The Development Of The Hydraulic Biotope Concept Within A Catchment Based Hierarchical Geomorphological Model

THESIS

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"It is easier to observe the movement of the stars, despite the incredible distance that separates one from another, than it is to understand the movement of water, even though this takes place beneath our very eyes".

Galileo Galilei 1564 - 1642

ABSTRACT

This thesis develops a technique for the identification, classification and quantification of instream flow environments. These features have been traditionally referred to as 'habitats' by lotic ecologists, in this research they are termed 'hydraulic biotopes'.

The hydraulic biotope is the lowest of six nested levels of a hierarchical geomorphological model. This model has been developed as a tool to assist river managers, researchers and conservationists to categorise or classify rivers with respect to their geomorphic characteristics. Each level of the model provides data at a different level of resolution. This ranges from the broad scale catchment data to the site specific 'habitat' or hydraulic biotope data. Although this thesis is primarily concerned with the development of the hydraulic biotope, the interaction of all catchment variables needs to be recognised. Detailed analysis of hydraulic biotope data in the Buffalo River are presented within the broader hierarchical model.

Consultation with lotic ecologists, together with a review of ecological literature, emphasised the need for a standardised terminology for the classification of ecologically significant instream flow environments. At present a fairly haphazard 'habitat' classification tends to be carried out by most researchers, this often leads to confusion in the identification and naming of different hydraulic biotopes ('habitats'). This confusion is exaggerated by the sharing of terminology between lotic ecology and fluvial geomorphology, usually for the categorisation of different types of features.

A review of the ecological literature emphasises the importance of flow hydraulics within a river to describe the distribution of biota. The hydraulic variables considered to be most significant include velocity and depth. As river morphology directly determines the prevailing distribution of depth, velocity and substratum, it is obvious that there are important links to be made between fluvial geomorphology and lotic ecology. This thesis explores the potential of the hydraulic biotope as a tool to help develop those links.

This thesis presents a standardised classification matrix for the identification of hydraulic biotopes. The matrix is simply based on water surface characteristics together with channel bed substratum. The validity of this matrix is tested by statistical analysis of hydraulic variables quantifying flow conditions within the various hydraulic biotope classes.

Data is presented from four different river systems, each representing a different sedimentological environment. Where possible the influence of discharge has been considered. Results from more than 3000 data points show that hydraulic biotopes have distinct hydraulic characteristics in terms of velocity-depth ratio, Froude number, Reynolds number, 'roughness' Reynolds number and shear velocity. These hydraulic indices represent flow conditions both as an average within the water column, and near the bed. Statistical analysis shows that the hydraulic characteristics of the various hydraulic biotope classes are relatively consistent both within different fluvial environments and at different stages of flow.

Unlike the morphological unit in which the hydraulic biotope is nested, in stream flow environments are shown to be temporally dynamic. Using the classification matrix as a tool for identification, hydraulic biotopes identified at one discharge are shown to be transformed from one class to another as a response to change in stage. The pattern of transformation is shown to be consistent within different sedimentological environments.

An examination of the associations between hydraulic biotopes and morphological units demonstrates that, although some hydraulic biotopes are common to all morphological units (backwater pools, pools and runs), some features have specific associations. In this study rapids were found to be prevalent in bedrock pavement, bedrock pool and plane bed morphology, while cascades, chutes and riffles were common to plane bed, step and riffle morphology.

Results from this research indicate that the hydraulic biotope, within the hierarchical geomorphological model, has the potential to aid the prediction of channel adjustment and associated 'habitat' (hydraulic biotope) transformation in response to changes in flow and sediment yield. These are likely to become increasingly important issues as South Africa strives to maintain a balance between the development of water resources to meet the needs of the rapidly expanding population, whilst at the same time maintaining the fluvial environment for sustainable use.

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CHAPTER ONE
GENERAL INTRODUCTION

1.1 INTRODUCTION

In April, 1992 the Geography Department at Rhodes University was awarded a contract to undertake a Water Research Commission (WRC) project to develop a hierarchical geomorphological classification system for South African rivers. The aim of this research programme was to provide lotic ecologists and river managers with a relevant geomorphological framework to aid the explanation of ecosystem processes and biotic distributions and contribute to a decision support system for management. To meet this aim, three broad objectives were identified:

- To ascertain the important geomorphic and hydraulic criteria in terms of instream 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.

