laing Dam. Immediately below Laing Dam a short steep reach can be distinguished on the long profile, but it was deemed too short to be identified as a segment. The next segment extends from 160 m to 120 m (Bridle Drift dam and is a low gradient segment which is transitional from foothill gravel bed to lowland river. Below Bridledrift Dam the river steepens significantly and a rejuvenated cascades zone is distinguished. From 60 m to the mouth the river returns to a foothill gravel bed zone.

7.5 THE REACH

7.5.1. Definitions

The reach is probably the most commonly used spatial scale within the river system. It is used by fluvial geomorphologists and aquatic scientists alike, but the term creates confusion not only because it has been variously defined, but also because it is not always easily recognisable as a physically discreet unit. The definition adopted here closely follows that given by Frissell *et al*. (1986). The reach is defined as an integrated geomorphological unit within which the local constraints on channel form are uniform, which has a characteristic channel pattern (straight or sinuous) and degree of incision, channel type and within which a characteristic assemblage of morphological units occur. The boundaries of reaches are marked by breaks in channel slope. The length of reaches varies with the position in the stream network and the heterogeneity of local control variables. Generally the length of a reach varies for hundreds of metres in low order streams to several kilometres in high order segments.

Reach control variables such as channel gradient, geology, bank and bed material and riparian vegetation determine the possible direction of the response to changes in flow and/or sediment load, in particular whether the reach acts as a source, transfer zone or sink for sediment. Characteristic channel forms are the result of these dynamic processes. Reach control variables and associated channel forms can be determined from large scale topographic maps, aerial photography and from field surveys.

There are two approaches to identifying and classifying reaches. Firstly one can make an inventory of channel characteristics along the length of the channel, from this the location of clear changes in channel features can be identified. Such an approach requires an intensive field survey of the channel system throughout the area of interest, possibly aided by the use of aerial photographs if available at a suitable scale. Such an exercise is both time consuming and expensive and is often not feasible in the context for example of an IFR workshop. A second method is to identify the reach breaks from features shown on topographic maps, after which a field study can be used to validate the breaks and to describe and classify features within reaches of interest. This second strategy is adopted here.

7.5.2 Identification of reach breaks from topographic maps using gradient changes.

Channel gradient has been found to be well correlated to many other channel properties including pattern, channel type and bed material and reach type. Changes in gradient should mark changes in channel characteristics and can therefore be used as a useful first approximation for the delineation of reaches from topographic maps. The channel gradient can be calculated from the distance between contours which intersect the channel. The method developed in this research is based on capturing the blue-line network data from 1: 50 000 topographic maps using the Geographic Information System pcArc/Info. If available 1: 10 000 Orthophotos can be used for a more detailed assessment. Although the use of a GIS is recommended to increase efficiency of data capture and analysis, it is possible to carry out the exercise by hand using conventional methods of map analysis.

In Quattro Pro view the imported **.dbf** or **.prn delimited** file with the long profile information that was created in Section 7.1.2. It is now necessary to create two more columns which give the gradient (vertical interval /arc length) and the percentage gradient change (∇G) measured as the gradient of a given arc as a percentage of the previous arc:

$$\nabla G = ((\text{gradient of lower arc/gradient of upper arc}) - 1) \times 100$$

A reduction in gradient will be negative, an increase in gradient positive. It should be noted at this point that reductions in gradient must always be between 0 and 100% whereas there is no theoretical upper limit to the percentage increase in gradient. This should be borne in mind when interpreting the results. It might be advisable to transform positive readings as follows so as to reduce the range to 0 and 100%

$$\text{Transformed value} = ((\text{gradient of upper arc/gradient of lower arc}) - 1) \times 100$$

An important question that arises in the definition of reach breaks is, if gradient change is important, what constitutes a significant gradient change? It is unlikely that two adjoining lengths of river will have identical gradients so that some change in gradient is inevitable, but not every new arc represents a new reach. By listing the arc gradients and their respective gradient changes it is possible to eyeball the points where major channel changes are likely to take place. Generally gradient changes of more than 50% mark distinct reach breaks, changes of less than 20 % are probably insignificant. Between these limits it is a matter of subjective judgement as to where breaks occur. Often it can be seen that there is a long stretch of river with relatively uniform gradients, and therefore similar reach types, separated by a short steep section. As a note of caution, in smooth river profiles there may be a small but progressive change in gradient, so that reach characteristics change gradually but perceptively down the system. The position of reach breaks will be relatively arbitrary, unless guided by other factors such as geology, valley form and so on. An example of a reach analysis based on gradients is given in Table 7.5.

7.5.3 Refinement of reaches using mapped information relating to valley floor conditions, degree of confinement and channel pattern.

Once the gradient based reach breaks have been identified, the next step is to consult the topographic maps, geology maps and any other available data source for other evidence of channel change. A video tape of the river can be used to give supporting evidence of channel change. This is most effective if the video is filmed after the initial gradient analysis has been carried out and the position of reach breaks noted on the video footage.

It must be remembered that the contour line can only give an approximate location for the break of slope, which may well be displaced up or downstream. Often reach breaks are co-incident with changes in geology; this can be ascertained from the geology maps and the reaches adjusted accordingly. Other factors which should be taken into account when identifying reaches from maps are the degree of confinement or lateral mobility, which is related to the configuration of the valley floor, and to the channel pattern. These characteristics are described in more detail below. Aerial photographs may be used with effect to help characterise reaches if the channel is both wide and open enough and the photographs are of a sufficiently large scale. If the scale is smaller than 1: 10 000, the necessary details will not be discernible.

Table 7.5 Reach analysis based on gradient changes. Bold type indicates percentage change values used to define reach breaks.

arc length (m)	height (m)	gradient	downslope gradient change (%)	upslope gradient change (%)	reach
338.73	1525- 1500	0.0738			1
1151.48	1450	0.0434	**-0.41**	0.70	2
227.15	1400	0.2201	4.07	**-0.80**	3
164.11	1350	0.3047	0.38	-0.28	3
920.53	1300	0.0543	**-0.82**	4.61	4
1327.34	1250	0.0377	-0.31	0.44	4
1811.83	1200	0.0276	-0.27	0.37	4
1853.90	1150	0.0270	-0.02	0.02	4
2462.89	1100	0.0203	-0.25	0.33	4
4178.86	1050	0.0120	**-0.41**	0.70	5
4515.01	1000	0.0111	-0.07	0.08	5
22611.07	950	0.0022	**-0.80**	4.01	6
7297.65	900	0.0069	2.10	-0.68	7
9122.64	850	0.0055	-0.20	0.25	7
3999.06	800	0.0125	1.28	**-0.56**	8
4075.78	750	0.0123	-0.02	0.02	8
2805.40	700	0.0178	0.45	-0.31	8
3672.66	650	0.0136	-0.24	0.31	8

Video and map analysis is a useful technique to support a desk study and to determine the exact position of reach breaks. At present, IFR studies in South Africa require that the river being researched is flown by helicopter and filmed along its entire length. The film of the river is conveniently divided into 5km segments and these are used to carry out a reach verification amongst other things. An experienced geomorphologist will study the video and for every 5km segment fill in a form (Table 7.6) and analyse the river with regard to channel pattern, substrate, bank condition etc. This form can be compared with the original longitudinal profile and refinements made to the position of reach breaks.

Table 7.6 Example of a video analysis form for the demarcation of reach breaks.

5km Segment Number	Confinement	Channel Pattern	Dominant Substrate	Reach Type	Bank Condition
1	c	s	b	Mpr	s
2	c	s	b	Mpr	s
3					
4					
x					

Confinement:	confined (c) moderate (m) unconfined (u)
Channel Pattern:	sinuous (s) meandering (m) braided (b) anabranching (a)
Substrate:	bedrock (b) cobble (c) sand (s)
Reach Type:	**Alluvial** step-pool (Asp) plane-bed (Apb) pool-riffle (Apr) regime (Ar)
	Bedrock cascade (Bc) planar-bedrock (Bpb) bedrock-fall (Bbf)
	Mixed pool-rapid (Mpr)
Bank Condition:	stable (s) eroded (e)

Once reaches have been identified from the maps or photographs, it is necessary to verify the location of reach breaks in the field and to describe the reach characteristic using a prescribed inventory as appended to this chapter.

i) Valley floor

The valley floor is classified according to the presence or absence of sedimentary deposits and their relationship to the modern channel. More than one feature may be present. Features defined in Section 3.5.4 are:

Flood plain
Erosional bench
Terrace
Valley side bench
Pediment
Valley floor absent

The *flood plain* is the relatively level alluvial area lying adjacent to the river channel and which has been constructed by the present river in its existing regime. The flood plain determines the area over which the channel is free to migrate. Inundation of the flood plain, with concomitant deposition of fine sediment, occurs relatively frequently, normally once every one to two years.

An *erosional bench* may take the place of the flood plain, especially where the potential for sediment accumulation is limited as in bedrock systems. It may form from active down cutting within a broader macro-channel.

Terraces are relict flood plains which have been raised above the level regularly inundated by flooding due to lowering of the river channel. They are often associated with rejuvenation. Unlike the flood plain, their sedimentary features are unrelated to the present river regime.

A narrow *valley side bench* or *lateral bench* may be present in upland areas with steep channel gradients where there is limited lateral development of the valley floor.

A valley floor will be *absent* where the hillslopes impinge directly onto the channel. Flooding takes place directly onto the base of the hillslope.

Pediments may dominate the valley floor in lowland semi-arid areas. A pediment is a low angled hillslope which is formed by surface wash processes and may be either erosional or depositional. The channel is incised into the pediment with or without flood plain development. Where a flood plain is absent, major flood events overtopping the channel will cause flooding of the pediment slopes close to the river but, because of the infrequent recurrence interval of flooding, slope processes predominate in determining its characteristics.

Not all these features can be identified positively from topographic maps. It may be difficult to distinguish between terraces and flood plains or erosional benches, unless the height differential is greater than the contour interval. The presence of valley side benches may be inferred where the valley floor is narrow and steep, but field verification is needed.

ii) Lateral mobility or entrenchment

Four categories of lateral mobility or entrenchment are given: confined, moderately confined, non-confined, and entrenched.

Confinement is a measure of the degree to which the channel path is constrained by the the macro-scale valley topography, which in turn defines the valley floor over which the channel could migrate. Confined channels are characteristic of steep sided v-shaped valleys, the valley floor if present is narrow and lacks alluvial material within which the channel could migrate. Most mountain streams, or rivers flowing through gorges, would be classified as confined. In such streams meandering is a result of valley form rather that lateral channel migration. An unconfined river flows across a broad valley floor, usually a flood plain, and is free to migrate laterally. As a result of long term lateral migration the valley floor will be composed of alluvial material. A moderately confined stream falls between the two. There is a distinct valley floor but the path that the channel takes is in large part determined by the valley side walls. This is a common form in South Africa.

An entrenched channel is one in which the channel is entrenched into the flood plain or, more frequently, an alluvial terrace, so that the active channel is confined by steep banks and/or terraces of relatively resistant material. It is possible that during extreme flood events some working of the entrenched channel walls may take place, causing lateral migration of the channel, but it is not a regular event.

Entrenched channels are often compound in form, with a relatively shallow active channel confined within a deeper macro-channel. In cross-section channels may either be simple or compound. A simple channel has one distinct bank level which reflects the bankfull discharge, higher flows spill over onto a flood bench or flood plain. A compound channel has two or more bank levels, often with a relatively shallow active channel contained within a much deeper macro-channel. The active channel can be distinguished as having a channel floor free of established terrestrial or riparian vegetation, but may be colonised by reeds and other aquatic plants. The banks of the active channel often define the edge of a flood bench contained within the macro channel. The riparian zone lies on the flood bench between the active channel and the macro-channel banks. Only extreme flood events over top the macro-channel.

The presence of a macro-channel is likely to require field verification.

iii) Channel pattern

Channel pattern can be classified in terms of single or multiple thread, the degree of sinuosity and whether it is braided or anabranching:

Single thread -	low sinuosity (SI<1.5) high sinuosity /meandering (SI>1.5)
Multiple thread -	braided (unstable) anastomosing (stable/vegetated)

Single thread and multiple thread channels can be readily distinguished from topographic maps, but the distinction between braiding and anabranching may require field verification to check the stability of the bars or islands. Sinuosity of single thread channels can be determined by dividing channel length for the reach by the valley length. Channel length can be extracted from the table created in Quattro for the reach analysis. Valley length could be digitised as a separate cover or measured directly from the map. With experience it will be possible to distinguish high and low sinuosity streams by eye; sinuosity will only need to be determined quantitatively where it is close to 1.5.

7.5.4 Field verification and reach inventories.

Two activities need to be carried out in the field, verification of reach breaks and compiling an inventory of the individual reaches. Observation of reaches is likely to be limited to vehicle access points, unless the observer walks, canoes or rafts the length of the channel. The method used will depend on the required accuracy and the time available.

Forms R1, R2 and R3 (appended to this chapter) detail the information that should be collected at the reach level. Firstly, valley floor, lateral mobility and channel pattern should be verified and the presence or absence of a macro- channel noted. The channel type, as determined by the dominant size of channel bed and bank materials should be noted. Channels may be one of three groups - bedrock, mixed or alluvial. Alluvial channels may be dominated by one of sand, gravel, cobble or boulder, or possibly two of these. The composition of the channel banks may be different from the bed. For example, a channel with a rocky bed may have alluvial banks, whilst a cobble bed channel may have sandy banks.

Form R2 relates to the classification of reach type in terms of assemblages of morphological units. These are described in more detail on Form M3. Although one reach type should dominate a reach, it is possible that there may be more than one reach type present. These should be indicated on the form.

Form R3 relates to the general riparian and catchment conditions in a reach. Riparian conditions include the riparian land use or vegetation cover, the presence or absence of a woody riparian strip along the channel banks and disturbances either in the riparian zone or within the channel itself. Catchment disturbances are limited to those which effect sediment inputs into the channel (erosion status of the catchment slopes) and flow regulation (presence of an impoundment upstream).

7.5.5 Reaches in the Buffalo River

The longitudinal profile of the Buffalo River is shown in Figure 7.2. The profile is characteristically concave upwards with a relatively sharp break in slope between the mountain and piedmont zones. Local steepening of channel gradient can be associated with geological outcrops of sandstone and dolerite. Within the lowland plateau the river and tributaries have incised their valleys but in most reaches have still developed a small flood plain.

The longitudinal profile of the Buffalo River provided the initial basis for sub-dividing the stream segments into stream reaches defined in terms of significant breaks in channel gradient. Field investigations have shown that stream reaches have consistent associations of bed form features (pool, riffle, step, pool), cross sectional morphology (floodplains, terraces, colluvial slopes, structural control features, lateral confinement, entrenchment), and plan view morphology (straight, sinuous, meandering, braided, anastomosing). Reaches can be classified into 'Reach Types' as given in Tables 3.3 and 3.4.

Using orthophotos at a scale of 1 : 10 000 and contour intervals of 5 metres, 34 reaches were identified. Field verification was carried out for each reach. Table 7.7 provides a summary of the reach characteristics observed in the Buffalo River.

7.6 SITE DESCRIPTIONS: THE MORPHOLOGICAL UNIT

7.6.1 Definitions

As defined in Chapter 2, the morphological unit is the basic structures comprising the channel morphology. They occur at a scale approximating to one channel width or greater. Morphological units may occur within the channel floor or they may be lateral features which comprise the adjacent areas which lie above the level of the normal flow. They can be erosional or depositional features formed in alluvium or bedrock. Morphological units that have been recognised in South African rivers are classified in Table 3.1 and Table 3.2. The morphological units are grouped into those associated with alluvial channels and those found in bedrock sections. In mixed channels both types of morphological unit may be present.

The data forms designed for use at the site or morphological unit scale differentiate between the macro- and micro- channels where appropriate. If a macro-channel is absent the relevant spaces should be given a record NP (not present).

Table 7.7 Summary of reach characteristics observed in the Buffalo River

Seg	Reach	Contour	Reach Type	Valley Form	Riparian Veg	Grade	Width (m)	Channel Pattern	Substratum	Morphological Units
1	1	1140-1060	Cascade	Confined	Coniferous forest	0.46	5	Straight	L.Cobble, c.gravel	waterfall, bedrock pool, plunge pool, cascade
	2	1060-1000	Cascade	Confined	Indigenous forest	0.4	7	Straight	Boulder, bedrock	waterfall, bedrock pool, plunge pool, cascade
	3	1000-980	Cascade	Confined	Indigenous forest	0.19	6	Straight	Bedrock, boulder	waterfall, bedrock pool, plunge pool, cascade
	4	980-660	Cascade	Confined	Indigenous forest	0.17	5	Sinuous	Bedrock, boulder	waterfall, bedrock pool, plunge pool, step
	5	660-640	Step-pool	Mod Confined	Indigenous forest	0.17	8	Sinuous	Boulder, cobble	waterfall, bedrock pool, plunge pool, step
	6	640-600	Plane bed	Unconfined	Indigenous forest	0.11	7	Sinuous	Cobble, boulder	plane bed, bedrock pool
	7	600-560	Plane bed	Unconfined	Indigenous forest	0.02	8	Sinuous	Cobble, boulder	plane bed
2	1	560-520	Pool-riffle	Unconfined	Indigenous forest	0	12	Sinuous	Cobble, gravel	alluvial pool, riffle
3	1	520-500	Planar brock	Unconfined	Mixed Woody	0	9	Irreg meander	Bedrock, boulder	rapid, bedrock pool
	2	500-455	Pool-rapid	Unconfined	Mixed Woody	0	13	Straight	Bedrock	rapid, bedrock pool
	3	455-450	Planar brock	Unconfined	Mixed Woody	0.01	16	Irregular	Bedrock	rapid, bedrock pool, bedrock pavement
4	1	450-445	Pool-riffle	Unconfined	Mixed Woody	0	15	Reg meander	Gravel, cobble	alluvial pool, riffle
	2	445-440	Bedrock fall	Unconfined	Indigenous forest	0.05	15	Straight	Bedrock	waterfall, bedrock pool, rapid
	3	440-435	Pool-rapid	Confined	Mixed Woody	0	30	Irreg meander	Cobble, gravel	alluvial pool, rapid
	4	435-410	Pool-riffle	Unconfined	Mixed Woody	0	15	Reg meander	Bedrock, cobble	alluvial pool, riffle, brock pool, brock pvmt
	5	410-400	Pool-rapid	Unconfined	Mixed Woody	0	18	Irreg meander	Bedrock, gravel	rapid, bedrock pool
	6	400-360	Planar brock	Unconfined	Mixed Woody	0	20	Straight	Bedrock	rapid, bedrock pool, brock pavement

Table 7.7 (continued) Summary of reach characteristics observed in the Buffalo River

Seg	Reach	Contour	Reach Type	Valley Form	Riparian Veg	Grade	Width (m)	Channel Pattern	Substratum	Morphological Units
5	1	360-330	Pool-rapid	Mod Confined	Shrubs & grasses	0	20	Anastomosing	Bedrock	rapid, bedrock pool, brock pavement
	2	330-315	Plane bed	Confined	Reeds & grasses	0	15	Sinuous	Cobble, gravel	plane bed, bedrock pool
	3	315-300	Planar brock	Confined	Reeds & grasses	0	15	Forced meander	Bedrock, boulder	waterfall, bedrock pool, rapid
6	1	300-275	Plane bed	Unconfined	Mixed Woody	0	12	Anastomosing	Boulder, cobble	plane bed, bedrock pool, rapid
	2	275-270	Bedrock fall	Part Confined	Mixed Woody	0	25	Forced meander	Bedrock	waterfall, bedrock pool, rapid
	3	270-250	Planar brock	Confined	Mixed Woody	0	15	Anastomosing	Bedrock, boulder	rapid, bedrock pool, brock pavement
	4	250-240	Riffle-pool	Part Confined	Mixed Woody	0.01	65	Straight	Boulder, bedrock	waterfall, bedrock pool, rapid, riffle
	5	240-195	Bedrock fall	Part Confined	Reeds & grasses	0	10	Forced meander	Bedrock	waterfall, bedrock pool, rapid, riffle
	6	195-180	Riffle-pool	Confined	Mixed Woody	0	25	Forced meander	Bedrock, boulder	bedrock pool, rapid, riffle
	7	180-160	Pool-rapid	Part Confined	Reeds & grasses	0	45	Straight	Cobble, gravel	rapid, bedrock pool, brock pavement
7	1	160-155	Pool	Confined	Reeds & grasses	0	30	Straight	Cobble, gravel	alluvial pool
	2	140-120	Bedrock fall	Confined	None	0.05	30	Forced meander	Bedrock, boulder	waterfall, bedrock pool, rapid, plunge pool
8	1	120-100	Riffle-pool	Part Confined	Mixed Woody	0	50	Reg meander	Boulder, bedrock	alluvial pool, riffle
	2	100-85	Bedrock fall	Part Confined	Mixed Woody	0	50	Straight	Bedrock	waterfall, bedrock pool, rapid, plunge pool
	3	85-60	Bedrock fall	Part Confined	Mixed Woody	0	80	Straight	Bedrock	waterfall, bedrock pool, rapid, plunge pool
9	1	60-10	Plane bed	Confined	Mixed Woody	0	70	Forced meander	Cobble, boulder	plane bed, bedrock pool, rapid
	2	10-0	Estuary	Confined		0	70			

7.6.2 Field mapping and cross section surveys

As a preliminary exercise, a sketch map should be made to show the main features of the site. The distribution of morphological units within the site should be recorded on a channel plan on form M1. If a more accurate plan is needed it will be necessary also to survey the site using a plane table, total survey station or equivalent equipment.

Channel cross-section form is measured by surveying transects across the channel. Standard practice is to take two transects, one each spanning the centre of a pool and the centre of a hydraulic control. These transects should encompass any lateral bars that are present and significant channel banks features.

A sketch should be made on Form M2 to show the main features across the section. Particular note should be made of the different morphological features in the active channel, the nature of the banks, the distribution of vegetation, the present water level and an estimation of the bank-full level or top of the active channel bank. Any flood lines marked by debris lines should also be noted.

7.6.3 Morphological units

Within the present classification hierarchy three types of morphological unit have been recognised as making up the active channel floor: pools, hydraulic controls and lateral features such as bars. As defined earlier pools are scour or erosional features with relatively high depth relative to width and, at the macro-scale, flow hydraulics are controlled by a downstream hydraulic control. The hydraulic controls may be aggradational or erosionally resistant features with relatively low depth relative to width and within which the macro-scale hydraulics are not controlled by downstream hydraulic features. Bars are aggradational features which determine the gross form of an alluvial channel. They may occur in a number of locations, along channel margins, within pools or across the channel, when they also act as hydraulic controls. Form M3 or M4 (for alluvial or bedrock channels respectively) should be used to record the aerial extent of each morphological unit as a percentage of the channel floor. Morphological units observed in the different reaches of the Buffalo river are given above in Table 7.7.

7.6.4 Perimeter conditions

The particle size composition of morphological units lying in the channel bed can either be estimated approximately by eye and feel, in which case the results are entered directly on to Form M4 or a more accurate estimation can be made by taking a random sample of 100 particles from each morphological unit. Form M5 allows data to be entered for four morphological units: the pool, the hydraulic control and up to two bars. The use of a transparent sheet with the diameters of standard particle size classes as given The composition of the channel banks should be estimated separately for the active channel and macro -channel if present. The particle size composition can be estimated by eye and feel and the results recorded on Form M4. Many banks exhibit clear stratification, with a lower layer of cobbles or coarse gravels being overlaid by finer material. If stratification is present the percentage presence of a given size class in each layer should be separated by a \. If bank stability is a major issue samples should be taken from the bank for laboratory analysis of particle size.

The condition of both the riparian vegetation and vegetation growing within the area of the channel floor is also important. Form M4 asks for an assessment of the density of the vegetation and its extent. Thus sparse woody vegetation distributed all along the channel banks would be categorised as SW (sparse widespread) whereas localised clumps of dense vegetation would be categorised as DL (dense, localised). Different columns are given for trees, shrubs, grass, reeds and herbaceous vegetation. A note should be made of the species if these are known. Separate entries are made for the right and left banks and for the vegetation growing in the active channel.

Bank condition is described in terms of stability and erosion indicators. Stable banks are normally well vegetated and show no signs of scouring or slumping. Active basal erosion is indicated by vertical banks, undercutting or slumping. Bank erosion may also be caused by subaerial processes, not directly related to the flow of the river, such as rainfall erosion, livestock trampling etc. The condition of the channel banks should be entered on to form M6 for the macro- and active channels, distinguishing between the right and left banks. Three classes are given, widespread, frequent and local. Widespread affects more than 70% of the bank, frequent between 30 and 70 %, local less than 30%.

The condition of the bed relates to the relative degree of aggradation or bed erosion, to the mobility of the bed and to the degree of embededness (Form M6). Indicators of aggradation include extensive bar deposits, mobile point bars, encroaching vegetation, embedded cobbles, extensive silt, sand or fine gravel depsoits in pools and silt drapes over the channel margins or boulders. Indicators of erosion include scour features in the bed such as small waterfalls and the presence of clean, sediment free pebbles and cobbles or extensive areas of bedrock pavement. Note should also be made of the structure of the bed surface. Armouring describes the condition in which the finer particles have been winnowed from the surface to leave a layer of coarser material overlying mixed sediments. Imbrication refers to a stable bed structure in which the particles overlap as in a tiled roof. Both armouring and imbrication are a measure of the frequency of bed disturbance and the time since the last major flood event.

7.6.5 Channel cross-section form

Channel cross-section form is measured by surveying transects across the channel as described under 7.6.2. Surveying can be carried out at three levels of accuracy depending on the scope of the survey.
Firstly, a sketch should be made to show the main features across the section (see 7.6.2). Secondly, a record of the approximate channel shape, average depth and width can be made using the data form on Form M7. If the channel is reasonably small, a tape can be stretched from active bank to active bank and depth readings taken from the tape to the channel bed at five points, the centre of the channel and two points placed at evenly spaced intervals on either side. The distance along the tape at which depth measurements are made and the total width should be recorded. To record the dimensions of the macro-channel, the total width and the maximum depth should be recorded. These measurements are difficult to make for large channels without the benefit of a surveyors level.

Accurate surveys of channel cross-sections can only be made using a surveyors level, theodolite or total survey station. Such surveys are essential if hydraulic modelling is to form part of the assessment, or long term morphological change is to be monitored. Significant points on the section must recorded on the survey.

7.6.6 General site conditions

A record should also be made of the general condition of the riparian zone as this may impact on channel condition within the site. Form M8 can be used for this purpose, its design is similar to that used to describe more general reach conditions, but the observations should be specific to the site.

7.7 THE HYDRAULIC BIOTOPE

7.7.1 Definitions

The final level of the hierarchy involves the identification and classification of 'hydraulic biotopes' within the morphological units. Hydraulic biotopes are defined as 'spatially distinct instream flow environments with characteristic hydraulic attributes. The classification of hydraulic biotopes is based on the visual characteristics of the flow which in turn give expression to the complex hydraulic interactions occurring between the body of the flow and the bed of the stream The scale of the hydraulic biotope varies from the order of 0.5 m^2 to that approximating to the morphological unit itself.

Any given morphological units will be composed of one or more of these hydraulic biotopes, the biotope assemblage depending firstly on the complexity of the morphological unit and secondly the flow discharge. As demonstrated in Chapter 6, morphological units which form hydraulic controls often contain a diverse assemblage of hydraulic biotopes whereas pool morphological units tend to be more homogenous. For all morphological units, the available evidence points to the greatest diversity being associated with intermediate discharges, with flow durations between 50 % to 70 %. The spatial pattern of hydraulic biotopes within a morphological unit can be determined from observations of surface flow characteristics, the flow type. The classification of the hydraulic biotope is determined by combining flow type and substrate according to Table 4.1 and form HB1.

7.7.2 Classification

Classification of hydraulic biotopes within a morphological unit can be carried out at a number of different levels of accuracy as described below. Research in the Buffalo River (Chapter 6) has shown that hydraulic biotopes are discharge dependent; it is important firstly to give a measure of discharge and, secondly, to make repeated surveys of hydraulic biotopes in order to establish the relationship with discharge.

1. Form HB1 is designed to give a broad indication of the proportion of hydraulic biotopes within the main morphological units at a site. The table asks for an assessment of the percentage of each hydraulic biotope, but does not give any indication of the pattern of the hydraulic biotope

2. Hydraulic biotope mapping allows a record to be made of the spatial distribution of hydraulic biotopes. From this both the overall composition and effects of spatial interaction can be assessed. Accurate mapping of hydraulic biotopes is a time consuming exercise and is normally carried out as part of a site specific research programme in which repeated measurements are to be made over time. The first step in hydraulic biotope mapping is to make an accurate survey of the distribution of morphological units within the study site. A convenient method to do this is to use a plane table

type survey. This survey of morphological units can then be used as a template onto which the hydraulic biotope distribution can be mapped.

Hydraulic biotope mapping is relatively straight forward in pools and over riffles where the depth to substrate ratio is relatively high. In morphological units such as cobble riffles, plane beds and bedrock rapids, where the coarse substrate has the effect of creating a complex mix of hydraulic biotopes, mapping of individual hydraulic biotopes becomes difficult. In such cases it may be necessary to map assemblages and attempt to give the percentage of each hydraulic biotope from which it is composed. The use of overhead fixed point digital photography promises to be a useful tool for mapping hydraulic biotopes.

3. Point surveys allows a sample survey to be taken from which the proportional composition and the change with discharge can be assessed, even in the most complex assemblages. The simplest survey technique is to lay out transects at set intervals across the channel and to classify hydraulic biotopes across the transect. Transect surveys can conveniently be combined with point samples of depth and velocity from which the hydraulic characteristics of the hydraulic biotopes can be ascertained. The required number of point samples will depend in part on the width of the wetted section and in part on its complexity, so that boulder strewn rapids will require many more points than a simple pool. As a general rule one point every two to three metres is probable sufficient in a pool and every half to one metre in a hydraulic control. A minimum of ten points should be sampled across a section.

   Velocity is commonly measured at 0.6 depth from the surface to give an assumed average for the flow profile. It is recommended that where time allows, a three point velocity profile is taken, with a reading taken as close to the bed as possible, and a reading at each of 0.8 and 0.2 depth from the surface. This will give a more appropriate assessment of near bed conditions which are critical to many aquatic organisms. Data forms for transect surveys are given in Table HB2

4. A rapid point survey may be made using form HB3 which combines flow type and substrate in a matrix. Note that a category 'surging' flow has been added to distinguish slow and fast runs. A tape is stretched across the morphological unit (a v-shaped design back and forth across the channel provides the basis of a useful sampling strategy). A sampling distance is selected to give a plus/minus fifty point sample. At each point the flow type, depth and substrate are noted and the depth recorded in the appropriate box on the form. This gives an efficient survey of the available habitat from which the proportions of hydraulic biotopes can be readily calculated. It assumes that the hydraulic conditions can be described adequately by flow type, depth and substrate, without the need for time-consuming velocity measurements. The method does not allow and assessment of the patchiness of hydraulic biotopes.

Hydraulic biotopes as observed in the Buffalo River are described in detail in Chapter 6. Extensive research demonstrated that hydraulic biotopes are strongly dependent on discharge. Common hydraulic biotope assemblages were found to be associated with specific morphological units. More restricted research in the Olifants River showed how in sand bed rivers the mobility of the bed sediment should also be taken into account. Preliminary findings from the Sabie River were used to develop the hydraulic biotope concept, but were based on non-formalized classifications. Results from the Sabie are not presented here.

APPENDICES TO CHAPTER 7

GEOMORPHOLOGICAL ASSESSMENT

REACH AND SITE INVENTORIES

REACH CHARACTERISATION

R 1

Recorder		**Date**		**River**	
Reach no.		**Contour range**		**Lat.**	
Length (km)				**Long.**	

Delete one

Channel gradient **(measured from topographic map scale: 1: 50 000/1:10 000)** ____________

Tick presence of any of the following features					
1. Valley floor		***2. Lateral mobility or entrenchment***		***4. Channel pattern***	
Flood plain		Confined: channel laterally confined by valley side walls		**Single thread**	
Erosional bench				I) low sinuosity (SI<1.5)	
Terrace		Moderately confined: channel course determined by macro-scale features, but some lateral migration is possible		ii) high sinuosity (meandering) (SI>1.5)	
Valley side bench				a) stable-sinuous	
				b) laterally mobile	
Pediment		Non-confined: channel free to migrate laterally over the valley floor (associated with flood plain)		**Multiple thread**	
				braided *(unstable)*	
Valley floor absent		Entrenched: channel confined by steep banks and/or terraces		anastomosing / anabranching	
		3. Channel form			
		Compound (macro-channel present)		*Simple (no macro-channel)*	

Channel type

Tick dominant type(s)		CHANNEL BED	CHANNEL BANKS
Bedrock			
Mixed (note dominant alluvial type(s) below)			
Alluvial	sand		
	gravel		
	cobble		
	boulder		

REACH CLASSIFICATION **R 2**

RIVER: ________________ *REACH No:* __________ *SITE No.* ________ *DATE:* ________

(Tick appropriate box)

Reach Type	Description	Tick
ALLUVIAL CHANNELS		
Step-Pool	Characterised by large clasts which are organised into discrete channel spanning accumulations that form a series of steps separating pools containing finer material.	
Plane-Bed	Characterised by plane bed morphologies in cobble or small boulder channels lacking well defined bedforms.	
Pool-Riffle	Characterised by an undulating bed that defines a sequence of bars (riffles) and pools.	
Regime	Occur in either sand or gravel. The channel exhibits a succession of bedforms with increasing flow velocity. The channel is characterised by low relative roughness. Plane bed morphology, sand waves, mid channel bars or braid bars may all be characteristic.	

BEDROCK CHANNELS		
Bedrock Fall	A steep channel where water flows directly on bedrock with falls and plunge pools.	
Cascade	High gradient streams dominated by waterfalls, cataracts, plunge pools and bedrock pools. May include bedrock core step-pool features.	
Pool-Rapid	Channels are characterised by long pools backed up behind channel spanning bedrock intrusions forming rapids.	
Bedrock rib	Formed in steeply dipping bedrock; alluvial areas separate rock ribs which span the channel, significant pools, rapids or falls absent.	
Planar Bedrock	Predominantly bedrock channel with a relatively smooth bed. Significant pools, rapids or falls absent.	

CATCHMENT AND RIPARIAN ZONE CONDITION (REACH) **R 3**

RIVER: ________________ ***REACH No:*** __________ ***DATE:*** ________

Riparian conditions

Riparian land use	aerial extent			Riparian / channel disturbance	degree of impact		
	local	freq-uent	wide-spread		low	mod	high
natural veld				surface erosion			
natural forest				gully erosion			
grazed veld				borrow pit			
pasture				clearance of riparian vegetation			
arable							
orchards				roads			
forestry plantation				bridge			
rural residential				drift / causeway			
urban residential				weirs			
urban industrial				channelisation			
woody riparian strip:				gabions			
dense, intact				large woody debris			
clumped				water abstraction			
sparse				storm discharge			
absent							
alien woody invasives specify:							
other				other			

Local catchment disturbance

erosion	low	mod	severe	probable cause(s)
upstream impoundment	yes	no		
			distance of top of reach downstream from dam wall (km)	
other (specify)				

M 1

CHANNEL PLAN: RIVER: ______________ REACH No: ________ SITE No. ________ DATE: ______

CHANNEL CROSS SECTIONS: *RIVER*: ____________ *REACH No*:__________ *SITE No*.__________ *DATE*:__________

M2

(indicate shape of channel and banks, position and type of vegetation, bank composition, benches, bars, flood levels pr esent water levels, bank full level)

left hand bank Right hand bank

Hydraulic control (specify ______________________________)

Pool

M 3

SITE MORPHOLOGY

RIVER: ______________ **REACH No:**__________ **SITE No.**________ ***DATE:***________

Morphological units

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

RIVER: ________________ *REACH No:* __________ *SITE No.* ________ *DATE:* __________ **M 4**

BEDROCK		
Morphological unit	**Description**	**% aerial cover**
Bedrock pool	Area of deeper flow forming behind resistant strata lying across the channel.	
Plunge pool	Erosional feature below a waterfall	
Bedrock backwater	Morphologically detached side channel which is connected at lower end to the main flow	
Waterfall	Abrupt continuity in channel slope; water falls vertically; never drowned out at high flows. Height of fall significantly greater than the channel depth.	
Cataract	Step like succession of small waterfalls drowned out at bankfull flows, height of fall less than channel depth.	
Rapid	Local steepening of the channel long profile over bedrock, local roughness elements drowned out at intermediate to high flows.	
Bedrock pavement	Horizontal or near horizontal area of exposed bedrock.	
Bedrock core bar	Accumulation of finer sediment on top of bedrock.	

Perimeter conditions

note approximate percentage in bank and bed; indicate stratified banks with a /		% silt + clay	% sand	% gravel	% cobble	% boulder	% bedrock
Bank composition Right bank	macro-channel						
	active channel						
Bank composition Left bank	macro-channel						
	active channel						
Bed composition	pools						
(Use data from form S4 if available. Note type of hydraulic control and bar(s) if present)	hydraulic controls						
	bars 1						
	2						
Note relative **density** (d = dense; m = moderate; s = sparse or scattered) and **frequency** (w - widespread, f - frequent, l - local)			trees	shrubs	grass	reeds	herbs
Bank vegetation - Right bank	macro-channel						
	active- channel						
Bank vegetation - Left bank	macro-channel						
	active-channel						
Instream vegetation							
Indicate main species if known							

BED MATERIAL SIZE DISTRIBUTION ***(To be used when more accurate assessment needed)*** **M 5**

RIVER: ________________ *REACH No:* _________ *SITE No.* _______ *DATE:* ________

Tally occurrences for a sample of 100 randomly selected clasts for each morphological unit
N.B. class limits for clast sizes adapted from Gordon et al. (1992) after Brakensiek et al. (1979)

	Hydraulic control		*Pool*		*Bar 1*		*Bar 2*	
MORPHOLOGICAL UNIT								
Clast size (mm)	*Tally*	*F*	*Tally*	*F*	*Tally*	*F*	*Tally*	*F*
v. fine sand/silt *<0.125*								
fine / medium sand *0.125-0.0.5*								
coarse/v. coarse sand *0.5 - 2.0*								
v.fine / fine gravel *2 - 8*								
medium gravel *8 - 16*								
coarse/ v.coarse gravel *16 - 64*								
small cobble *64 - 128*								
large cobble *128 - 250*								
small boulder *250 - 500*								
medium boulder *500 - 1000*								
large / very large boulder *1000 - 4000*								
bedrock								

CHANNEL CONDITION **M 6**

RIVER: ______________ *REACH No:* __________ *SITE No.* ________ *DATE:* _____

Bank condition

	macro-channel						active channel					
	Right bank			**Left bank**			**Right bank**			**Left bank**		
	wide-spread	freq-uent	local	wide-spread	freq-uent	local	wide-spread	freq-uent	local	wide-spread	freq-uent	local
stable banks												
active basal erosion												
subaerial erosion												

stable banks	well vegetated, no sign of erosion
active basal erosion	vertical banks, undercutting, slumping
subaerial erosion	sloping bank, sparsely vegetated, active rilling, livestock trampling, etc.

Bed condition

INDICATOR	**TICK PRESENCE**	**REMARKS**
general bed condition		
imbricated		
armoured		
loosely packed or no packing		
indicators of erosion / channel degradation		
waterfalls in bed/ local bed scour		
well sorted and/or clean / loose gravels		
bedrock pavement		
indicators of aggradation		
mobile point bars		
extensive bar deposits		
embedded cobbles		
encroaching vegetation		
silt , sand or fine gravel deposits in pools		
silt drapes on channel margins/ boulders		

M 7

TRANSECT DATA: CROSS SECTION FORM

RIVER: ________________ ***REACH No:*** __________ ***SITE No.*** ________ ***DATE:*** ________

MORPHOLOGICAL UNIT 1						
Cross section channel form (insert measured values)						
	macro -channel		active channel			
channel width (m)						
distance from LHB (m)						
channel depth	max.					
form ratio						

Bank Characteristics (tick appropriate box)											
bank shape		macro-		active		bank	macro-		active	
		RB	LB	RB	LB		RB	LB	RB	LB
vertical						< 10°				
concave						10° - 30°				
convex						30° -60°				
undercut						60° - 80°				
stepped						> 80°				

MORPHOLOGICAL UNIT 2						
Cross section channel form (insert measured values)						
	macro -channel		active channel			
channel width (m)						
distance from LHB (m)						
channel depth	max.					
form ratio						

Bank Characteristics (tick appropriate box)											
bank shape		macro-		active		bank	macro-		active	
		RB	LB	RB	LB		RB	LB	RB	LB
vertical						< 10°				
concave						10° - 30°				
convex						30° -60°				
undercut						60° - 80°				
stepped						> 80°				

M 8

CATCHMENT AND RIPARIAN ZONE CONDITION (SITE)

RIVER: ________________ *REACH No:* __________ *SITE No.* _______ *DATE:* _____ *LATITUDE:* ________ _____ *LONGITUDE:* ______________

Riparian conditions

Riparian land use		aerial extent			Riparian / channel disturbance		degree of impact		
		local	freq-uent	wide-spread			low	mod	high
natural veld					surface erosion				
natural forest					gully erosion				
grazed veld					borrow pit				
pasture					clearance of riparian vegetation				
arable					roads				
orchards					bridge				
forestry plantation					drift / causeway				
rural residential					weirs				
urban residential					channelisation				
urban industrial					gabions				
					large woody debris				
					water abstraction				
					storm discharge				
other					other				

Local catchment disturbance

erosion	low	mod	severe	probable cause(s)
upstream impoundment	yes	no		
			distance downstream from dam wall (km)	
other (specify)				

HYDRAULIC BIOTOPES **HB 1**

RIVER: ________________ *REACH No:* __________ *SITE No.* ________ *DATE:* _________

Flow level at time of sampling (tick box)	dry	isolated pools	low	medium	high	flood	% aerial cover

Hydraulic biotope	General description	Flow type (see table below)	pools	HCs[2]
Backwater	a morphologically defined area along-side but physically separated from the channel, connected to it at its downstream end; occur over any substrate	Barely perceptible or no flow		
Slackwater	an area of no perceptible flow which is hydraulically detached from the main flow but is within the main channel; occur over any substrate	Barely perceptible or no flow		
Pool	Has direct hydraulic contact with upstream and downstream water; occur over any substrate	Barely perceptible flow		
Glide	Occur over any substrate as long as the depth is sufficient to minimise relative roughness. Glides exhibit uniform flow with no significant convergence or divergence.	Smooth boundary turbulent flow: clearly perceptible flow without any surface disturbance.		
Chute	Typically occur in boulder or bedrock channels where flow is being funnelled between macro bed elements. Chutes are generally short and exhibit flow acceleration, often due to flow convergence.	Smooth boundary turbulent flow exhibiting flow acceleration		
Run	Occur over any substrate apart from silt; relative roughness low. They often occur in the transition zone between riffles and the downstream pool;.	Rippled flow		
Riffle	Occur over coarse alluvial substrates from gravel to cobble; relative bed roughness high.	Undular standing waves or breaking standing waves		
Rapid	Rapids occur over a fixed substrate such as boulder or bedrock.	Undular standing waves or breaking standing waves		
Cascade	Occurs over a substrate of boulder or bedrock. Small cascades may occur in cobble where the bed has a stepped structure due to cobble accumulations.	Free-falling flow, contact with substrate largely maintained		
Waterfall	Associated with bedrock steps, cliff like features or large channel spanning boulders. Face near vertical or overhanging.	Free-falling flow, generally separated from substrate.		

[2] HC hydraulic control (riffle / rapid/ etc)

Definition of flow types used in Table 1

No flow.	no water movement
Barely perceptible flow	smooth surface, flow only perceptible through the movement of floating objects.
Smooth boundary turbulent	the water surface remains smooth or shimmers; streaming flow takes place throughout the water profile; turbulence can be seen as the upward movement of fine suspended particles
Rippled surface	the water surface has regular disturbances which form low transverse ripples across the direction of flow
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

TRANSECT DATA: FLOW MEASUREMENTS **HB 2**

RIVER: ________________ ***REACH No:*** __________ ***SITE No.*** ________ ***DATE:*** ________

remarks	*point distanc e (m)*	*flow depth (m)*	*velocity* $(m\ s^{-1})$	*velocity* $(m\ s^{-1})$	*velocity* $(m\ s^{-1})$	*distance to start of hydraulic biotope (m)*	*flow type*	*substrate*	*hydraulic biotope*
			d =	*d =*	*d =*				

State depth of velocity measurement from surface as a ratio of the depth. Use 0.6 if only one measurement; bottom, 0.8 & 0.2 to give a velocity profile.