The research presented in this thesis represents work undertaken to meet the first of these objectives; the development of a geomorphic / hydraulic link with the instream habitat; this has been termed the hydraulic biotope concept. The product of this work can be described simply as a classification system for the comparison of ecologically significant instream flow environments. This classification incorporates the use of standardised terminology to describe habitats, specified criteria to identify them and quantitative measures to characterise them. To a limited extent the classification has been extended to include geomorphic associations at the scale of the morphological unit.

The hydraulic biotope is only one component of a six tier hierarchical geomorphological model which has been developed to meet all the objectives of the WRC project. The physical unity of the drainage basin means that research carried out at any one level of the hierachy should be nested within the remaining levels. Detailed research carried out on the hydraulic biotopes in the Buffalo River is considered within this hierarchical framework.

1.2 THE SOUTH AFRICAN CONTEXT

As South Africa strives to meet the ever increasing demand for potable water, the development of water storages on rivers has taken place on a massive scale resulting in almost universal river regulation throughout Southern Africa (Davies *et al.*, 1993). By 1986 the South African Department of Water

Affairs and Forestry (DWAF) estimated that there were 520 major regulating structures in the country capturing approximately 50% of the mean annual runoff (DWAF, 1986). These statistics do not take into account the thousands of smaller farm dams scattered around catchments throughout South Africa. The exceptionally high rate at which rivers have been impounded is a response not only to a 3.7 % per annum population growth rate, but also to a number of factors which influence the scarcity of water in South Africa. One of these is the great variation in run-off, which differ from season to season and from year to year and require large volumes of water to be stored to bridge long periods of drought. Furthermore the high temperatures and dry air in many parts of the country bring about high evaporation rates. The preponderance of sparse vegetation and fragile ecosystems which are easily degraded cause heavy silt loads which lead to reduced water quality and ever decreasing storage capacities.

Impounding the major rivers in South Africa has not, on its own, been enough to meet the ever increasing demands for water, particularly from rapidly developing industrial areas such as Gauteng, situated on the relatively dry plateau of the interior where most of South Africa's raw materials occur. In an attempt to meet the requirements of the water scarce areas of South Africa, the DWAF has initiated the transfer of large volumes of water between catchments. These large schemes have been in operation since the early 1960s, and are achieved by large expensive engineering schemes using combinations of dams, pumping stations, pipelines, canals, tunnels and weirs. In all probability it is to these schemes that the new government will turn to try to meet the objectives of the Reconstruction and Development Programme in South Africa. These objectives include the development of water resources to meet the basic requirements of clean water (25 litres per person) within 200 metres of their dwelling, at present not available to approximately 17,5 million people.

Traditional thinking from South African water users and managers has been that any water that flows into the sea is 'wasted' water; it is this philosophy that has motivated the remarkable exploitation of our riverine environments. It has been realised only relatively recently that the manipulation of rivers, either by impoundment or by the transfer of water between or within catchments, is a major threat to river conservation and management. Ecological studies within South Africa have been directed largely as a response to this pressure, with the major focus on instream flow requirements (Gore & King, 1989; O'Keeffe *et al.*, 1989; Tharme, 1992; Tharme & King, 1992; King & Tharme, 1994) and the effects of reduced flows on the biotic characteristics of selected catchments (Palmer, 1991).

The research focus has been strengthened by a major paradigm shift within the DWAF which recognises that rivers are more than mere channels for water supply and sewerage disposal. The environment of rivers has been recognised as a legitimate user of water (DWAF, 1986) and it has more recently been accepted that "The environment should not be regarded as a 'user' of water in competition with other users, but as the base from which the resource is derived and without which no development is sustainable" (DWAF, 1995; p31). To ensure that rivers maintain their integrity as renewable natural resources, considerable research effort has been initiated in South Africa to try to define the boundaries within which rivers can be utilised on a sustainable level. A basic premise is that ecosystem processes must be maintained, a goal which requires considerable understanding of the basic organic and biological processes operating in our rivers. As O'Keeffe (1995) points out, there are significant gaps in this ecological understanding which has led to a focus on habitat maintenance rather than species management.

It is important to recognise that the morphology of the river channel provides the physical habitat for lotic ecosystems and reflects the various anthropogenic disturbances occuring in the catchment such as land use changes, impoundments and inter basin transfers. These impacts may lead to an adjustment of channel morphology 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; Ferguson, 1987; Chang, 1984, 1986).