HYDRAULIC BIOTOPE ANALYSIS **HB 3**

RIVER____________________ SITE________________ MORPHOLOGICAL UNIT__________________ DISCHARGE ____________

OBSERVER ________________________ DATE _____________ (Record water depth in relevant box)

Substrate (diameter in mm)	Dry	No Flow	Barely Perceptible Flow	Smooth Boundary Turbulent Flow	Rippled Flow	Surging Flow	Undular Standing Waves	Standing Waves	Chutes	Free Falling
Silt (<0.125)										
Sand (0.125-2)										
Fine gravel (2-16)										
Coarse gravel (16-64)										
Mixed (cobble with gravel, & sand)										
Cobble (64-250)										
Boulder (250-1000)										
V. large boulder or bedrock (>1000)										

CHAPTER EIGHT
APPLICATION OF THE HIERARCHICAL MODEL TO RIVER MANAGEMENT

8.1. INTRODUCTION

River basin management requires an integrated approach which relates local channel processes to the wider catchment variables that account for the production of runoff and sediment. Runoff and sediment in turn control the physical characteristics of the channel network. The hierarchical geomorphological model is proposed as a framework for effective basin management. Being based on spatially nested levels of resolution it provides a scale based link between the channel and the catchment. The methodology has the ability to highlight areas of potential disturbance and to focus attention in an objective manner on components of the fluvial system at a number of different scales. The system has been applied to a number of Instream Flow Requirement assessments as well as to the development of a sampling strategy for the setting up of a National Biomonitoring Programme. Application to these two activities will be described below.

8.2 INSTREAM FLOW REQUIREMENT ASSESSMENTS

8.2.1 Background

The assessment of instream flow requirements is an important component of Environmental Impact Assessments for large scale engineering developments such as impoundments and interbasin transfer schemes. Instream flow assessment is the process of determining the flow regime required to maintain a river at some pre-determined conservation status (King *et al.*, 1983). The amount of water encompassed in the modified flow regime is known as the Instream Flow Requirement (IFR). A number of methods have been developed world wide to aid this assessment (Estes & Osborn, 1986). Ecologists, in liaison with hydrologists, have been at the forefront of making this assessment; only recently have the potential geomorphological impacts of these schemes, and their implications for stream ecology, been recognised in the assessment process.

South African river scientists and managers, through a series of workshops, are working towards a more holistic method which relies on current knowledge and available data to provide a first estimate of the IFR. The building block methodology described by King *et al.* (1993) and King & Louw (1995) specifically incorporates flows which are thought to be important in terms of geomorphological processes and maintenance of channel structure. Geomorphologists were first invited to contribute to the IFR process in 1992, at the same time as the project on river classification began. The IFR process and the classification project have developed in parallel; the hierarchical model has become the framework for geomorphological inputs into the IFR procedure.

Since 1992 the authors have been involved in a number of IFR assessments, the Berg River in the Western Cape, the Mzimvubu in the Eastern Cape, the Senqu in Lesotho, the Tugela and Mvoti in Kwa-

Zulu Natal and the Mogalakwena in Northern Province. In this chapter the Tugela River will be used to illustrate the application of the hierarchical model and associated geomorphological concepts to the assessment of Instream Flow Requirements (DWAF, 1985).

8.2.2 The Building Block Methodology and the Role of the Geomorphologist

The Building Block Methodology is based on the concept that the stream ecosystem is adapted to a range of flows which are categorised into three groups: low flows, freshes and floods. Low flows or base flows have the longest duration and provide seasonal habitat for the individual species. Freshes are small, short-lived flow increases which provide essential flow variability, initiate scouring and cleansing of the river bed, dilute poor-quality water and possibly trigger spawning of fish. Floods are substantial flow increases which cause significant bed scour, bank erosion and sediment transport within the channel and, through overtopping the banks, provide the hydraulic link between the channel and the flood plain. The task of the natural scientist is to identify those components of the natural flow which are most essential to stream processes, to quantify these components with respect to magnitude, frequency, duration and timing, and to devise a modified flow regime which is a 'skeleton of the original, natural flow regime, encompassing commonly-occurring low flows interspersed with selected higher flows of specific ecological or geomorphological significance' (King and Louw, 1995 p. 2).

There are five important geomorphological issues which need to be considered in the context of river impoundments and associated interbasin transfer schemes and which form a greater or lesser component of IFR exercises. The first two issues are addressed at the catchment and channel network scale and include a general assessment of potential morphological change and the selection of representative reaches within which the IFR sites are located and to which the Building Block Methodology is applied. Once sites have been selected, the geomorphologist's first task at each IFR site is to estimate the flows required to maintain channel form and to predict morphological changes that, inevitably, will occur. The second task is to assess the flow related availability of hydraulic habitat. Lastly, returning to broader issues, in the case of an interbasin transfer an assessment should be made of the impact of flow transfers on the receiving channel.

These issues need to be addressed at a number of temporal and spatial scales as summarised in Table 8.1. From the ecological point of view, the fundamental scale of interest is the assemblage of habitats provided by the water flowing over a particular substratum; in the short term this is determined by the interaction of channel morphology and instantaneous flow discharge, in the medium term habitats change with discharge according to at-a-station hydraulic geometry and in the long term change occurs as channel morphology responds to catchment driven geomorphological processes. The relationship between these different scales and the hierarchical model is indicated in Table 8.1

Table 8.1. The geomorphological significance of instream flows

PROBLEM	TIME SCALE	INFORMATION NEEDS	LEVEL OF HIERARCHY
Spatial and temporal availability of habitats.	Short term (<1-5 years)	Distribution of biotopes and associated flow hydraulics; channel cross-sections, substratum type, flood plain morphology.	Biotope and morphological unit.
Maintenance of substratum characteristics:			
Seasonal flushing of substrate.	Short term (<1-5 years)	Substratum particle size distribution, cross-section hydraulic geometry, channel gradient, rate of sediment supply from upstream.	Morphological unit, reach and segment
Modification to substrate.	Medium term (2-20 years)		
Maintenance of channel form:			
Channel plan and cross-section adjustment.	Long term (10-100 years)	Channel cross-sections, gradients, bed and bank resistance, sediment supply, natural flow regime.	Morphological unit, reach and segment
Information transfer	Not applicable	Catchment indices	Catchment

8.2.3 Instream Flow Requirements for the Tugela River

Background

The Tugela catchment drains an area of 29 039 km^2, rising on the escarpment of the Natal Drakensberg and flowing through the eastern slopes to the Natal coast (Figure 8.1). Rainfall over the upper catchment is high, contributing to the availability of significant water resources in this catchment. Estimated naturalised mean annual runoff from the catchment varies between 3 850 and 4 400 m^3/a (DWAF, 1985). Since the early seventies the catchment has been developed as a water supply area for Gauteng, South Africa's industrial heartland around Johannesburg. The Department of Water Affairs and Forestry

(DWAF) is currently engaged in a planning exercise (Vaal Augmentation Planning Study - VAPS) for the further augmentation of Gauteng's water supply and is considering further development of the Tugela system through the Tugela Vaal Transfer Scheme (TVTS). An IFR exercise was carried out as part of the pre-feasibility study for TVTS in 1995, culminating in a workshop in September 1995 (DWAF, 1995). The distribution of existing and proposed dam sites and IFR sites are shown in Figure 8.1. As geomorphologists the authors were involved in assessing the geomorphological flow requirement for the Tugela and a number of its tributaries, but for the purpose of this report only those sites on the Tugela itself will be considered.

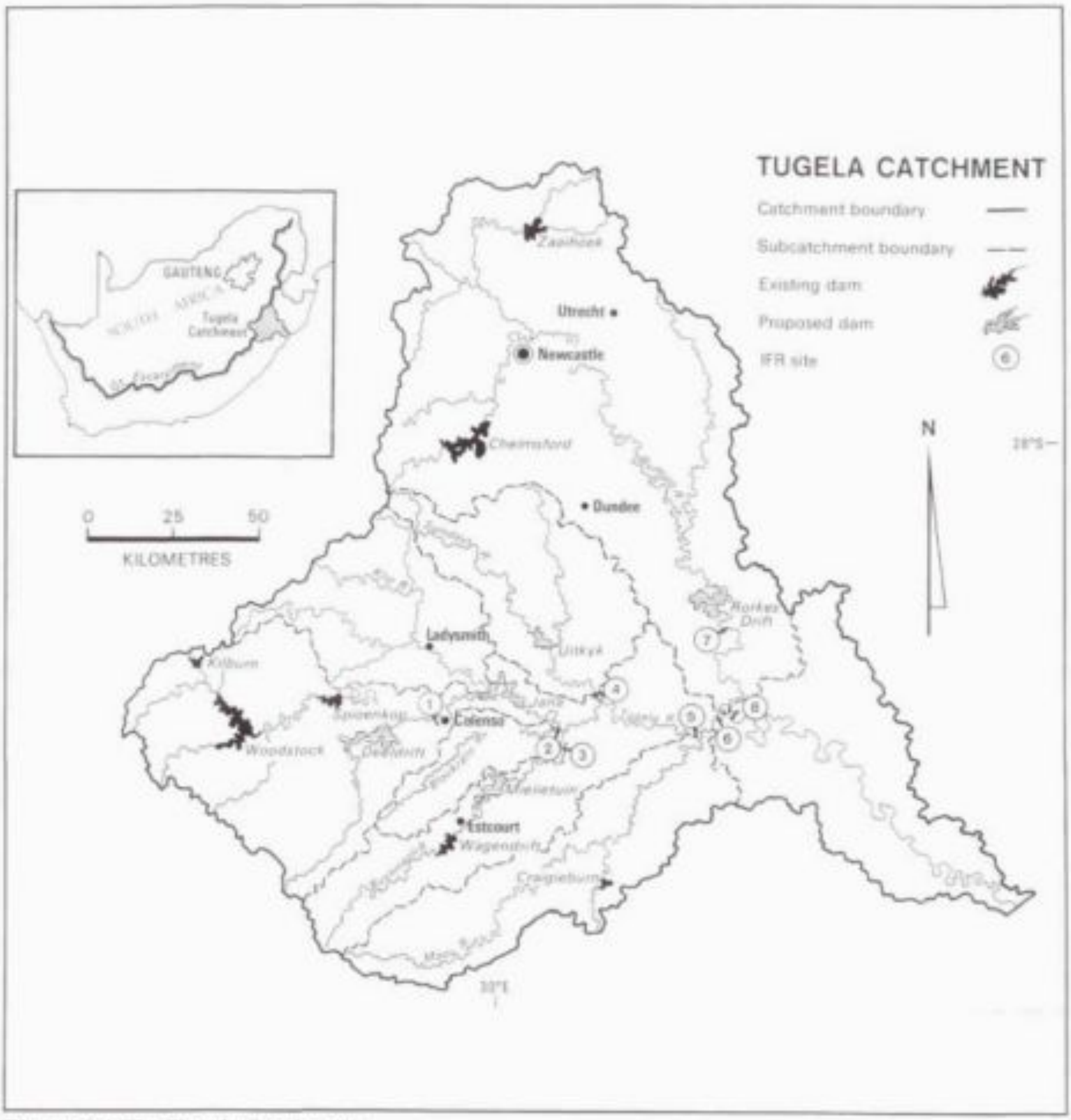


Figure 8.1 The Tugela Catchment

A Geomorphological Framework for Instream Flow Assessment

The Building Block Methodology as proposed by King and Louw (1995) focuses on selected sites within the channel. It is important, however, that these sites be seen within the wider context of the drainage network and river catchment. The hierarchical framework was used to provide the sampling framework for site selection and thus to aid extrapolation of site specific data. A summary of the hierarchy as applied to the Tugela catchment and river channels is presented in Tables 8.2 and 8.3. Hydraulic biotopes are not included in this table, but will be discussed below in relation to the IFR site assessments.

Runoff and sediment zones

Mean annual precipitation over the catchment is shown in Figure 8. 2. Areas of high rainfall and runoff production are coincident with the escarpment. The eastern slopes are much drier and produce commensurately less runoff. Natural sediment production is related to rainfall, slope gradient, soils and vegetation. The higher areas of the catchment have a low sediment production potential due to less erodible soils and a good ground cover whereas a high potential sediment production occurs lower down the catchment due to the combination of highly erodible soils, a sparse vegetation cover, dense rural settlement and steep valley side slopes due to a rejuvenated system (Figure 8.2).

Table 8.2 Geomorphological subdivisions of the Tugela River

Segment/ Macro-reach	Altitude range (m)	Distance from source (km)	Gradient	Zone characteristics	Channel characteristics (reaches and morphological units)
1/ Mountain head wall	2980-2300	0-1.09	0.731	mountain catchment escarpment slopes; steep gradient channels; basalts, sandstones; mountain grassland and forest; high runoff areas, low sediment yields	very steep headwater stream, bedrock channel, waterfalls
1/ Mountain stream	2300-1300	1.08 - 17.12	0.14 - 0.037		steep mountain stream, bedrock, boulder and cobble dominating channel
2/ Foothills	1300-961	17.12-87.43	0.0077	foot of escarpment to confluence with Tugela; lower slopes; sandstones and mudstone, temperate/transitional forest; local pockets of cultivation and dense settlement, irrigation on flood plain moderate runoff, low to locally moderate sediment production **Deeldfrift dam**	mixed channel - fractured bedrock, cobble bed; pool-riffle, pool-rapid
3/ Upland plateau	961 - 940	87.43 - 121.50	0.00048	*Tugela confluence to gorge*, undulating topography, geology and vegetation as zone 4, cultivated lands on flood plain terraces, low settlement density low erosion and moderate runoff. **IFR 1**	low gradient, entrenched, irregular wandering, sand bed channel within flood plain terraces; well vegetated banks; long pools with tributary bars, lateral and braid bars; marked aggradation downstream of confluence; infrequent bedrock bars across channel give rise to short rapid sections with vegetated islands;

4/ Upper gorge	940 - 786	121.50 - 137.80	0.011	*Gorge to Klip River confluence*: confined valley, limited direct catchment area, but steep valley side slopes contributing coarse sediment; high rural population density to north of river little increase in runoff, but some increase in sediment potential	laterally confined bed rock channel in gorge; massive boulders, large rapids and cobble riffles, short pools, locally cobble bars in wider sections; stable channel
5/ Lower Gorge	786 - 640	137.80 - 178.60	0.0039	*Klip River confluence to Bloukrans River*, gorge less confined, shales, shallow soils and degraded karroid vegetation, high rural population density to north of river significant inputs of sediment from Klip River catchment, probably moderate runoff. Local inputs through gorge of coarser sediment. **Jana Dam**	lower gradient, laterally confined cobble and bedrock channel; long pools, riffles and rapids over cobble and bedrock, stable channel
6/ Rejuven-ated foothills	600 - 448	193.31 - 244.70	0.0029	*Bloukrans River to Buffalo River*: shales, erodible soils, karroid vegetation, dense rural population, serious erosion on terraces and terrace banks; aggradation in channel fairly high runoff and moderate sediment input from Bushmans River, high sediment and moderate runoff input from Sundays and Mooi rivers. (Segment breaks) Increased area of direct contribution with low runoff/high sediment. **IFR 2,4,5**	single thread sinuous channel with wide terraces, locally laterally confined; large pools, islands, cobble riffles and wide lateral cobble bars, locally riffles and rapids over bedrock; relatively stable bed
7/ Rejuven-ated foothills	448 - 0	244.70 - 451.46	0.0025	*Buffalo River to river mouth*. sandstones, less erodible soils, coastal tropical forest, high rural population density, major sediment and runoff input from the Buffalo River, but relative proportions of flow and sediment probably little changed; no major tributaries below Buffalo confluence, but relatively large and steep direct contributing area **IFR 8**	sinuous wide channel, wide lateral cobble bars and cobble riffles; locally more confined with bedrock outcrops, widespread braiding, especially in lower reaches

Table 8.3 Reach Characteristics of Segment 6, Tugela River

Segment/	Reach	Length	Gradient	Reach characteristics
6a/ Klip to Sundays	6.1	12.51	0.0016	single thread, sinuous channel, pool-riffle with cobble bars, relatively stable, but islands on maps suggest aggradation **(IFR site 2)**
	6.2	6.11	0.0033	laterally confined channel; pools and islands in mixed bedrock and cobble, badly eroded valley side slopes
6b Sundays to Mooi	6.3	6.15	0.0033	sinuous channel; large pools, islands, cobble riffles and large lateral cobble bars, relatively stable
	6.4	8.00	0.0034	laterally confined channel; pools, riffles and rapids over bedrock, boulders and cobbles, stable
	6.5	5.56	0.0023	sinuous channel with wide terraces; wide cobble lateral bars, long pools, cobble riffles and bars; serious erosion on terraces and terrace banks; aggradation in channel
	6.6	12.25	0.0016	similar to 6.5, but increased aggradation in form of cobble bars (vicinity of Tugela Ferry)
	6.7	11.31	0.0036	similar to 6.5, significant siltation of cobble bars, **(IFR site 5)**
6c Mooi to Buffalo	6.8	8.12	0.0041	similar to 6.5, significant siltation of cobble bars, **(IFR site 6)**

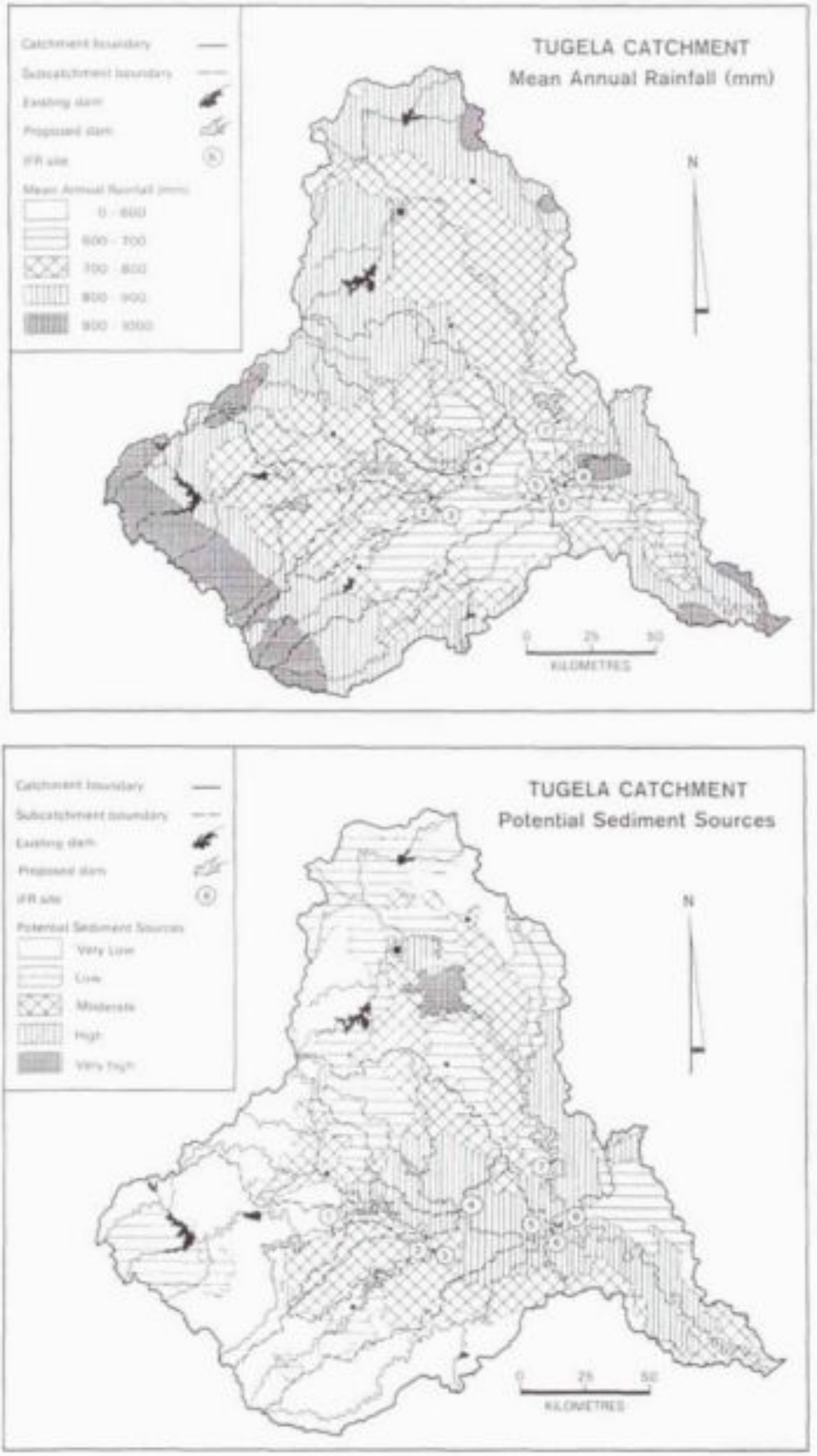


Figure 8.2 Mean annual rainfall and potential sediment sources for the Tugela catchment

Segments

The main channel of the Tugela River was subdivided into segments based on channel gradient and the assumed distribution of runoff and sediment production from the catchment (Table 8.2). The long profile of the main channel is shown in Figure 8.3. In the Tugela catchment uplift during the Plio-Pliestocene period was in the order of 800 m. A characteristic feature of rivers in this area is the level upland plateau zone above a well defined gorge. The steepened channel slopes resulting from rejuvenation maintains a foothills type channel with typical pool-riffle or pool-rapid morphology throughout the lower Tugela. Sediment inputs increase down the channel system so that whereas the headwater channels tend to be either a bedrock or equilibrium alluvial channel, in the lower zones the increased sediment loading is associated with aggrading and braided channels. There is an absence of meandering sand bed rivers due to the steepened gradients in the lower courses.

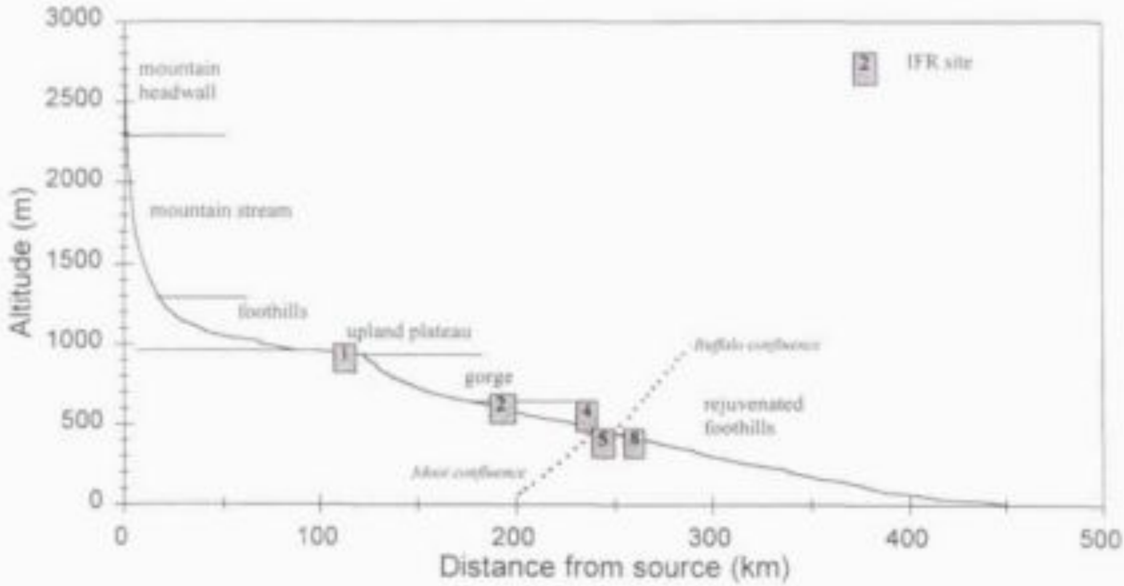


Figure 8.3 Long profile of the main channel of the Tugela River

Reaches, Morphological Units and Hydraulic Biotopes

Characteristics of reaches and their associated morphological units are indicated in Tables 8.2 and 8.3. Hydraulic biotopes can be associated with morphological units but are discharge dependent. They are discussed further in section 6.3.

Assessment of Impoundment Impacts on Channel Morphology

The geomorphological impacts of impoundments have been described by a number of authors (Kellerhals and Gill, 1973; Gregory and Park, 1974; Petts, 1980; Williams and Wolman, 1984; Sherard and Erskine, 1991; Erskine, 1985). Dams have two immediate effects, the first is to trap sediment behind the dam wall and therefore to reduce the sediment supply to the channel, the second is to store water and to reduce both the magnitude and frequency of floods. The net result of these two processes depends firstly on the relative locations within the channel network of the impoundment and the reach for which the assessment is to be made, secondly on the cumulative effect of lateral inputs of sediment and runoff and, thirdly, on the characteristics of the reach itself. The geomorphological hierarchy provides a logical framework within which to make this assessment.

Possible impacts can be summarised as follows:

- degradation and armouring immediately below the dam due to removal off fines by sediment free water (Hammad, 1972)
- accommodation adjustment, wherein the resistant nature of the channel and lack of sediment inputs prevents significant change to the channel (Petts, 1979)
- aggradation and formation of tributary bars due to the reduced flow in the main channel being incompetent to transport continued sediment inputs from tributaries (Kellerhals and Gill, 1973): this may lead to narrowing/deepening of the channel and channel contraction (Gregory and Park, 1974) as the channel becomes adjusted to the reduced flood flows.

Two examples of predicted channel adjustment will be given by way of illustration. The reader should refer back to the maps of runoff and sediment potential given in Figure 8.2 and to the description of channel segments given in Table 8.2.

Deeldrift dam

The channel segment below the Deeldfrift dam site has a very low gradient (segment 3), and will be subject to further aggradation which will, however, be ameliorated by the low sediment inputs to this section. This is due in part to trapping of sediments in both Deeldrift dam and the existing Spioenkop dam on the main Tugela, and in part to low sediment yields from the adjacent catchment. It is likely that some reworking of the sandy sediment already in the channel will take place, with the possibility of channel contraction and tributary bar formation. Aggradation of pools will increase with distance from the dam wall. Downstream of this segment the channel steepens as it enters the gorge (Segments 3 and 4). Accommodation adjustment will take place in Segment 3 due to the steep gradients and resistant bed; some aggradation, particularly in the form of tributary bars, could take place in Segment 5 due to the lower gradient coupled with increased sediment inputs from tributaries, in particular the Klip river (Figure 8.2). By the time the river leaves the gorge it is unlikely that the upstream impoundment will have any noticeable effects because of the relatively small percentage of the catchment runoff controlled by the upstream dam at this point.

Jana Dam

The Jana dam site is situated in the gorge below the confluence with the Klip river. The channel below the dam site (Segment 5) is moderately steep, with bedrock and boulder, and relatively low lateral sediment inputs. The potentially high sediment inputs from the Klip river catchment will be trapped in the dam. Some degradation/armouring is likely to occur immediately below the dam, further downstream accommodation adjustment will occur because of the stable nature of the bed. Reach 6.1 below the gorge has a much lower gradient, so that aggradation, possibly in the form of mid channel bars, would be expected (Table 8.3).

Selection of Representative Sites

Site selection procedures

The selection of IFR sites is a critical component of the IFR process. The sites form the reference points at which the Building Block Methodology is applied and from which results are extrapolated. The study area within which sites are selected is normally taken as lying between the proposed dam development and the downstream point beyond which impacts become insignificant or for which flows cannot be regulated by that development. Within the study area, reach and site selection is based on a number of ecological and practical criteria. In order to select sites representative of the physical habitat it is first necessary to take account of the longitudinal geomorphological zonation of the river as represented by segments and their associated reaches, with due regard for the locality and characteristics of tributaries. Ecological considerations include the habitat integrity/conservation status of the different river reaches, the habitat diversity for aquatic organisms, marginal and riparian vegetation, critical sites for ecosystem functioning (riffles are particularly sensitive to low flows) and the local communities' social requirements relating to the river. Practical considerations include the suitability of sites for accurate hydraulic modelling, locality of gauging weirs with good quality flow data, suitability of sites for follow up monitoring and, last but not least, accessibility. Actual site selection is a compromise of the above.

Site Selection for the Tugela IFR

As noted above, it is recommended that site selection be made after analysis of the longitudinal geomorphological zonation of the river has been completed. In the case of the Tugela IFR this was not done so that the geomorphologists' task was to assess the degree to which the pre-selected reaches represented the system.

The distribution of sites along the main channel relative to segments and reaches is indicated in Tables 8.2 and 8.3. It is evident that not all segments were represented; there is an absence of sites from confined channels and gorges whilst IFR2 is located in an uncharacteristically low gradient area, but possibly one in which aggradational impacts would be felt. Given the nature of the system, a range of channel types should have been included so as to represent the full diversity of available habitats: confined/unconfined, bedrock/alluvial, high gradient/low gradient. Table 8.4 presents a list of sites that would have been recommended on geomorphological criteria. This selection is based on the assumption that financial and time constraints only allow the selection of five IFR sites.

Table 8.4. Recommended IFR sites based on geomorphological criteria.

Recommended segment or reach	Justification	IFR site selected
3	low gradient segment immediately downstream of the Deeldrift dam; aggradation and morphological change probable, loss of limited rapid habitat	yes
5	moderate gradient, confined channel immediately below the Jana dam site; high habitat integrity and good diversity of available habitat	no
6.1	low gradient channel at outlet from the gorge; area prone to aggradation and possible morphological change	yes
6.4	moderate gradient, confined channel below confluence with Sundays, increased sediment flux, probably good natural diversity of available habitat.	no
7	moderate gradient channel below confluence with Buffalo river, increased flow discharge and sediment flux	yes

Application of the Building Block Methodology to an IFR site

As noted previously, the Building Block Methodology is based on a process by which flows of different duration and magnitude are built upon each other to produce the modified flow regime for each IFR site. The primary task of the geomorphologist is to recommend flows which will most closely maintain both the overall channel form in terms of width and depth and the characteristics of the channel bed so as to retain suitable habitats. Geomorphologists, therefore, are concerned primarily with high flows which are capable of scouring the bed and keeping banks free of encroaching vegetation. A second task of the geomorphologist is to describe the relationship between hydraulic habitat, morphological units and varying flow discharges, a relationship encompassed by the hydraulic habitat concept.

Channel Forming and Maintenance Flows

Recommendations regarding channel forming flows can be problematical. Although channel form is the net result of the full suite of flows which pass through the system, the dominant discharge concept implies that floods of a moderate magnitude but high frequency, occurring once every one to two years in humid areas, are the most effective in maintaining channel form and in transporting sediment (Section 3.2.2). These are also the floods which are most likely to be stored in the reservoir, so that recommending flood flows for IFRs creates an immediate area of conflict between engineering and environmental needs and it is important that estimates of the flood component for the IFR are fully justified.

According to the dominant discharge concept, either the bankfull discharge or the 1.5 year flood can be used as an estimate of the channel forming discharge in humid regions for an alluvial river with a channel perimeter that is reasonably free to adjust to changing flows. These conditions may not hold for South African rivers such as the Tugela. Firstly, as the flow regime becomes more variable, as in semi-arid areas, the bankfull discharge is of a higher magnitude than the 1.5 year flood, and may have a recurrence interval of between three to ten years (Pickup & Warner, 1976). Secondly, in coarse bed channels, dominated by coarse gravel or cobble, discharges greater than bankfull may be needed before the flow becomes competent to cause effective bedload transport (Carling, 1988). Thirdly, some channels, as is the case for many South African rivers, have a complex form, with an active channel equivalent to the normal bank full level and a macro-channel which accommodates extreme flood events (Graf, 1988; van Niekerk *et al.* 1995). The macro-channel, often entrenched into a terrace, appears to take the place of a true flood plain. In terms of IFR recommendations, it is the smaller active channel which must be the focus of attention. Finally, these relationships will only hold for alluvial channels; they will not hold for bedrock channels.

Despite these important departures, the dominant discharge concept provides a logical premise upon which to recommend channel forming flows. It has become common practice to recommend one flood discharge approximating to bankfull to be provided every one to two years depending on the timing of flood producing storm events over the catchment. What the long term effect will be of reducing the natural range of flood flows to one bankfull event is not known; long term monitoring of regulated channels will be important if IFRs are to be refined in the future.

Not only do the higher flows sculpture channel form, but they are also important for maintaining suitable substrate conditions on the channel bed. Seasonal flushing of fine materials from the surface matrix of gravel bed rivers prepares the stream bed for fish spawning and helps to maintain an open matrix which provides refuge for invertebrates during inclement conditions such as floods. The more frequent overturning and transport of the coarse matrix itself cleanses coarse material of fine debris and algae as well as maintaining channel structure. It is therefore important that the IFR includes flushing flows of a smaller magnitude, but relatively high frequency, perhaps two or three times a year. These are termed channel maintenance flows in this report.

The IFR site 5 will be used as an example of how channel forming flows and channel maintenance flows were derived for the Tugela River. Figure 8.4 shows the cross section at this site. Three separate morphological channels can be distinguished: the low-flow thalweg channel which follows the lowest point of the river bed and always contains water as long as the river is flowing, the active channel more or less coincident with the bank-full channel, and the macro-channel flanked by high terraces.

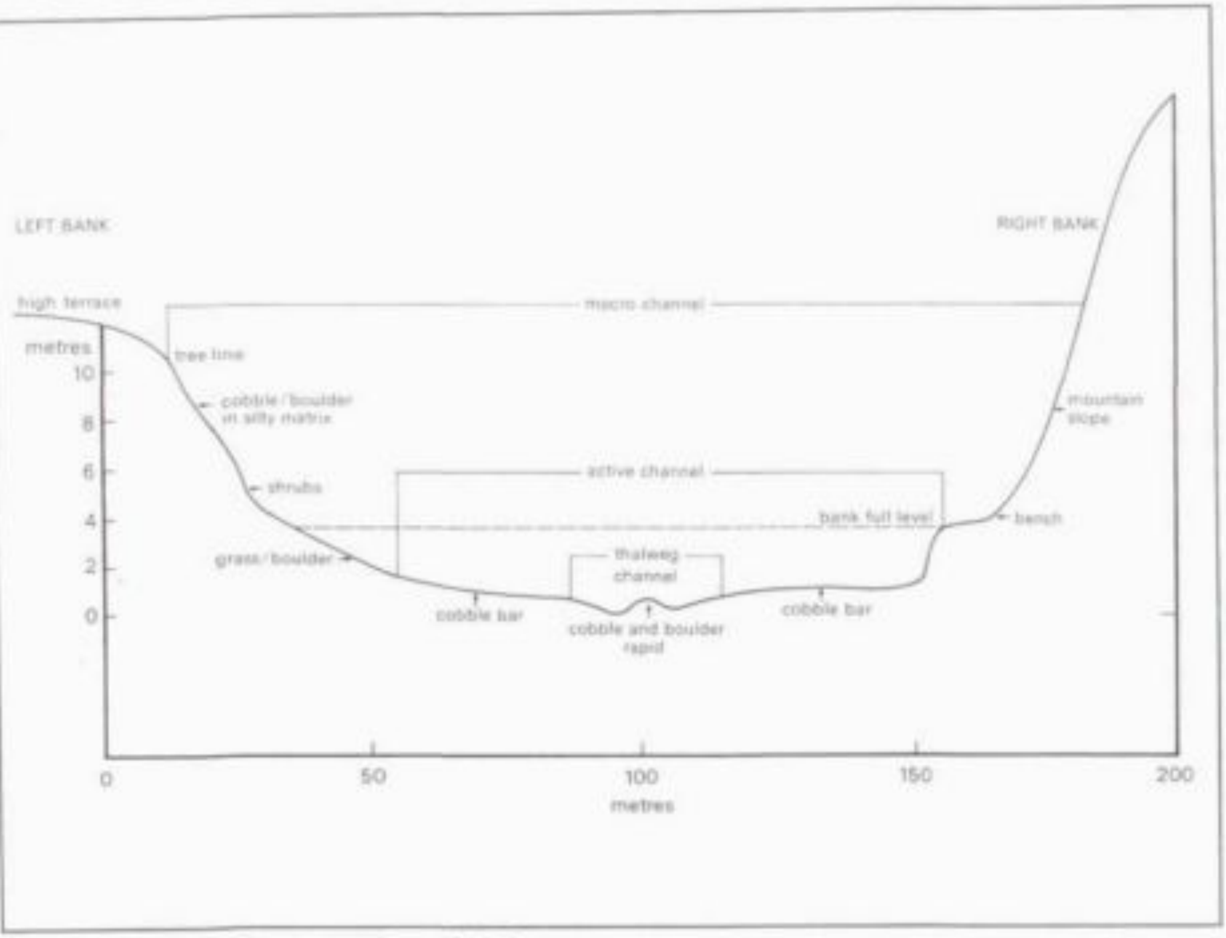


Figure 8.4 Surveyed cross section at IFR 5

Assessing the level of bankfull discharge for the Tugela river was problematical due to a number of factors. It was first necessary to recognise the distinction between the active and macro-channel. Secondly, as is commonly the case (Williams 1978), it was not easy to identify the bankfull level of the active channel as morphological breaks are not co-incident on both channel banks (Figure 8.4). Thirdly, major floods in 1984 and 1987 may have been responsible for enlargement of the active channel.

Assessment of the effective discharge for sediment transport was also difficult. The channel bed was composed of coarse cobble and boulder with interstitial sand deposits. The prediction of critical flows in mixed bed 'gravel' streams is notoriously difficult (Bathurst, 1987). Small particles become trapped between the larger ones so that initiation of sediment transport is influenced by the larger particles. Once the larger particles start to move the whole bed may become mobilised. As a simplification, estimations of critical velocities for movement are often based on the median particle diameter. Hjulström's curve (Hjulström 1935 in Gordon *et al.* 1982) was used to give a first estimate of the critical velocity required to move cobble size material. For medium cobble a velocity in excess of 2.5 m s^{-1} would be required. To winnow out the coarse sand between the cobbles a much lower velocity of 0.3 m s^{-1} is required (not accounting for shielding by larger particles).

Flow hydraulics were calculated by DWAF hydraulic engineers from cross-sectional surveys (DWAF, 1995). These analyses indicated that approximately 100 m^3s^{-1} is required to just cover the cobble bar, giving an estimated mean velocity of 1.6 m s^{-1}. This should be sufficient to cause removal of finer material and flushing of organics and loose debris, but insufficient to transport the larger gravel and cobbles. A flow of 320 m^3s^{-1} is required to inundate the channel up to the edge of the in-channel bench on the right hand bank (mean velocity 2 m s^{-1}), more or less co-incident with the lower limit of woody vegetation on the opposite bank, whilst 1400 m^3s^{-1} is required to inundate the channel to the base of the steep macro-channel bank (mean velocity > 3 m s^{-1}). A discharge within this range should therefore be sufficient to initiate cobble movement and appears to be related to the present active channel.

These discharge values should be checked against the flow record so as to estimate their recurrence intervals. An upstream flow gauge provided forty two years of data from which flood frequencies could be assessed. Flows in excess of 320 m^3s^{-1} are exceeded in almost all years, whereas flows only rarely exceed 1400 m^3s^{-1}. A flood of 650 m^3s^{-1} approximates to the flood with a recurrence interval of 1.5 years. It was decided to recommend an annual flood of 300 m^3s^{-1}. This is a conservative estimate of the channel forming discharge, but one believed to be sufficient to perform many of the geomorphic functions. If an annual flood of this magnitude was maintained through regulation, it is likely that some encroachment of woody vegetation would occur onto the present grassy slope, with an associated build up of fine sediments; this may well be re-instating conditions present before the large floods of the 1980s. Despite possible channel narrowing, a good width of cobble bar should be maintained. A velocity of 2ms^{-1} associated with a discharge of 320 m^3s^{-1} is probably at the lowest limit of the magnitude required to entrain cobble sized material, but is more than adequate to winnow out sand. Some movement of coarse sediments, and adequate sand flushing, should continue. In time, as the channel became narrower, mean velocities should increase over the remaining channel width so that transport of the coarser materials would become more effective. It must be remembered that the largest floods will be relatively unaffected by the dam and will be retained as a component of the modified flow regime.

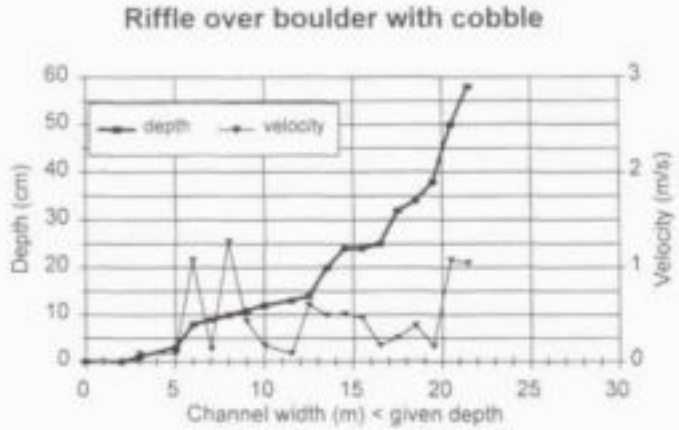
A more frequent channel maintenance event (thrice yearly) of 100 m^3s^{-1} was also recommended. This would just cover the exposed cobble bar and would provide sufficient velocity to move sand and other fines without disturbing the cobbles themselves.

Assessment of Hydraulic Habitat

The most immediate problem addressed by ecologists determining the IFR is the change in available habitat for specified species in relation to the range of flows to be imposed on the channel. Available habitat is site specific (and species specific) and requires detailed surveys of the channel morphology at the IFR sites. Ecologists normally relate habitat availability to baseflow conditions. These will vary seasonally, but have a relatively high consistency from year to year.

Morphological units and associated hydraulic biotopes were described at each IFR site and transects set up for hydraulic studies across each morphological unit. In order to assess available habitat at the observed flow a survey was carried out across the central transect, noting flow depth, velocity (0.4d from the bottom as described in Chapter 4), substrate, flow type and hydraulic biotope at approximately 1 to 2 metre intervals depending on the length and complexity of the transect.

The survey transect at IFR5 was located on a boulder/cobble riffle lying between two shallow pools. The flow transect for habitat assessment was taken across the riffle as this provided the greatest habitat diversity as well as being the area most vulnerable to habitat loss during low flows. The distribution of depth and velocity over the riffle is shown in Figure 8.5.



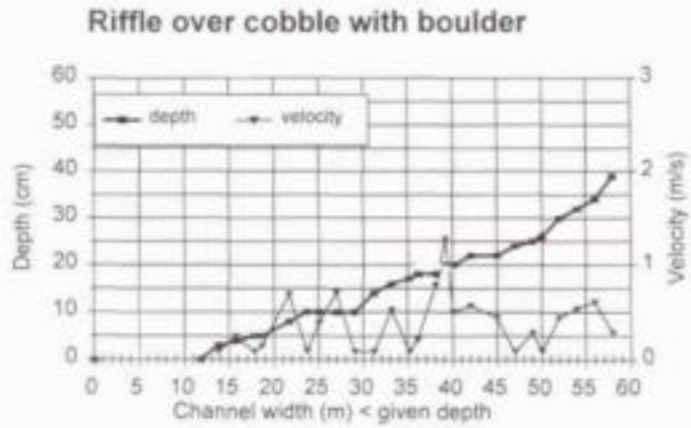


Figure 8.5 Cumulative depth distribution curves over riffles at sites IFR5 (boulder with cobble) and IFR8 (cobble with boulder). Point velocities are given against the associated depth.

It is interesting to note the different depth distribution between this morphological unit (a riffle over boulder with cobble) and that for the site downstream at IFR8 (a riffle over cobble with boulder). It is clear that whilst the riffle over cobble provides an even spread of depths over the observed range, the presence of boulders tends to give a stepped distribution which was similar to that observed over a bedrock rapid. This difference was born out by a number of the sites visited in the Tugela.

Observed hydraulic biotopes in the thalweg channel at site IFR5 were dominated by rapid flow, with runs and chutes in lateral areas. The site was visited only once so it was not possible to observe how hydraulic biotopes changed with discharge. From the research results described in Chapter 6 it was possible to infer probable changes. It can be expected that the rapid flow would be maintained at much lower discharges, or would become riffle flow, but the lateral biotopes would be lost as the flow became increasingly confined to the narrow thalweg channel. The extent of rapid flow in the thalweg channel would increase at higher discharges, but runs, chutes and riffle would increase in lateral areas as flow extended further into the cobble bar of the active channel.

Impact on receiving channels

Water transfer schemes from areas of water surplus to areas of water deficit are widespread in South Africa. It is a common practice to use existing river channels as conduits for such transfers. The geomorphological and ecological consequences of transferring large volumes of water into small headwater streams can be severe. With the exception of a study on the impacts of transfers into the Nahoon system (Hughes, 1984), as yet the DWAF has given scant attention to the geomorphological effects on receiving systems. Although existing and proposed developments on the Tugela are an integral part of a water transfer scheme, the impacts outside the Tugela catchment were not included in the terms of reference for the IFR workshop. It is recommended that they be assessed at Feasibility stage. The geomorphological characteristics of the channel will be an important component of this assessment.

Conclusions

Since South African geomorphologists were first invited to attend an IFR workshop in 1992, they have become increasingly involved in developing the Building Block Methodology. Geomorphology has become an important component at all stages of the process, including the overall assessment of the catchment scale impacts, site selection and the recommendation of flows for channel maintenance. Geomorphologists are also involved in developing relationships between channel morphology and hydraulic habitat so that on-site, at-a-discharge assessments can be better extrapolated to channel reaches and to a range of discharges. In outlining the geomorphological inputs to an IFR assessment carried out for the Tugela river, this paper has presented a number of geomorphological concepts which have been applied to the IFR process. The development of the Building Block Methodology is a dynamic process, and the refinement of geomorphological ideas develops with it. As our experience of the geomorphology of South African rivers expands, so too will our ability to manage them in a sustainable manner. It is hoped that the ideas presented here will assist that management.

8.3 THE NATIONAL BIOMONITORING PROGRAMME FOR RIVERINE ECOSYSTEMS

Geomorphologists have been invited to participate in the setting up of a National Biomonitoring Programme on two accounts. The first was an invitation to participate in the Spatial Framework Workshop (Brown and Eekhout, 1996) held in Cape Town in January 1996. The second was a request to develop geomorphological indices to be used as part of the monitoring protocol. These indices would also apply to follow up monitoring following impoundment.

8.3.1 Geomorphological contributions to the development of criteria for setting up a spatial framework for biomonitoring

The aim of the workshop was to produce, using expert knowledge, a first estimate of possible biotic sub-regions for South Africa within pre-designated biogeographic regions. Biogeographic regions have been identified (Eekhout, *et al*. 1997) which are intended to account for variation in the biotic character of rivers at a national scale. The concept of the sub-regions was developed to account for variation in biotic character which is a consequence of the longitudinal zonation of a river. This longitudinal zonation is a direct reflection of altitudinal changes down the long profile and associated variations in temperature, discharge, sediment load and channel form. It was therefore recognised that a geomorphological framework would provide a logical starting point for river zonation.

Geomorphology was approached from two aspects. The first was a general overview of the geomorphology of each biogeographic region: the second was the geomorphological zonation of specific rivers representing a range of biogeographic regions. The aim of the general overview was to subdivide the biogeographic regions into physiographic areas, firstly as an aid to the identification of zones within each region and, secondly, to ascertain the degree of geomorphological similarity between different catchments within one region. Zonation of specified river systems was carried out for rivers for which the authors had some first hand knowledge and was based on the identification and classification at the segment level of the hierarchical framework .

Nine rivers were selected for a more detailed study of geomorphological zonation. These rivers represented a broad range of biogeographic regions from 6 to 11. The accompanying reports gave a description of zonation along the long profile. Zonation was described in terms of the segment classifications given in Section 3.6.1: *Mountain headwall, Mountain stream, Foothills, Transitional, Lowland, Upland plateau, Gorge, Rejuvenated foothills*. The Berg River is presented here as an example.

Geomorphological zonation of the Berg river

The catchment and long profile

The Berg River flows for 213 km from an altitude of 1500 m amsl in the Franschoek Mountains north through Paarl and Wellington before trending north west to west to the Berg Estuary. As can be seen from the long profile in Figure 8.6, the river drops steeply, reaching an altitude of below 200 m as it leaves the main mountain mass at the confluence with the Franschoek river. From here the catchment opens up as the river flows through the lowlands. Major tributaries are the Klein Berg, the Vier en Twentig and Krom which drain the Olifants Mountains to the north east and the Sout which drains the lowlands to the south. The total catchment area covers 7715 km^2. Mean annual precipitation over the mountains exceeds 2500 mm, but falls off quickly in the valley bottoms and lowland areas to between 400 - 500 mm. Over much of the lower catchment rainfall is between 250 and 400 mm. The catchment geology can be divided into three main zones, the mountain area underlain by the quartzitic sandstones of the Table Mountain Group and the Cape Granite Suite, the lowland areas are underlain by predominantly shales and greywacke of the Malmsbury Group and Pleistocene windblown sands and alluvial deposits of the coastal plain. Soils in the mountain areas are very shallow and are classified as rock, the lowland areas are dominated by the Swartland form which is characterised by a generally fine texture, whereas the sandy Fernwood form is found in the coastal areas. The vegetation of the mountain areas is classified as Mountain fynbos; in the lowlands very little of the natural vegetation of coastal Renosterbos remains; the area is cultivated extensively for wheat. In the foothills area around Paarl and Wellington most land is under vineyards.

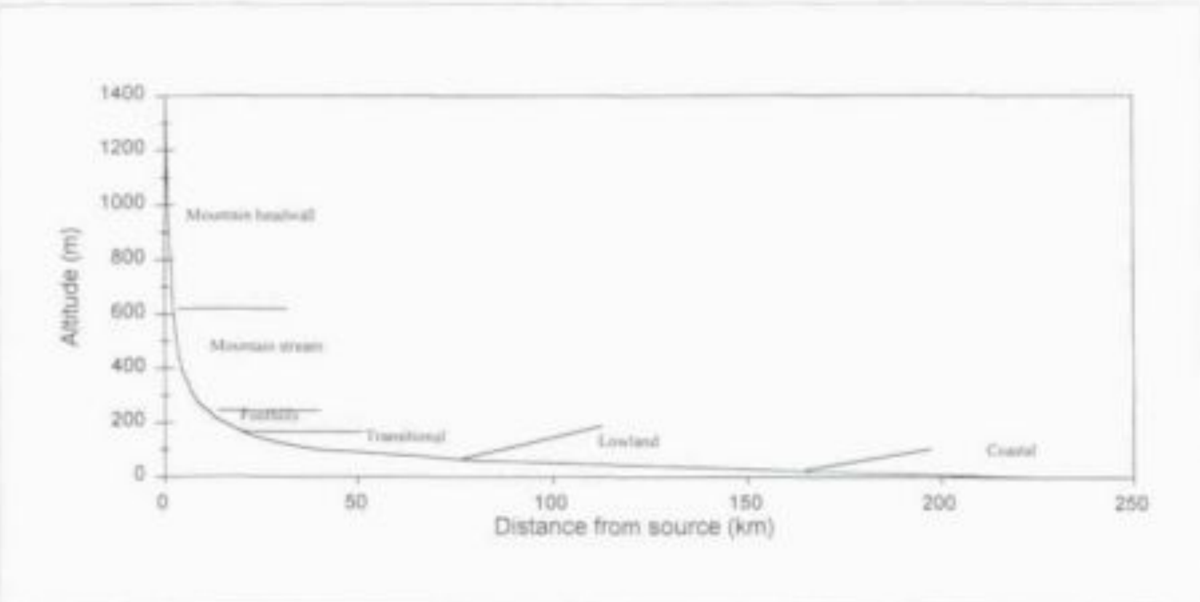


Figure 8.6 Long profile of the Berg River

Runoff and sediment response zones

Runoff follows a similar pattern to precipitation, with a large proportion of the runoff being generated in the mountainous areas where high rainfall combines with thin soils and steep slopes. The runoff from the Franschoek and Berg catchments above their confluence is in the order of $600 \times 10^6 m^3 yr^{-1}$. Downstream of the confluence runoff production decreases rapidly, being in the order of $100 \times 10^6 m^3 yr^{-1}$ between Paarl and Wellington, with higher contributions from the mountains to the north. As the catchment opens out in the lowland area runoff is reduced to around $30 \times 10^6 m^3 yr^{-1}$. Although there are some fairly large tributaries in terms of catchment area (Sout, Krom and Twee en Twentig) their runoff contribution is negligible. Tributaries from the Olifants mountains to the north east also produce moderated amounts of runoff. Runoff from the quaternary catchments within the Berg system is shown in Table 8.5.

Table 8.5. Mean Annual Runoff by Quaternary Catchment

Catchment	Area km^2	MAR mill. m^3
G11 (Mountain zone)	745	607.49
G12b (Foothills)	1350	103.24
G12a (Groot Winterhoek)	790	236.24
G13 (Lowlands)	1880	36.04
G14a (Sout)	1300	33.67
G14b (Coastal plain)	1650	13.80
Total	7715	1030.48

Sediment zones are based on a consideration of topography, geology, soils and erodibility, vegetation cover and/or land use. In the mountainous areas upstream of the Franschoek confluence annual sediment yields are low due to the resistant nature of the Table Mountain sandstones and the thin soils. A combination of steep slopes and high rainfall is, however, conducive to debris slides, as are clearly visible throughout the upper catchment. The granites are likely to be particularly susceptible to weathering and mass erosion. Although the total amount of material produced in this manner is not great, the calibre of the material, ranging from sand size up to large cobble, is such as to make a significant contribution to the bedload. It is likely that rates of bedload movement in these high gradient mountain streams is moderately high.

Below the Franschoek confluence the river flows through a wide alluvial plain of sand sized material, whilst tributaries drain the Malmsbury shales. Further downstream below Wellington the river flows directly over the Malmsbury Group. Soil in these areas are more prone to erosion, whilst the low rainfall does not support a good ground cover. Severe erosion was noted in the lowlands during the rapid expansion of wheat growing areas up to the late 1930s (Talbot, 1945). In the Paarl area the sparse cover offered by vineyards is also conducive to erosion of the sandy alluvial soils. Although improved conservation methods since the 1930s have reduced erosion, sediment yields from the cultivated lowland areas remain moderately high. The calibre of sediment produced from these areas will range from sands (contributing to bedload) to silts (contributing to the suspended load).

Geomorphological zonation of the river channel

The main channel of the Berg River was subdivided into six geomorphological zones based on channel gradient, inputs of runoff and sediment from the catchment and the consequent variation in channel form and size and bed material size. The main features of each zone are summarised in Table 8.6. It should be born in mind that site visits by the authors have been limited to the zones 3 and 4 and 5 and to the Skuifraam IFR Site 3/96 at the top of zone 6.

Table 8.6. Geomorphological zonation of the Berg River

Zone	Altitudinal range (m)	Distance from source (km)	Gradient	Catchment features	Channel features	Landuse and Disturbance
1 Mountain headwall	1400 - 600	0 - 2	0.33	very steep slopes, Table Mountain sandstone, fynbos vegetation, thin soils,	very steep head wall streams, *bedrock channels with waterfalls*	
2 Mountain stream	600 to 220	2 - 13	0.0714	confined valley, colluvial foot slopes, Table Mountain sandstone and granites, fynbos vegetation, mass movements	narrow valley floor, steep gradient mountain stream, incised channel, *rapids, cascades, bedrock pools*	pine plantations, black wattle in riparian zone
3 Foothills	220 - 160	13 - 21	0.0076	steep valley side slopes, open valley floor, Table Mountain sandstone and granites, fynbos.	cobble bed braided channel with shallow pools, riffles, rapids and plane bed morphology	pine plantations, black wattle in riparian zone,
4 Transitional	160 - 100	21 - 40	0.0036	open topography with gentle slopes, wide alluvial flood terraces, underlying geology shales and greywacke, natural vegetation Renosterbos	transition zone, sinuous channel, sharp reduction in gradient increased channel width, cobble bed pool - riffle morphology and lateral cobble bars, increasing sand deposition.	viticulture on alluvial terraces, bulldozing of channel

5 Transition2	100 - 60	40 - 81	0.0010	as for zone 4	increased channel sinuosity - irregular/wandering, further reduction in gradient, variable channel width, infrequent islands or divided channel, mixed bed (cobble and sand) grading to sand in lower reaches, long pools with cobble riffle and lateral bars, possible aggradation in pools	highly disturbed channel, middle section urbanised channelisation, bank stabilisation, straightening etc viticulture dominating land use, *Eucalyptus grandis* in riparian zone, much woody debris in channel
6 Lowland	60 - 20	81 - 165	0.00047	As for zone 5	irregular meanders, single thread channel, highly variable channel width; some channel division where shrubby vegetation survives in riparian zone; sand bed channel, pool morphology with infrequent lateral bars and rapids.	cultivated lands (wheat), badly eroded in the first half of this century, channel impounded by weir
7 Coastal	20 - 0	165 - 213	0.00033	windblown sands less confined valley,	irregular meanders, narrow channel, sand bed, narrow lateral bars, plus estuarine reaches	

8.3.2 Geomorphological indices for the National Biomonitoring Programme

Geomorphological processes determine channel morphology which in turn provides the physical framework within which the stream biota live. A biomonitoring programme requires an initial geomorphological classification of the channel to allow, firstly, comparison between sites and, secondly, long term monitoring of morphological change to which possible changes in the available habitat can be linked. This requires the application of a separate but related monitoring index. Two indices are recommended: a channel classification index and a hydraulic biotope diversity index.

Channel classification index

A recommendation was made to develop a channel classification based on a framework such as that of Rosgen (1984) which uses reach characteristics to classify 86 naturally occurring river types (section 3.5). Rosgen's classification would need to be refined and modified to incorporate reach types characteristic of South African rivers and to extend the classification to include segments and reaches based on desk studies (GIS data base). These aspects of river classification are well developed within the hierarchical geomorphological model.

A reach classification would be applied to the reach within which a biomonitoring site was situated. Classification would be based on an inventory modelled on recommendations set out in Chapter 7. Classification of the river reach would be based on simple classification of features such as sinuosity, channel pattern, entrenchment, width-depth ratio, morphological units, bed and bank material, bed and bank condition, evidence of erosion or deposition. Such a classification scheme would allow comparisons between sites as well as indicating the site's sensitivity to disturbance and recovery potential.

It was also recommended that a base line condition or template from which channel change can be assessed would require a detailed survey of plan and cross sectional form at each site. This data would provides valuable input for the modelling of hydraulic conditions likely to be experienced at each site.

Hydraulic biotope diversity index

A hydraulic biotope diversity index (HBDI) is being developed which describes the available hydraulic habitat for instream biota associated with different morphological units at different discharges (Rowntree and Wadeson, 1996). Habitat is classified using hydraulic biotope classes assessed from observations of flow depth, flow type (surface flow characteristics) and substrate class. The index is based on the proportion of hydraulic biotopes within each morphological unit compared to an extended regional baseline condition. Data collection involves hydraulic biotope mapping based on the original site plan together with point classification across transects. Flow discharge data at the time of sampling would also be required.

Hydraulic biotope diversity was measured for selected sites in the Buffalo River using the Hydraulic Habitat Diversity Index (HBDI). Results showed that in nearly all cases the index showed the highest habitat diversity for intermediate discharges, indicating that in terms of instream flow requirements, it is these intermediate discharges that would provide the most favourable habitat conditions. It is suggested that the HBDI has the potential to provide a tool for assessing instream flow requirements and for monitoring long term changes in habitat diversity.

8.4 CONCLUSION

The geomorphological model presented in this report provides a conceptual framework which can be used to support the decision making process in catchment management. Two examples have been given as to how this can be achieved.

To provide effective answers this model must be linked to process models which estimate the hydrological and sediment response of the catchment and river system. The level of sophistication of the chosen models depends on our level of understanding of the processes themselves, the availability of the necessary data, and the financial and time constraints of the manager. In a management context the latter two constraints tend to be the limiting ones. The proposed hierarchical framework lends itself to the application of both simple process models appropriate for the rapid assessments often needed in decision making and also the more complex research models which scientists strive for in their long term goal of predicting system response to management decisions and catchment developments.

The system allows the manager to enter at any level and follow the hierarchy either upwards or downwards. An advantage of the system is that it provides a framework that can be applied at a range of levels depending on the resolution of available data and the degree of sophistication of the hydrological and sediment models to which it is linked. Hence it provides a management tool that can be used within a range of financial and time constraints.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

9.1 OVERVIEW

The aim of the research programme described in this report was to provide ecologists and river managers concerned with conserving ecosystem health or integrity with a relevant geomorphological framework to aid the explanation of ecosystem processes and biotic distributions and contribute to a decision support system for management. Specific aims of the project were threefold: to ascertain the important geomorphological criteria which determine habitat sensitivity to natural or anthropogenic disturbance; to develop a methodology for selected catchments for classifying the physical habitat of lotic ecosystems (running water); to extend this methodology to a wide range of South African river systems as a management tool for the assessment of conservation potential.

This project set out to develop a geomorphological classification of South African river systems that would provide a framework for ecological research and river ecosystem management. It was important that the classification system was both relevant to and intelligible to river ecologists and managers. The first task was to determine the scales and components of the river system that were most relevant to ecological studies, the second was to develop a consistent and clearly defined set of geomorphological terms to describe those components. The third was to put this into a classification framework that was able to link the various scales relevant to river systems.

Geomorphologists, river ecologists and river managers all work at a number of different scales which need to be incorporated into a workable classification system. River ecologists work primarily at the habitat scale, which for invertebrates is at the scale of the cobble on the river bed or for fish the underbank pool. A particular stretch of river is seen as a mosaic of habitats which can be related to the different channel morphologies. Geomorphologists have traditionally focussed their research at the reach scale, characterised by an assemblage of channel forms which create a distinct channel cross-section and plan-form. Reaches are composed of morphological units which contain the ecologist's habitats. Managers in turn need to take a broader perspective related to management units within which discharge for example can be regulated. These management units relate to river segments which are at the scale of river network components. These different scales can be seen to fall within a nested hierarchy, from habitat, morphological unit, reach to segment. Above all these scales is the river catchment which defines the land area contributing runoff and sediment to the channel system and which ultimately controls the driving forces for geomorphological change and ecosystem processes. A hierarchical classification approach was therefore adopted in this project. This approach followed the conceptual model proposed by Frissel *et al.* (1986) and Naiman *et al.* (1992) as a basis for river classification.

Early on in the project it became clear that it would not be possible to develop a conventional 'classification' system for all levels of the geomorphological hierarchy. It is impractical to produce a comprehensive classification of whole river systems in the traditional sense as the complexity of each drainage basin makes it a unique entity. Because this project was designed to link the most important physical variables within the catchment, at a number of different scales, it was felt that it may cause confusion to talk of a hierarchical classification in the present context. In the traditional ecological literature, hierarchical classification refers to the development of a technique for ordering or arranging features measured at the same spatial scale into various levels of similarity or dissimilarity. This would require a radically different approach to that developed here. In contrast the approach used in this project was to modify and apply extant geomorphological classifications to the different levels of a hierarchical geomorphological model. The hierarchical model promoted in this report describes the linkages between the catchment which supplies water and sediment to the channel network, the drainage network through which the sediment and water are routed, and the channel morphology at the reach scale which provides the habitat for stream organisms.

Three catchments were selected for initial model development, the Sabie River in the eastern Transvaal, the Buffalo River in the Eastern Cape and the Olifants River in the western Cape. These river systems encompass a wide range of environmental variables and spatial scales. They are also systems which are the focus of ecological studies and for which a significant amount of ecological and channel morphology data is already available. Much of the work at the start of the project centred on the Sabie River. This river was the focus of research in the Kruger National Park Rivers Research Programme (KNPRRP) and at the start of this project there was no geomorphologist specifically attached to that programme. With the appointment of a geomorphologist to the KNPRRP it was more logical to shift the focus of our own project away from the Sabie. Thus, although our experience in the Sabie provided useful insights into the range of river morphologies to be found in this country, little formal research was carried out in this river. The work by van Niekerk and Heritage in the Sabie provided an excellent compliment to our own work in other river systems and their classifications have been integrated where appropriate into our own.

Through the course of the project the authors had the opportunity to visit and work in a much larger number of rivers than at first anticipated. Between 1992 and 1996 they were involved in Instream Flow Requirement (IFR) assessments for the Berg and Olifants Rivers (Western Cape), Kei, Mzimvubu and Great Fish Rivers (Eastern Cape), Sabie and Letaba (Mpumalanga), Mogolakwena (Northern Province), Movoti and Tugela (KwaZulu-Natal). Other rivers, such as the Molenaars in the Western Cape, were also included in the research programme due to common research with ecologists. The extensive experience of different rivers derived through this work was significant in increasing our understanding of the range of river systems to be found within South Africa and was important in refining our classifications of river morphology and reach types. As our thinking progressed, the IFR workshops also provided us with the opportunity to apply the hierarchical framework in a management context. As a result the classifications and techniques described in this report were not developed specifically from work in the Sabie, Buffalo and Olifants as was first proposed. Rather they are the result of wisdom gleaned from a much wider range of rivers. The local river, the Buffalo, was used to formally test the different levels of the hierarchy.

Following discussions with South African river ecologists and extensive reviews of the international literature, it became clear in the early stages of the project that although geomorphologists and ecologists often used the same terminology when describing physical habitat, the interpretation of terms often differed. A considerable amount of time was therefore spent in explaining geomorphological processes and defining geomorphological terms (Chapter 3). It was found that there were not always standard definitions available in the literature so that a number of the definitions given here were developed for specific South Africa geomorphological features. Chapter three provides the basis for classification at the hierarchical levels from the morphological unit upwards.

The most important research outcome of this project was the development of the hydraulic biotope concept and the associated hydraulic biotope classification as reported on in Chapter Four. Defined as 'a spatially distinct in-stream flow environment characterised by specific substratum and hydraulic attributes', the hydraulic biotope provides an appropriate scale for linking geomorphological and ecological research. At the Citrusdahl workshop in February 1995 (Rowntree 1996a) it was agreed that the hydraulic biotope provided "a practical unit of data collection that can be recognised by both geomorphologists and ecologists and it is the finest scale at which both disciplines can conveniently work together," (Rowntree, 1996a p.42.). At this same workshop a hydraulic biotope matrix was developed which classified hydraulic biotopes in terms of a particular combination of flow type and substrate, where flow type describes the appearance of the surface of the water and is taken to be a surrogate of the complex of hydraulic conditions in the water column. This hydraulic biotope classification came about as the result of early deliberations by Wadeson in his PhD research, parallel studies undertaken by Padmore and Newson in the United Kingdom and the experience of ecologists, in particular King and O'Keeffe who were present at the workshop.

Relating hydraulic biotopes to flow characteristics requires an understanding of flow hydraulics at a scale relevant to stream biota. Chapter Five of this report presented a basic review of hydraulic theory which is designed to be accessible to ecologists. This review also layed the basis for the design of the field testing of the hydraulic biotope classification that was carried out in the Buffalo river. Two areas of flow were seen to be significant, the mean flow of the water column and the near bed flows. The mean flow of the water column is important in defining habitat for swimming organisms (fish), and can be described by the velocity-depth ratio, the Reynolds number and the Froude number. The near-bed flow conditions are more important for the benthic organisms; these conditions can be described by the 'roughness' Reynolds number and the shear velocity. The effect of bed roughness was also accounted for by the use of roughness flow classes following the classification of Davis and Barmuta (1989). These five hydraulic varaibles plus the roughness flow classification were all found to be useful in distinguishing hydraulic biotope classes. The Froude number is considered to be particularly useful in describing mean flow conditions in the water column as it takes into account the hydraulic effects of both depth and velocity, the two variables most commonly used to describe hydraulic habitat. Because it is non-dimensional the value of the Froude number is independent of scale so that small and large features will group together if their hydraulic characteristics are similar. The 'roughness' Reynolds number is thought to be particularly appropriate in describing the near bed conditions because it combines a measure of shear stress with that of roughness height, the latter being a measure of effective substrate size.

Wadeson's PhD research, reported on in Chapter Six of this report, concentrated on validating the classification using test sites on the Buffalo River. His results confirmed that the hydraulic biotopes that had been recognised at the Citrusdal workshop could be distinguished in terms of their hydraulic characteristics using the indices described in Chapter Five. Consistent results were found over five contrasting sites (step-pool, plain bed, pool-riffle, planar bedrock and bedrock pool-rapid) and four discharges ranging from minimum flows up to spate flows. Wadeson also demonstrated the dynamic nature of hydraulic biotopes. For any one morphological unit the composition of the hydraulic biotope assemblage changed with discharge. For all morphological units the greatest variability in hydraulic biotopes was observed for discharges with a flow duration of between 70 percent and 50 percent flow exceedence.

Although rigorous testing of the hydraulic biotope classification was carried out only in the Buffalo River, early work during the development phase was undertaken in a range of rivers including the Great Fish (Eastern Cape), the Sabie (Mpumalanga), the Molenaars (Western Cape) and the Olifants (Western Cape). This early work is fully reported on in Wadeson's PhD thesis (Wadeson, 1996). Of the research carried out in the developmental phase, only the Olifants work is reported on fully in this report. The reach studied in the Olifants was a sand bed reach and provides an interesting contrast to the Buffalo River. The main differences observed were that hydraulic biotopes in a sand bed river display a greater homogeneity than do those in boulder or cobble bed rivers due to the lower bed roughness, but bed mobility becomes an important criteria which must be considered.

The hydraulic biotope matrix as a tool for the identification of different hydraulic biotope classes appears to be extremely useful as it has been shown to be valid at a number of different spatial and temporal scales. Statistical analysis of results supported the hypothesis that hydraulic biotope classes recognised at different sites and at different discharges do not show significant difference in their hydraulic characteristics as defined by the Froude number, 'roughness' Reynolds number and shear velocity. Specific associations appear to exist between channel morphology and hydraulic biotope class distribution. The relationships described here were for a localised selection of morphological units in one river system. The next challenge is to extend this research to a wider range of morphological units and river environments to see if general relationships can be found. This would provide an important step forward in formulating models which predict available habitat from channel geomorphology and could prove invaluable to future instream flow assessments.

Chapter seven integrates the different levels of the hierarchy into a framework for geomorphological classification. The Buffalo River and its catchment was used to demonstrate the different techniques used. This section takes a top-down approach, starting with the catchment and ending with the hydraulic biotope because this is the approach which is normally followed in describing a river system. Starting with a general description of the catchment, the catchment is then subdivided into homogenous response zones which are determined to be homogenous with respect to runoff and potential sediment production.

Due to a lack of widespread data on measured flood runoff and sediment yield, response zones must be modelled from known catchment characteristics. A wide number of models are available with different efficiencies in terms of data requirements, modelling algorithms and output accuracies. It is recommended that the user decides on the most appropriate model for the task in hand. In this report it was decided to make use of the quaternary catchment data on simulated mean annual runoff and sediment yield that is available from WR90 (Water Research Commission, 1990). Methods are described as to how the data can be extracted from the WR90 data base in pcARCINFO and put into the correct format for input to the next level of the hierarchy, the segment. Segments are defined as lengths of channel network which lack distinct changes in discharge, sediment transport capacity and sediment load along their length. They are defined, therefore, in terms of the channel network and the long profile. Longitudinal zonation based on broad gradient classes, comparable to the ecological zonation of the 1950s and 1960s, is introduced at the segment level. To derive segments it is necessary to combine the output from the response zone analysis with an analysis of the river long profile. River long profiles are digitised in pcARCINFO and the data manipulated in Quattro Pro. The long profile data is also used to make a preliminary subdivision of segments into reaches based on changes in channel gradient.

Description of the first three levels of the geomorphological hierarchy are based on desk top studies using available digital data bases and hard copy maps. Reach breaks can also be determined using a desk top approach, but classification of reaches in terms of channel type, plan form and channel morphology must normally be carried out in the field. For some rivers aerial photography is available at a suitable scale to assist the field classifications, as was the case for the lower Sabie River (van Niekerk *et al.*, 1995), whilst video footage from a low flying helicopter has become a standard resource for IFR workshops. The reader is referred to Chapter Three where classifications appropriate to the reach and morphological unit scale were detailed . Field data sheets are presented in Chapter Seven. These data sheets include those appropriate to collecting data at the lowest level of the hierarchy, the hydraulic biotope.

The geomorphological model presented in this report provides a conceptual framework which can be used to support the decision making process in catchment management. Although the model is presented as a top-down system, in reality it allows the manager to enter at any level and follow the hierarchy either upwards or downwards. An advantage of the system is that it provides a framework that can be applied at a range of levels depending on the resolution of available data and the degree of sophistication of the hydrological and sediment models to which it is linked. Hence it provides a management tool that can be used within a range of financial and time constraints.

Through the course of the project the project researchers were increasingly called upon to apply their geomorphological expertise to river management issues. In addition to participation in the assessment of instream flow requirement, this included inputs into the National Biomonitoring Programme for Riverine Ecosystems (renamed the River Health Programme). It was found that the hierarchical model lent itself well to these management applications. Examples were given in Chapter Eight. Since the culmination of this project geomorphologists have continued to be active in the field of river ecosystem management and the hierarchical model has been used increasingly as a framework for classifying river systems, for assisting sampling design and as the basis for geomorphological monitoring.

9.2 RESEARCH PRODUCTS AND RECOMMENDATIONS FOR FURTHER WORK

The tangible research products described in this report were twofold. The first was a set of techniques for describing and classifying components of river systems within a framework which conceptualises the links between different scales in the catchment system. The second was the development of the hydraulic biotope concept and associated classification as the finest spatial scale at which geomorphologists, hydraulic engineers and ecologists can conveniently work together. The project also had a number of other less tangible but equally significant outcomes. Most important it helped to strengthen links between river ecologists and geomorphologists and contributed significantly to bringing about the recognition of geomorphology as an essential component basic to our understanding of river processes and ecological functioning. As a result geomorphological frameworks have become adopted as standard in many river management applications such as in the Building Block Methodology for Instream Flow Requirement assessments.

The ir are a number of directions which should now be followed in order to take this classification system further. These apply particularly to catchment scale modelling, segment scale modelling, morphological unit scale modelling, initiation of a national inventory of South African rivers and application of the hierarchical geomorphological model to management situations.

9.2.1 Catchment scale modelling

To provide effective answers this model must be linked to process models which estimate the hydrological and sediment response of the catchment and river system. The level of sophistication of the chosen models depends on our level of understanding of the processes themselves, the availability of the necessary data, and the financial and time constraints of the manager. In a management context the latter two constraints tend to be the limiting ones. The proposed hierarchical framework lends itself to the application of both simple process models appropriate for the rapid assessments often needed in decision making and also the more complex research models which scientists strive for in their long term goal of predicting system response to management decisions and catchment developments. There is much scope for further work in developing both flood models and sediment production models at the sub-catchment scale. The potential for using satellite imagery as a data source at the catchment level should also be explored. Satellite imagery would be particularly useful for analysing vegetation cover. Vegetation is one of the main variables affecting sediment yield, but is the most difficult to quantify because it is so easily altered as a result of land use changes. Remote sensing could be invaluable in providing an up-to -date evaluation of catchment cover and condition.

9.2.2 Segment scale modelling

The segment is defined in terms of the control variables determining sediment transport, discharge and sediment load. Yet we still have a poor understanding of the relationship between flow discharge and sediment transport and the translation of this relationship into channel morphology. This is particularly true of South African rivers where bedrock controlled channels are ubiquitous. The concept of dominant or channel forming discharge needs to be tested and refined for different classes of river reaches in South Africa.

9.2.3 Morphological unit scale modelling and hydraulic biotopes

Detailed testing of the hydraulic biotope classification was restricted to the Buffalo River. Research should be extended to a wider range of environments. The hydraulic validity of the classification needs further testing as does the discharge related relationship between hydraulic biotopes and morphological units. Although the hydraulic biotope classes were derived in consultation with ecologists, the ecological validity of the classification had not been put to test. To do so must be a priority. The work is now being carried out in the Western Cape under the direction of Dr King from the Fresh Water Research Unit at the University of Cape Town should go along way towards testing the ecological validity of the hydraulic biotope classes.

9.2.4 Application of the hierarchical geomorphological model to management situations

With increasing pressure on our river resources it is essential that we can provide clear geomorphological guidelines to river managers. Further research is needed to refine the hierarchical model for application to management issues such as Instream Flow Requirements and the National Biomonitoring Programme (now the River Health Programme) and, more recently, the Preliminary Reserve Project. These two latter initiatives have pointed to the need for an extension of the hierarchical approach not catered for in the present methodology. The hierarchical approach can be applied efficiently where there is only one (or possibly two or three) main stream of concern in one catchment as is the case in an IFR estimation. The River Health Programme and Preliminary Reserve Project, however, require that segment level classification is extended to all significant streams in the river network. This raises a need to develop rapid techniques for applying catchment, zone and segment level classifications on a regional basis.

There is also potential to develop the hydraulic biotope classification as a method for predicting discharge related changes in available habitat and as a monitoring tool. Hydraulic biotope monitoring within a framework of morphological units and reaches could have application in both IFR assessments and as a monitoring tool in the River Health Programme. Research is needed to develop efficient methods of data collection, analysis and presentation before the hydraulic biotope is likely to become widely adopted outside a pure research context.

9.2.4 Initiation of a national inventory of South African rivers

An increasing amount of data on the geomorphology of South African rivers has become available and will continue to do so as research continues. It would be appropriate to bring this information together in a national inventory. A library of pictures should be developed of channel types, morphological units and biotopes to facilitate identification and communication. Standardisation of data collection procedures should be introduced for channel descriptions, and the data should be complied into a national data base.

9.3 CONCLUSION

The aims of this project and the extent to which these they have been achieved is summarised in Table 9.1.

Table 9.1 Aims and achievements of the project.

AIM	ACHIEVEMENT
To ascertain the important geomorphological and hydraulic criteria in terms of habitat.	Development of the biotope concept, biotope classification based on hydraulic criteria.
To develop a methodology for selected catchments for classifying the geomorphological components of lotic ecosystems.	Development of the hierarchical geomorphological model, application to the Buffalo river
To extend this methodology to a wide range of South African river systems as a management tool for the assessment of conservation potential.	Application of the hierarchical model as a framework to IFR workshops for assessing geomorphological impacts of impoundments

For a classification system to be ecologically relevant, it must be based on a valid relationship between channel morphology and aquatic habitat. This relationship was developed through the hydraulic biotope concept which links discharge-dependent hydraulically determined patches in the stream to the more persistent, discharge-independent morphological units. Hydraulic biotopes and morphological units are distinguished as occurring within different time and space scales, a distinction that was often blurred in the past.

The hydraulic biotope is the lowest level of a hierarchical classification which links aquatic habitat to river catchment through a number of cascading levels. The hierarchical geomorphological model was applied as a classification tool to describe the geomorphology of the Buffalo river. Although the conceptual basis of this model is similar to that proposed by a number of earlier authors such as Frissel *et al.* (1986), the model presented here makes a significant step forward in that it has strived to give working definitions of all components at all levels of the hierarchy. The model should not, however, be seen as a final classification system. It is based on the best available definitions of presently known river systems in South Africa. As the model is applied more widely and an increasing number of channel morphologies are encountered it is anticipated that definitions will be modified and extended for some time to come.

The final aim of this project was to extend this methodology to a wide range of South African river systems as a management tool for the assessment of conservation potential. There is no doubting that this has been the case. The methodology has already found favour amongst ecologists dealing with management issues. With further development to meet the increasing demands for geomorphological inputs to management issues the hierarchical geomorphological model should prove itself as 'a relevant geomorphological framework to aid the explanation of ecosystem processes and biotic distributions and contribute to a decision support system for management' (Aims, p.3 this report.

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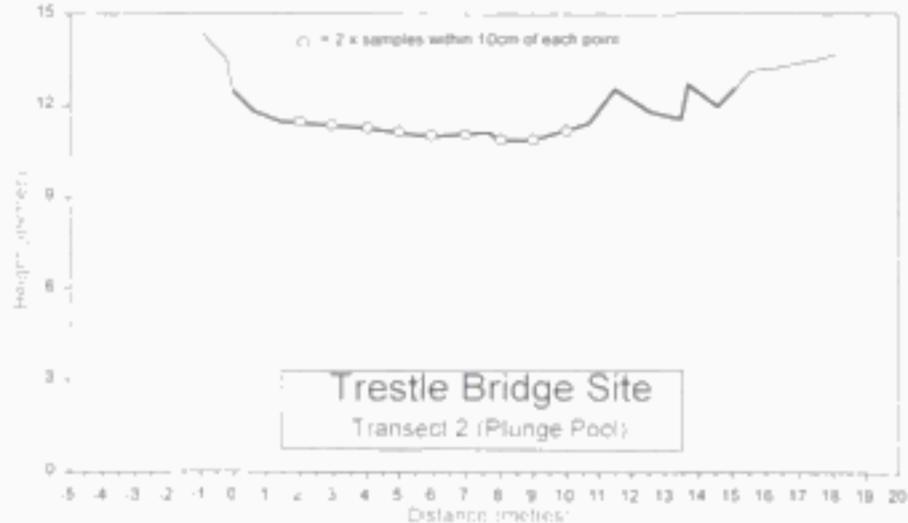
APPENDIX A

CROSS SECTION DATA - BUFFALO RIVER


○ = 2 x samples within 10cm of each point
Trestle Bridge Site
Transect 1 (Plunge Pool)
Distance (metres)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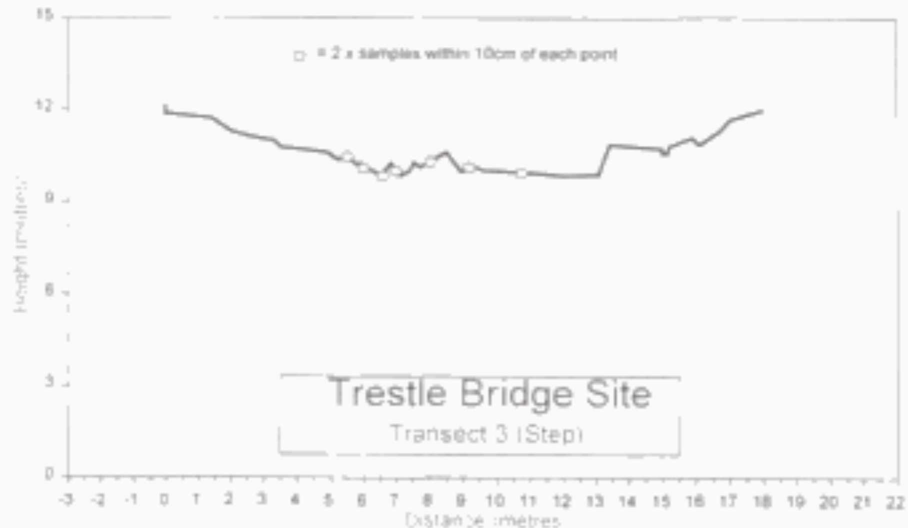
Trestle Bridge Site
Transect 2 (Plunge Pool)
Distance (metres)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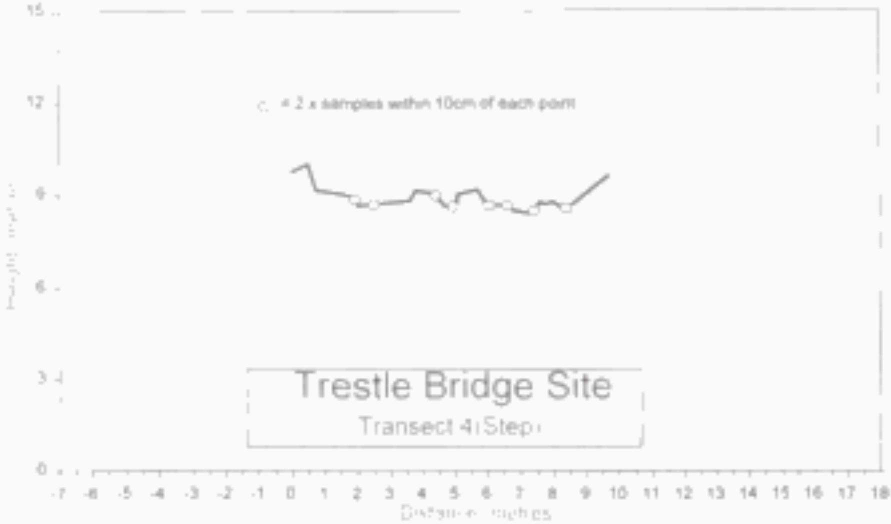
Trestle Bridge Site
Transect 3 (Step)
Distance (metres)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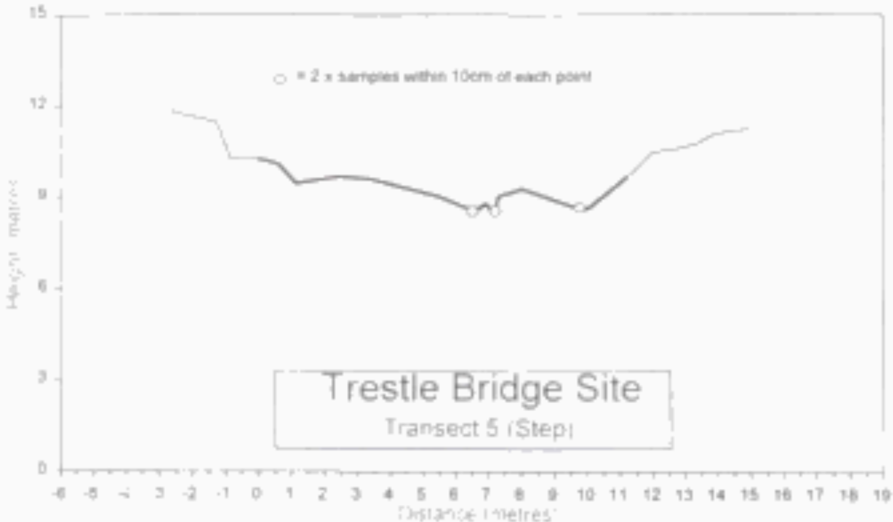
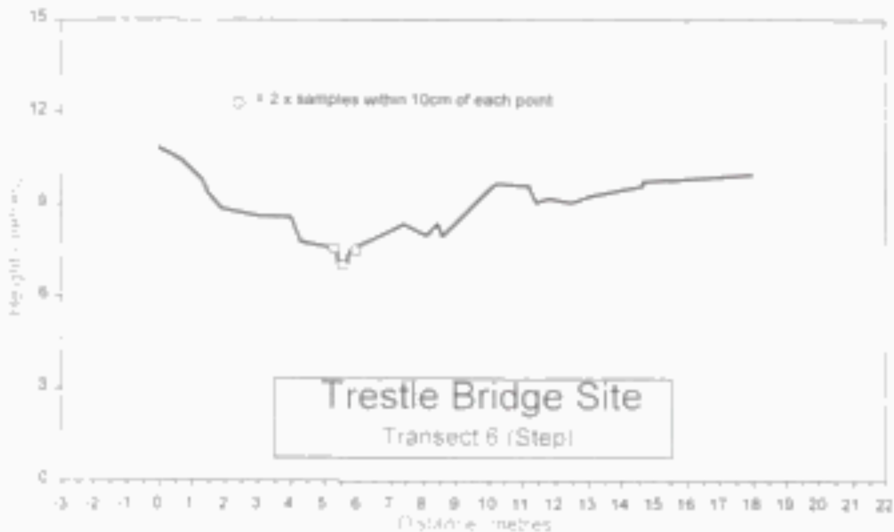
Trestle Bridge Site
Transect 4 (Step)
Distance (metres)


○ = 2 x samples within 10cm of each point
Trestle Bridge Site
Transect 5 (Step)
Height (metres)
Distance (metres)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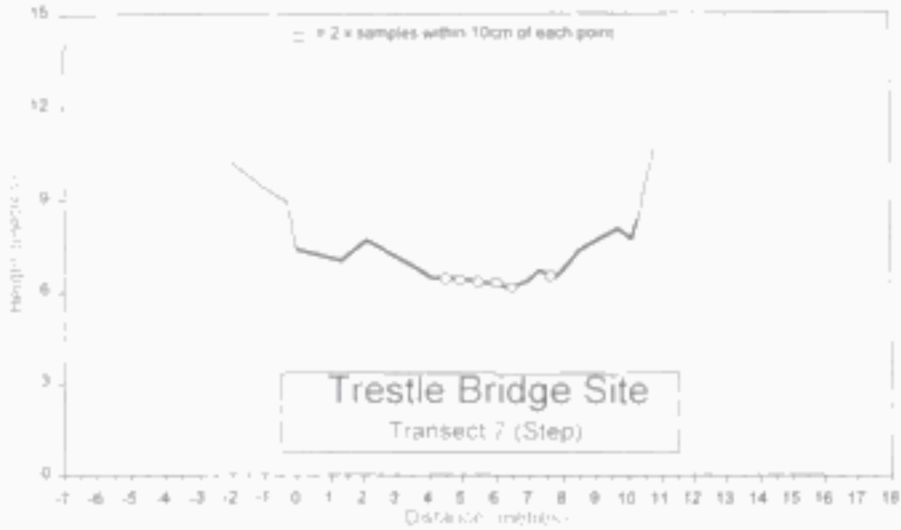
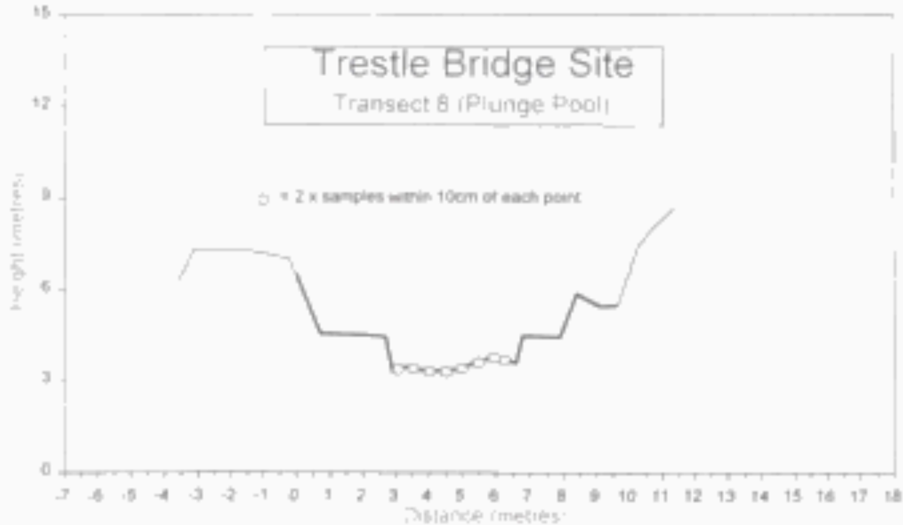
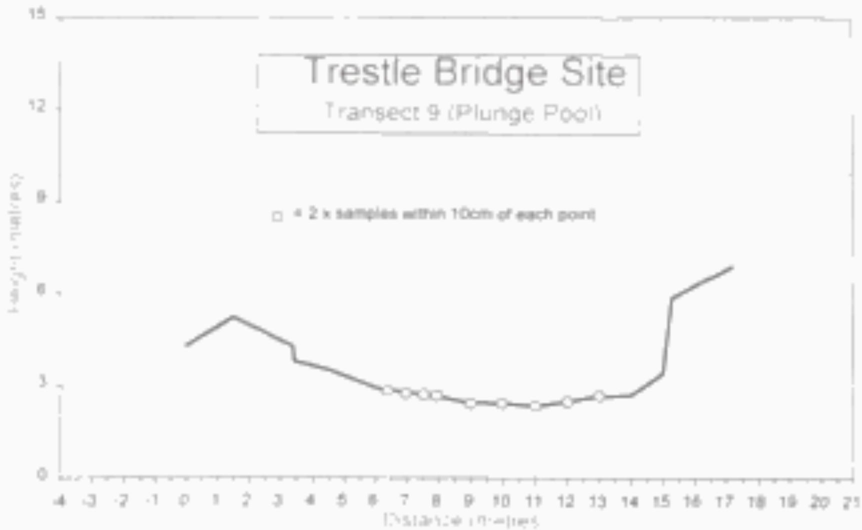
Trestle Bridge Site
Transect 6 (Step)
Distance (metres)


□ = 2 x samples within 10cm of each point
Trestle Bridge Site
Transect 7 (Step)
Height (metres)
Distance (metres)


Trestle Bridge Site
Transect 8 (Plunge Pool)
□ = 2 x samples within 10cm of each point
Height (metres)
Distance (metres)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Transect 9 (Plunge Pool)
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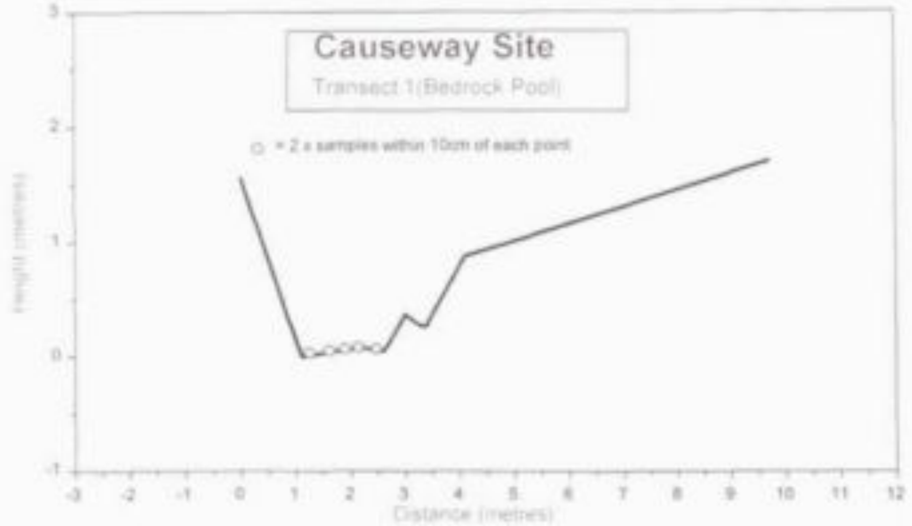
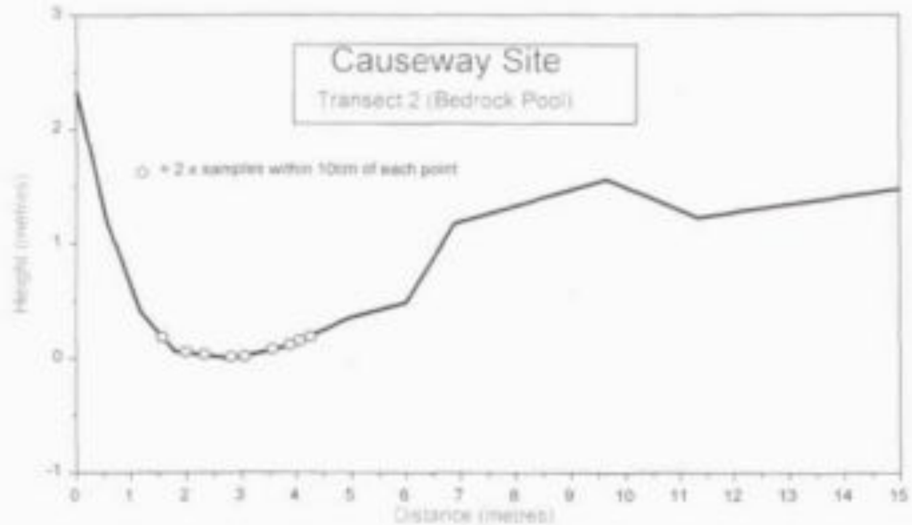
Height (metres)
Distance (metres)


Causeway Site
Transect 1(Bedrock Pool)
○ = 2 x samples within 10cm of each point
Height (metres)
Distance (metres)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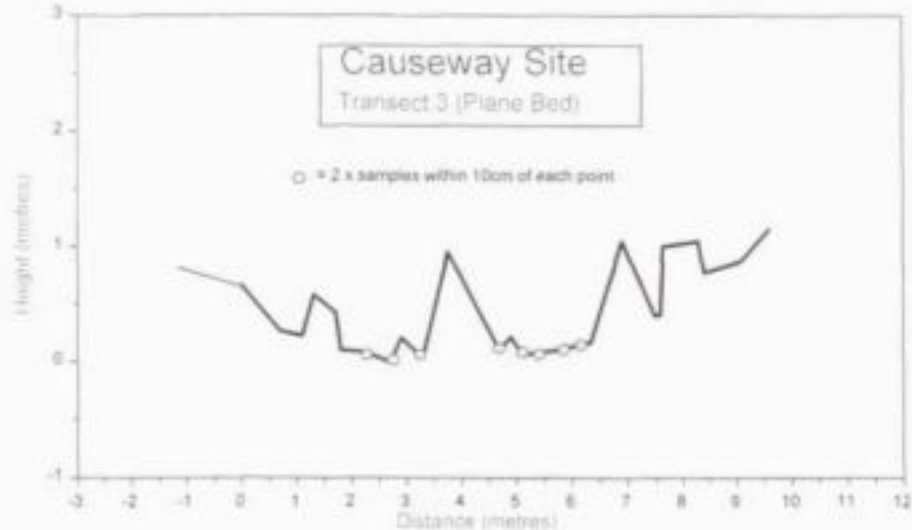
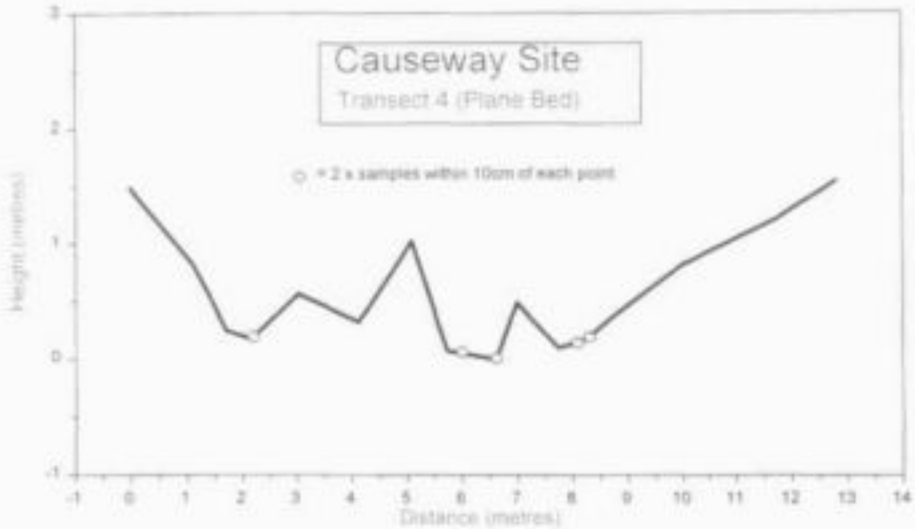
Height (metres)
Distance (metres)


Causeway Site
Transect 3 (Plane Bed)
○ = 2 x samples within 10cm of each point
Height (metres)
Distance (metres)


Causeway Site
Transect 4 (Plane Bed)
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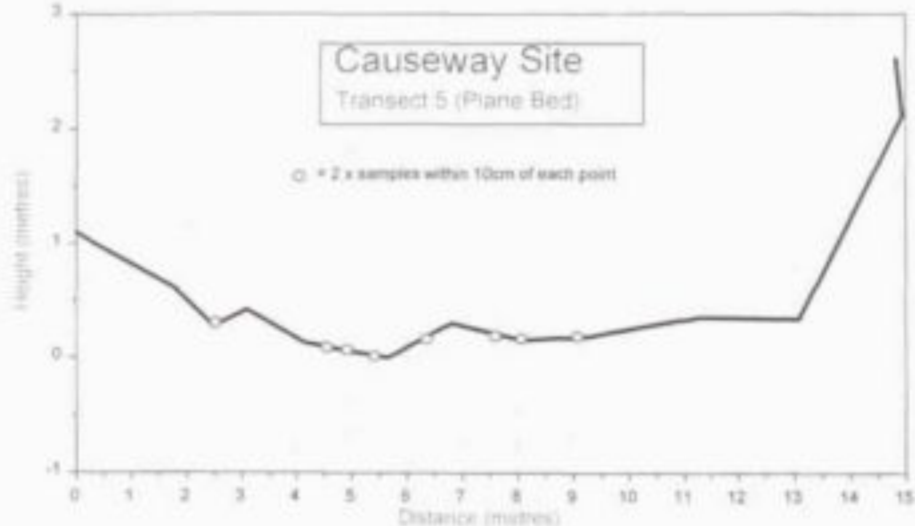
Height (metres)
Distance (metres)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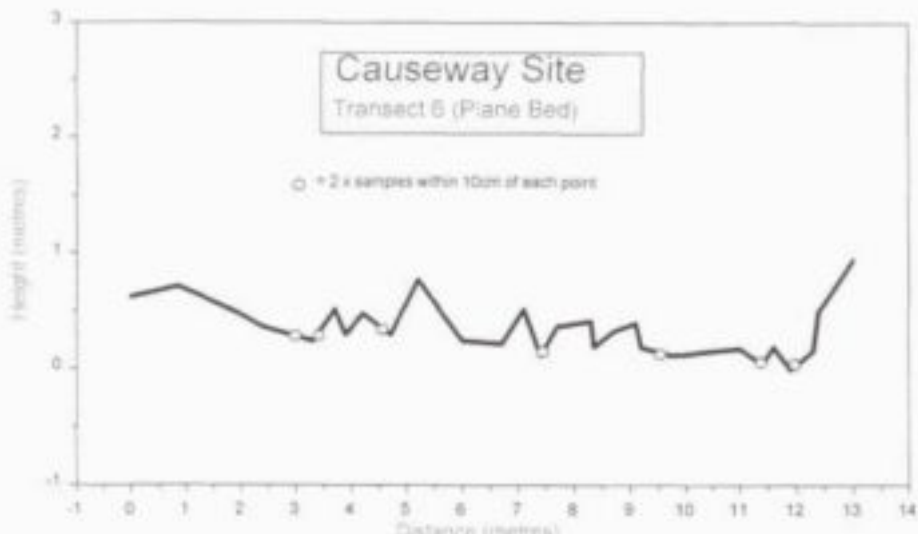
Height (metres)
Distance (metres)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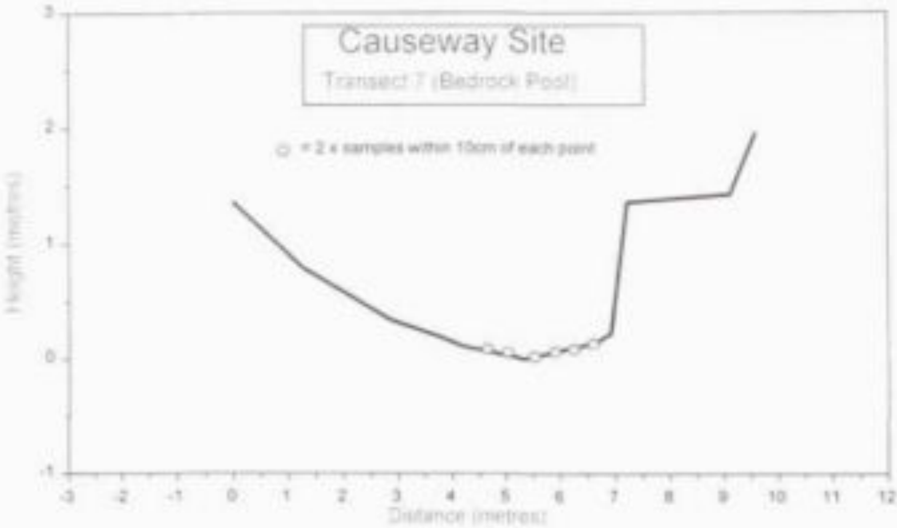
Distance (metres)


Causeway Site
Transect 7 (Bedrock Pool)
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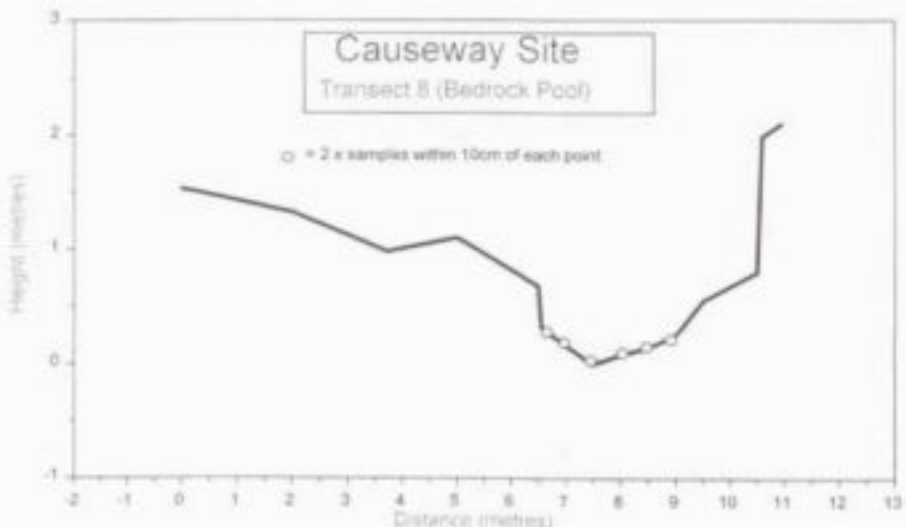
Height (metres)
Distance (metres)


Causeway Site
Transect 8 (Bedrock Pool)
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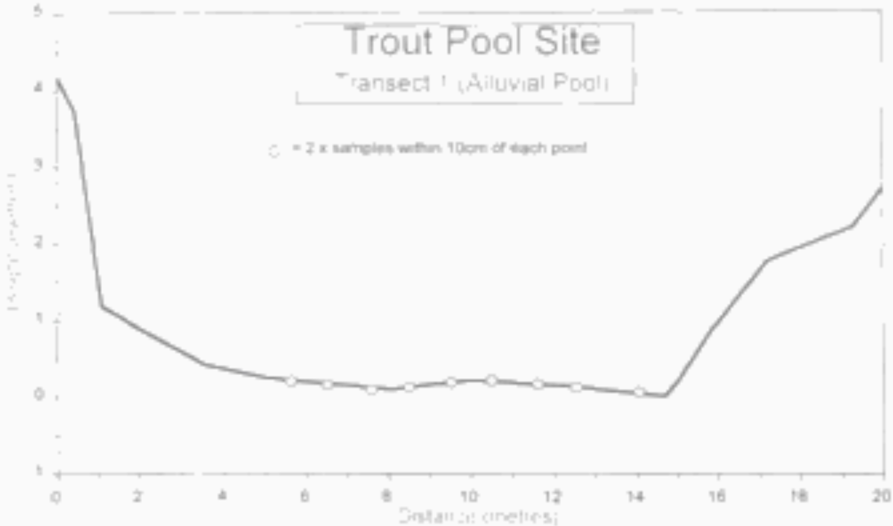
Height (metres)
Distance (metres)


Trout Pool Site
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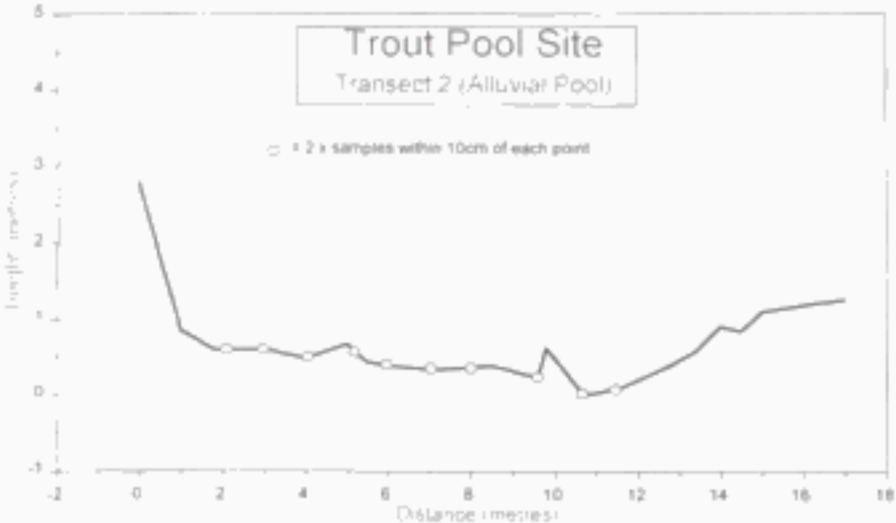
= 2 x samples within 10cm of each point
Distance (metres)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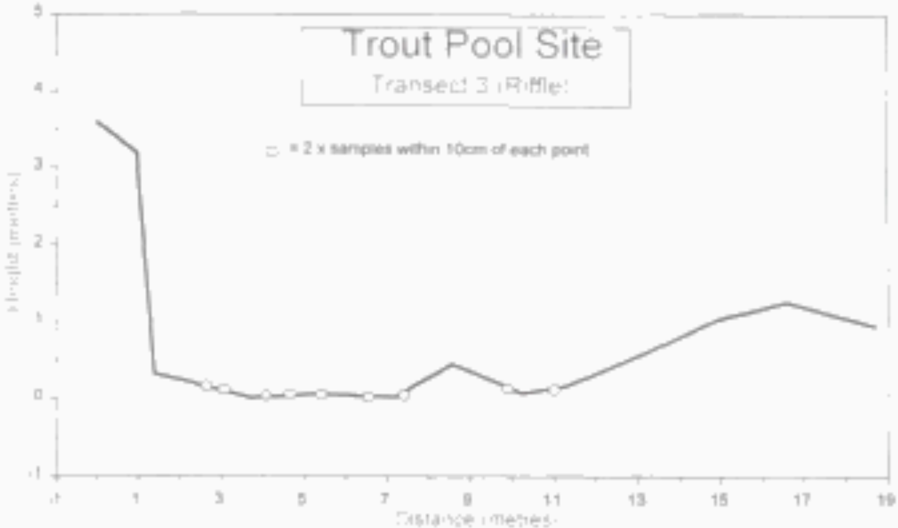
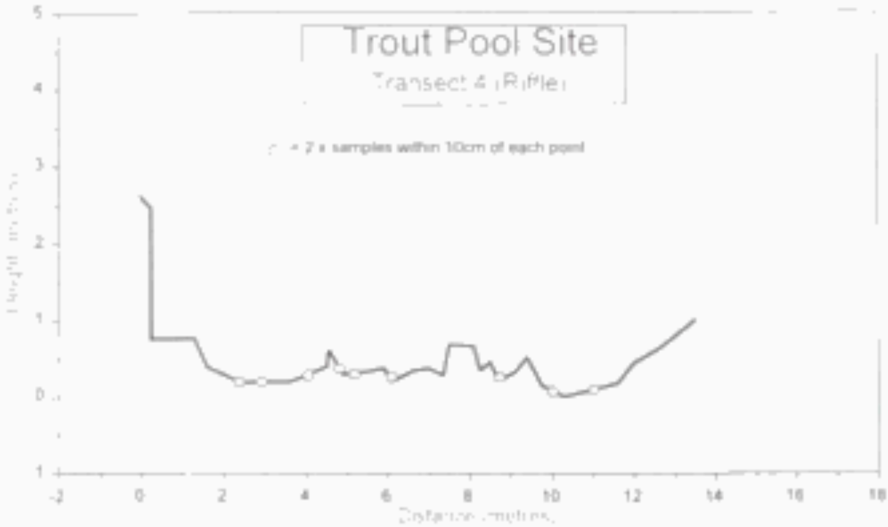
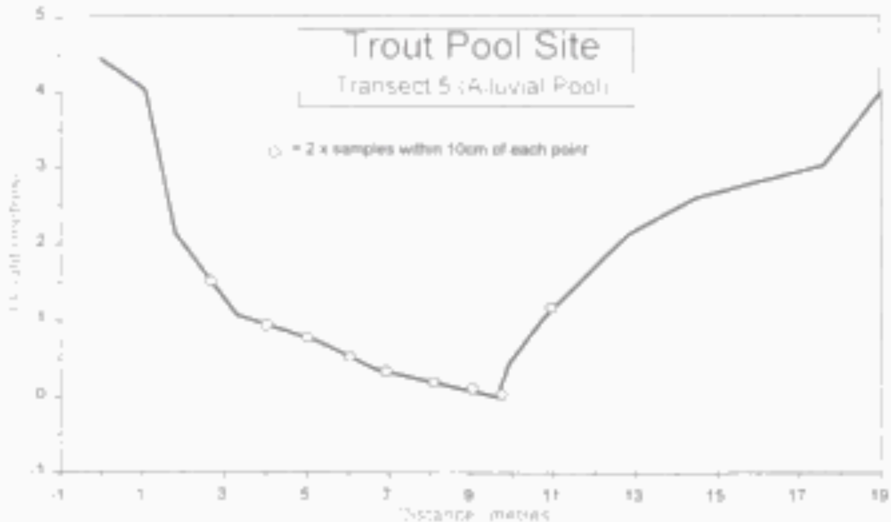
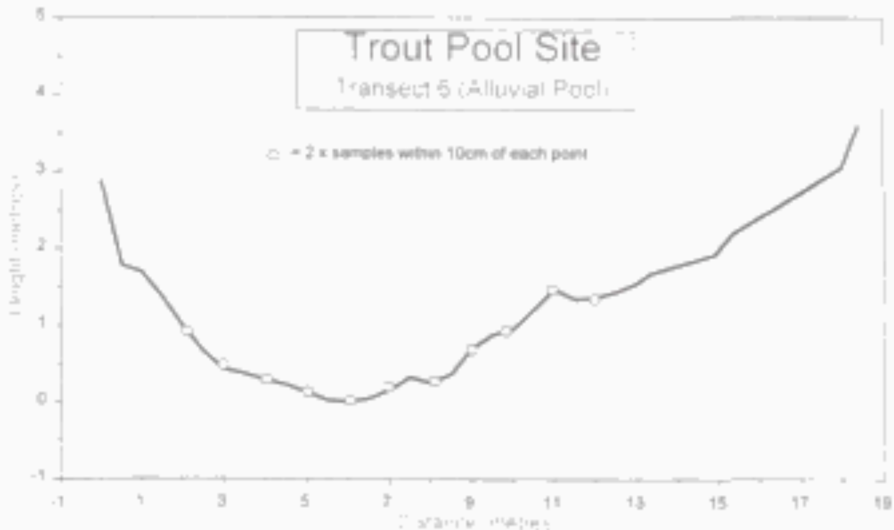
Distance (metres)


Trout Pool Site
Transect 3 (Riffle)
= 2 x samples within 10cm of each point
Distance (metres)


Trout Pool Site
Transect 4 (Riffle)
= 2 x samples within 10cm of each point


Trout Pool Site
Transect 5 (Alluvial Pool)
= 2 x samples within 10cm of each point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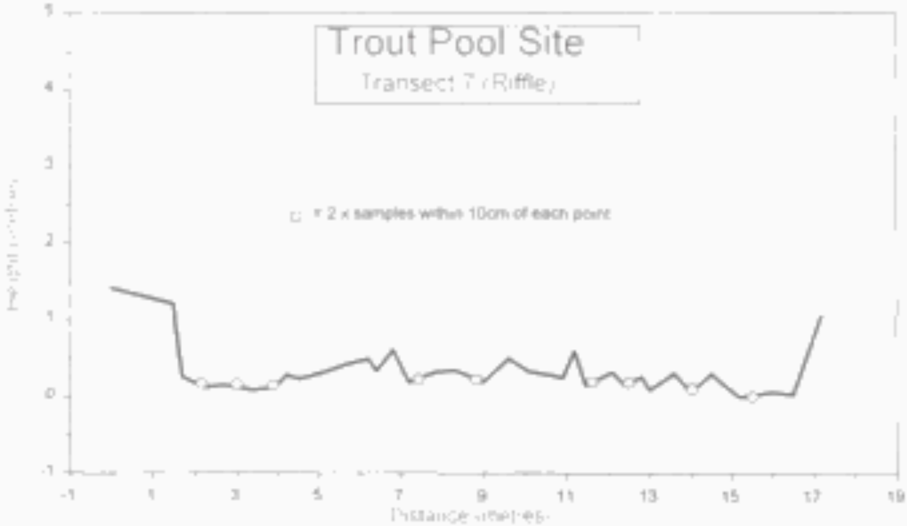
Transect 6 (Alluvial Pool)
= 2 x samples within 10cm of each point


Trout Pool Site
Transect 7 (Riffle)
= 2 x samples within 10cm of each point
5
4
3
2
1
0
-1
-1
1
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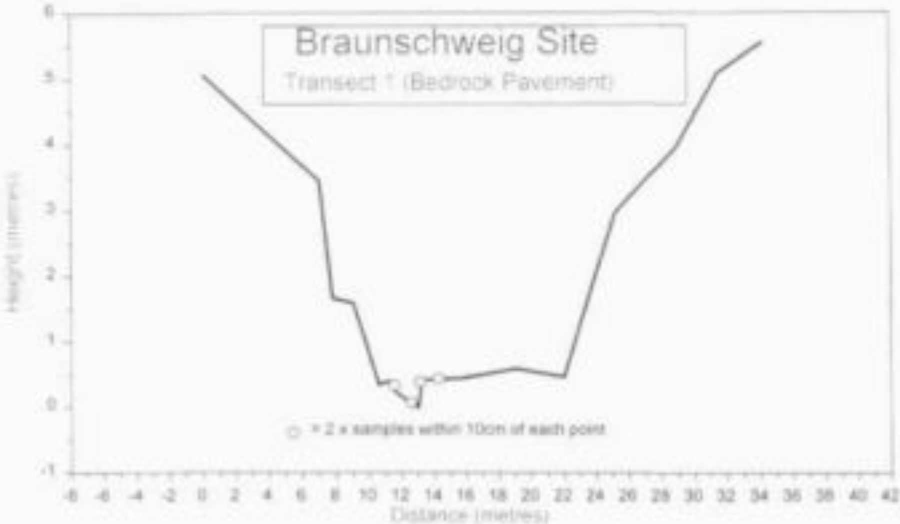
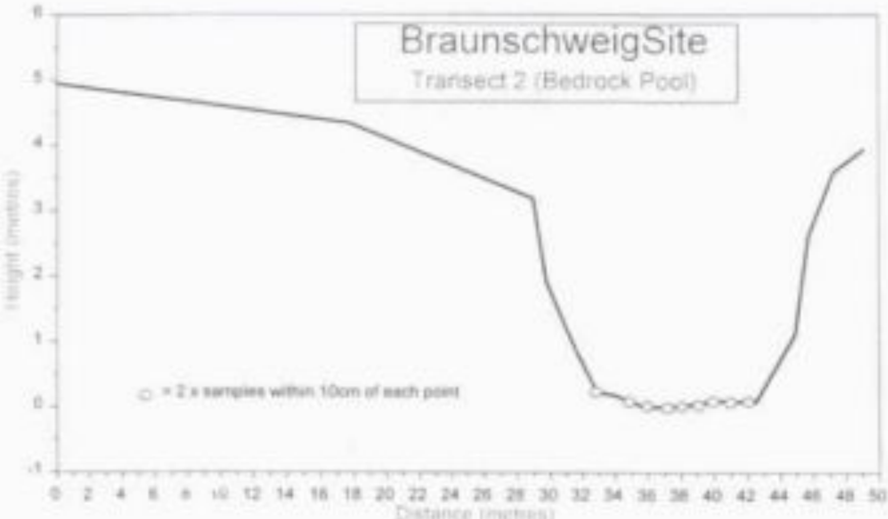
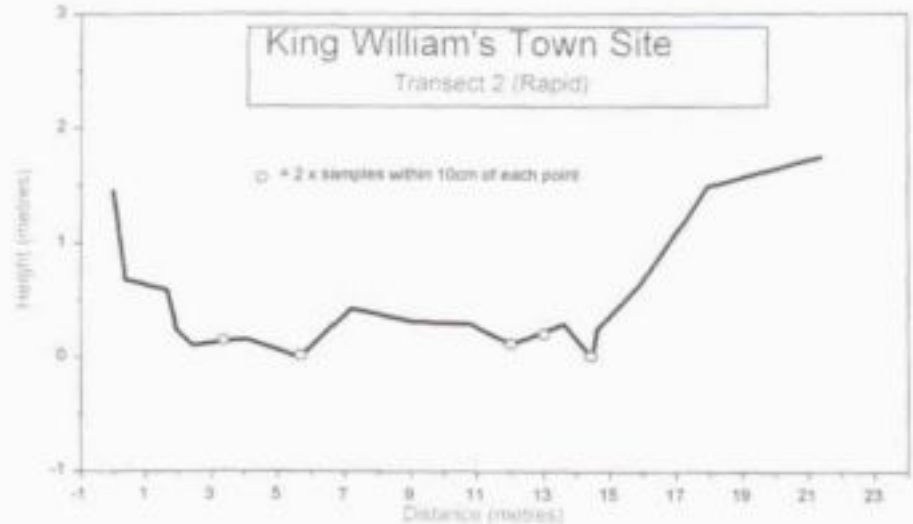
11
13
15
17
19


Braunschweig Site
Transect 1 (Bedrock Pavement)
Height (metres)
○ = 2 x samples within 10cm of each point
Distance (metres)


BraunschweigSite
Transect 2 (Bedrock Pool)
Height (metres)
○ = 2 x samples within 10cm of each point
Distance (metres)


BraunschweigSite
Transect 3 (Bedrock Pavement)
Height (metres)
Alluvial Backwater
○ = 2 x samples within 10cm of each point
Distance (metres)


King William's Town Site
Transect 1 (Bedrock Pool)
○ = 2 x samples within 10cm of each point
Height (metres)
Distance (metres)


King William's Town Site
Transect 2 (Rapid)
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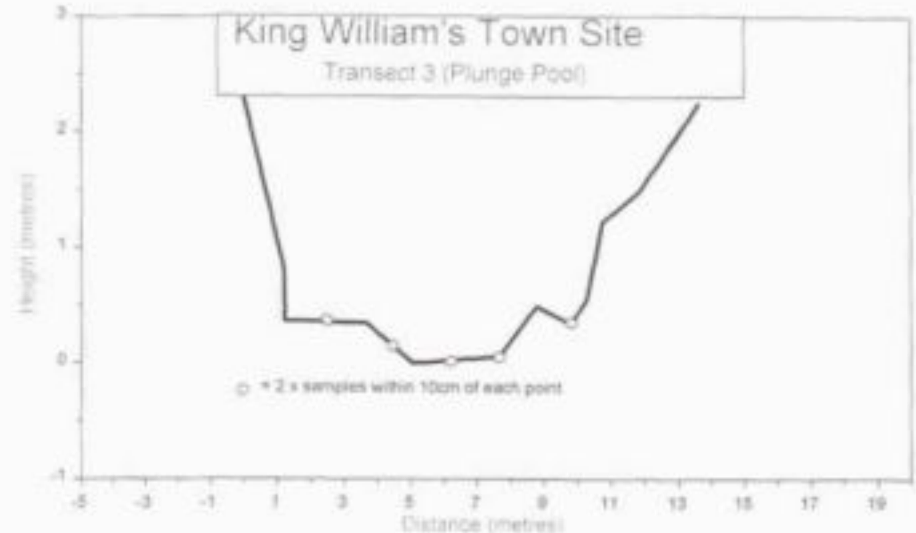
Height (metres)
Distance (metres)


King William's Town Site
Transect 3 (Plunge Pool)
○ = 2 x samples within 10cm of each point
Height (metres)
Distance (metres)

APPENDIX B

SUMMARY STATISTICS FOR VELOCITY AND DEPTH

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 1.

SITE	MORPH UNIT	BIOTOPE	No	Velocity (m.sec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
1	PLUNGE POOL	B-W Pool	49	.000	.002	.000	.027	.02	.36	.32	.74
		Pool	16	.008	.012	.010	.024	.21	.43	.34	1.04
	STEP	B-W Pool	2	.001	.001	.001	.001	.01	.033	.035	.06
		Pool	5	.000	.020	.018	.038	.012	.228	.25	.27
		Run	11	.000	.055	.063	.088	.04	.085	.06	.17
		Riffle	3	.000	.123	.123	.246	.03	.045	.045	.06
		Chute	6	.107	.169	.157	.276	.06	.094	.1	.12
2	BEDROCK POOL	B-W Pool	13	.000	.002	.000	.009	.16	.225	.225	.28
		Pool	47	.000	.010	.000	.075	.01	.208	.2	1.0
		Run	1	.076	.076	.076	.076	.04	.04	.04	.04
	PLANE BED	B-W Pool	2	.000	.003	.000	.007	.02	.14	.14	.22
		Pool	14	.000	.004	.000	.033	.04	.121	.11	.2
		Run	5	.000	.055	.000	.274	.01	.048	.05	.1
		Riffle	3	.000	.064	.000	.194	.01	.033	.04	.05
		Cascade	3	.000	.227	.244	.373	.01	.062	.08	.08
3	RIFFLE	Pool	25	.000	.004	.000	.048	.01	.072	.03	.35
		Run	8	.023	.071	.068	.117	.04	.09	.1	.15
		Riffle	8	.018	.199	.231	.326	.04	.068	.05	.16
		Chute	1	.455	.455	.455	.455	.06	.06	.06	.06
	POOL	B-W Pool	58	.000	.003	.000	.028	.02	.732	.645	1.96
		Pool	3	.01	.011	.010	.012	.19	.236	.24	.28
		Run	3	.023	.049	.058	.068	.09	.12	.12	.14
4	ALUV B-WATER	B-W Pool	7	.000	.000	.000	.000	.15	.192	.2	.22
	BEDROCK POOL	B-W Pool	2	.000	.005	.005	.010	.2	.235	.235	.27
		Pool	16	.000	.018	.019	.042	.2	.251	.255	.3
	BEDROCK PVMT	B-W Pool	1	.001	.001	.001	.001	.14	.14	.14	.14
		Pool	7	.000	.018	.018	.028	.13	.18	.145	.27
		Run	5	.000	.036	.013	.087	.2	.26	.26	.31
5	PLUNGE POOL	B-W Pool	5	.000	.004	.000	.015	.12	.206	.15	.46
		Pool	5	.000	.014	.015	.024	.17	.368	.46	.52
	RAPID	B-W Pool	9	.000	.002	.000	.013	.02	.088	.095	.13
	BEDROCK POOL	B-W Pool	7	.000	.010	.011	.017	.14	.205	.2	.27
		Pool	7	.000	.004	.000	.017	.1	.28	.34	.46

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 2.

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
1	PLUNGE POOL	B-W Pool	25	.000	.008	.000	.035	.08	.446	.475	.72
		Pool	37	.000	.015	.012	.073	.02	.353	.34	.8
	STEP	B-W Pool	2	.000	.000	.000	.000	.05	.06	.06	.07
		Pool	6	.024	.031	.030	.039	.02	.191	.245	.28
		Run	14	.000	.088	.078	.236	.04	.078	.08	.19
		Riffle	7	.000	.121	.137	.236	.02	.067	.06	.16
		Chute	6	.107	.329	.197	1.11	.04	.092	.045	.28
2	BEDROCK POOL	B-W Pool	7	.007	.011	.010	.017	.18	.266	.24	.43
		Pool	55	.000	.020	.017	.068	.02	.182	.2	.38
		Run	2	.039	.044	.044	.05	.05	.06	.06	.07
	PLANE BED	B-W Pool	1	.000	.000	.000	.000	.14	.15	.15	.16
		Pool	10	.000	.021	.015	.116	.04	.126	.135	.24
		Run	15	.000	.120	.087	.336	.005	.066	.06	.16
		Riffle	5	.000	.077	.058	.157	.01	.066	.08	.1
		Cascade	2	.000	.073	.073	.147	.04	.06	.06	.08
3	RIFFLE	B-W Pool	1	.000	.000	.000	.000	.01	.016	.02	.02
		Pool	25	.000	.046	.033	.167	.02	.096	.1	.2
		Run	19	.023	.136	.107	.336	.04	.111	.09	.24
		Riffle	15	.048	.231	.167	.703	.02	.076	.06	.16
		Chute	1	.375	.375	.375	.375	.13	.13	.13	.13
	POOL	B-W Pool	30	.000	.008	.009	.024	.01	.553	.51	1.16
		Pool	13	.010	.024	.021	.042	.08	.220	.18	.44
		Run	6	.021	.061	.076	.087	.06	.103	.095	.17
4	ALUV B-WATER	B-W Pool	6	.000	.003	.000	.010	.05	.18	.21	.22
	BEDROCK POOL	B-W Pool	2	.008	.008	.008	.008	.18	.18	.18	.18
		Pool	16	.000	.013	.013	.024	.18	.239	.22	.34
	BEDROCK PVMT	B-W Pool	1	.013	.022	.022	.032	.25	.255	.255	.26
		Pool	7	.035	.056	.057	.079	.14	.176	.18	.2
		Run	5	.061	.147	.124	.260	.32	.338	.33	.36
		Glide	1	.515	.574	.570	.64	.34	.35	.36	.36

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 2 (continued)

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
5	PLUNGE POOL	B-W Pool	1	.010	.010	.010	.010	.5	.5	.5	.5
		Pool	9	.000	.011	.013	.017	.2	.321	.22	.57
	RAPID	B-W Pool	2	.000	.000	.000	.000	.12	.125	.125	.13
		Pool	3	.046	.058	.050	.079	.09	.116	.11	.15
		Run	3	.035	.097	.090	.172	.15	.165	.165	.18
		Glide	1	.803	.958	.89	1017	.18	.2	.2	.22
	BEDROCK POOL	B-W Pool	7	.000	.003	.000	.013	.17	.272	.3	.36
		Pool	7	.000	.011	.013	.020	.15	.287	.31	.45

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 3.

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
1	PLUNGE POOL	B-W Pool	12	.000	.005	.004	.013	.09	.3	.3	.62
		Pool	44	.010	.024	.019	.087	.13	.575	.57	1.18
		Run	12	.028	.108	.083	.227	.06	.254	.215	.62
	STEP	B-W Pool	6	.000	.000	.000	.000	.08	.136	.14	.18
		Run	18	.028	.117	.117	.266	.09	.214	.2	.37
		Riffle	15	.078	.193	.147	.614	.05	.119	.1	.32
		Rapid	1	1.01	1.01	1.01	1.01	.18	.18	.18	.18
		Cascade	2	.256	.276	.276	.296	.1	.11	.11	.12
		Chute	6	.157	.293	.271	.514	.06	.101	.08	.22
2	BEDROCK POOL	B-W Pool	4	.009	.014	.013	.020	.34	.36	.34	.4
		Pool	58	.000	.039	.039	.094	.07	.261	.27	.54
		Run	3	.087	.087	.087	.087	.32	.32	.32	.32
	PLANE BED	B-W Pool	1	.000	.000	.000	.000	.13	.13	.13	.13
		Pool	5	.000	.036	.038	.068	.05	.163	.14	.28
		Run	21	.000	.101	.097	.276	.04	.105	.1	.2
		Riffle	6	.058	.142	.112	.296	.04	.071	.07	.11
		Cascade	5	.117	.326	.246	.782	.04	.084	.1	.14
3	RIFFLE	B-W Pool	2	.000	.009	.009	.018	.15	.155	.155	.16
		Pool	14	.000	.040	.028	.137	.11	.20	.20	.31
		Run	22	.018	.165	.147	.385	.04	.160	.155	.36
		Riffle	23	.038	.280	.227	.822	.04	.154	.15	.41
		Chute	2	.67	.723	.723	.77	.18	.23	.23	.28
	POOL	B-W Pool	31	.000	.005	.000	.018	.14	.803	.8	2.03
		Pool	41	.000	.018	.020	.072	.05	.653	.36	1.9
		Run	2	.068	.097	.097	.127	.23	.24	.24	.25
4	ALUV B-WATER	B-W Pool	6	.000	.000	.000	.000	.006	.19	.20	.24
	BEDROCK POOL	B-W Pool	2	.000	.005	.005	.010	.20	.235	.235	.27
		Pool	16	.000	.016	.019	.035	.20	.251	.255	.30
	BEDROCK PVMT	B-W Pool	1	.008	.018	.018	.028	.10	.14	.14	.18
		Run	9	.058	.133	.105	.346	.14	.204	.20	.36
		Rapid	3	.157	.271	.271	.385	.12	.25	.25	.38
		Glide	1	.71	.803	.847	.84	.34	.35	.36	.36

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 3. (Continued)

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
5	PLUNGE POOL	Pool	10	.009	.014	.013	.024	18	.332	.20	.58
	RAPID	B-W Pool	2	.000	.000	.000	.000	.14	.14	.14	.14
		Pool	2	.033	.040	.040	.048	.12	.12	.12	.12
		Run	4	.048	.085	.087	.117	.18	.242	.26	.27
		Glide	1	.157	.390	.251	.98	.15	.155	.155	.16
		Chute	1	.107	.112	.112	.117	.22	.23	.23	.24
	BEDROCK POOL	B-W Pool	6	.000	.008	.007	.020	.18	.323	.33	.44
		Pool	8	.017	.023	.022	.030	.05	.205	.19	.34

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 4.

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
1	PLUNGE POOL	Pool	22	.006	.070	.072	.117	.38	.702	.735	1.12
		Run	42	.028	.224	.183	.626	.4	.874	.87	1.3
		Riffle	3	.847	1.30	1.29	1.77	.68	.817	.825	.94
	STEP	Run	16	.094	.23	.205	.559	.28	.52	.51	.96
		Riffle	15	.338	.80	.49	1.60	.20	.38	.4	.62
		Rapid	6	.98	1.46	1.25	2.17	.55	.826	.91	.98
		Cascade	5	.648	.945	.914	1.42	.32	.448	.42	.56
		Chute	6	.781	1.10	.969	1.55	.20	.276	.28	.34
2	BEDROCK POOL	Pool	3	.094	.168	.205	.205	.48	.573	.58	.66
		Run	57	.072	.447	.471	.759	.42	.658	.68	.88
		Rapid	3	.869	.965	.914	1.11	.44	.66	.64	.90
	PLANE BED	Pool	1	.117	.117	.117	.117	.38	.38	.38	.38
		Run	24	.083	.484	.482	1.09	.20	.371	.36	.48
		Riffle	5	.537	1.44	1.55	1.99	.20	.308	.320	.380
		Chute	7	.404	.92	.892	1.77	.16	.296	.34	.40
3	RIFFLE	Run	27	.105	.443	.404	1.04	.15	.402	.40	.60
		Riffle	24	.227	.77	.825	1.71	.10	.428	.445	.68
		Cascade	6	.493	.76	.80	1.0	.15	.298	.335	.36
		Chute	7	.759	1.02	.892	1.36	.14	.30	.24	.58
	POOL	Pool	44	.006	.147	.128	.360	.34	1.22	1.19	2.2
		Run	28	.249	.45	.449	.892	.26	.492	.48	.86
4	ALUV B-WATER	Pool	6	.050	.072	.072	.094	.28	.308	.32	.32
	BEDROCK POOL	Pool	8	.028	.078	.083	.116	.37	.41	.415	.44
		Run	9	.138	.198	.205	.249	.38	.412	.395	.50
		Glide	1	.53	1.20	1.13	1.99	.16	.322	.34	.44
	BEDROCK PVMT	Pool	7	.000	.039	.039	.094	.07	.261	.27	.54
		Run	3	.161	.227	.183	.338	.40	.48	.46	.58
		Rapid	7	.249	.573	.559	.847	.34	.409	.365	.58
		Glide	3	.157	.867	.847	1.77	.04	.47	.42	.95

SUMMARY STATISTICS FOR VELOCITY AND DEPTH AT DISCHARGE 4. (Continued)

SITE	MORPH UNIT	BIOTOPE	No	Velocity (msec-1)				Depth (metres)			
				Min	Avg	Mdn	Max	Min	Avg	Mdn	Max
5	PLUNGE POOL	Pool	4	.050	.083	.083	.116	.28	.505	.52	.70
		Run	4	.249	.445	.471	.559	.41	.53	.43	.75
		Glide	2	.75	1.03	.98	1.71	.22	.44	.45	.68
	RAPID	Run	4	.382	.443	.437	.515	.32	.36	.36	.40
		Glide	4	.559	.589	.559	.648	.34	.38	.34	.46
		Chute	2	.515	.559	.581	.581	.36	.42	.44	.46
	BEDROCK POOL	Run	10	.072	.265	.316	.426	.53	.588	.545	.72
		Glide	4	.648	.781	.770	.936	.44	.47	.46	.52