Scientists, conservationists and managers realise that if our rivers are to be managed so as to conserve their ecological integrity 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 aid the prediction of channel adjustment and associated habitat transformation in response to changes in the flow and sediment regime. Methods such as the Instream Flow Incremental Methodology (IFIM) already exist to asses the availability of habitat under changing flow conditions (Bullock & Gustard, 1990; Gore & King, 1989). Unfortunately this method is inappropriate for large scale use in South Africa because it is based on the availability of generous amounts of time, expertise, finances and biological data (King & Tharme, 1994).

At a meeting held in Lydenburg in the Eastern Transvaal, South Africa (O,Keeffe *et al.,* 1987), a number of prominent scientists, conservationists and managers gathered to discuss the need for a national classification system, which they believed would provide a logical framework in which to place all further ecological river research. Because of the ecological bias of the participants of this particular meeting, the importance of the various components of the physical environment were largely ignored. As a result of their findings, a national river classification system for South Africa was initiated. This was originally to consists of three parts which deal respectively with regional flow patterns (led by Dr J. King, funded by the Water Research Commission), regional patterns of water chemistry (led by Dr J. Day, funded by the Water Research Commission), and biogeographical patterns of riverine biota (led by Dr J. King, Dr J. Day and Dr J. O'Keeffe, funded by the Department of Environmental Affairs). A fourth component to the national river classification was soon to follow, a system that would attempt to link the biotic and physical components of the river system. "A hierarchical geomorphological model for the classification of South African river systems", was launched in April 1992, funded by the Water Research Commission (WRC).

1.3 RIVER CLASSIFICATION

1.3.1 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 practitioners 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 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). 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. However, the classification of streams is complicated 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; Decamps & Naiman, 1989). 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).

1.3.2 Theoretical background

Stream classification has been attempted by many researchers from different disciplines who have used a number of variables at different spatial scales. This general introduction highlights those classifications that are primarily geomorphic in origin. Davis (1890) produced perhaps one of the most familiar, but much refuted, whole stream classifications on the basis of observed erosional patterns. Another well recognised, and utilized, whole river classification system was that of Horton (1945), adapted by Strahler (1957), which provided a means of obtaining stream order and linkage number. Unfortunately these simple, single variable techniques do not take into account the complex system of linked components situated within a particular geographical environment.

Schumm (1979) envisaged an idealised fluvial system as consisting of three channel zones based on sediment production and transport: 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. This idealised and simplistic description has been adopted by numerous researchers for the classification of river systems.

The simple model of Schumm (1979) 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 its own characteristic particle size distribution. Pickup stresses that these zones reflected variations in the controls of gradient, bed material, stream power potential along the channel, and the ability to move different sized materials at different frequencies. The resultant zones had a distinctive set of slope, sinuosity and width/depth ratio values.

More recently Brussock *et al.* (1985) proposed a system to classify running water habitats into longitudinal classes based on their channel form 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. This work 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.

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 and 1994) and Kellerhals and Church (1989). Many of these classifications incorporate the ideas of Frissell *et al.* (1986) who extended an earlier approach of Warren (1979) by incorporating spatially nested levels of resolution and produced a framework which addresses form or pattern within a number of hierarchical levels, as well as origins and processes of development.

Naiman *et al.* (1992) provide a useful summary of three working hierarchical systems which have gained a fairly wide usage in North America. Brussock *et al.* (1985) and Rosgen's (1985) stream classifications provide detailed descriptions of the reach within the context of the stream network.

Unfortunately the systems are not linked to hillslope processes and the boundaries are relatively indistinct. On the other hand Cupp's (1989) classification is specific to a portion of a stream (or reach) and has relatively distinct boundaries. Unfortunately, although it places the reach within the local valley topography, it does not relate the reach to the catchment. These systems fall short of the view held by many researchers (Van Deusen, 1954; Slack, 1955; Hynes, 1970; Platts, 1974 and 1979; Morisawa and Vemuri, 1975; Lotspeich and Platts, 1982 and Frissell *et al.*, 1986) that the structure and dynamics of the stream are determined by the surrounding catchment as illustrated in Figure 1.1. Frissell *et al.'s* hierarchical model attempts to make this link.

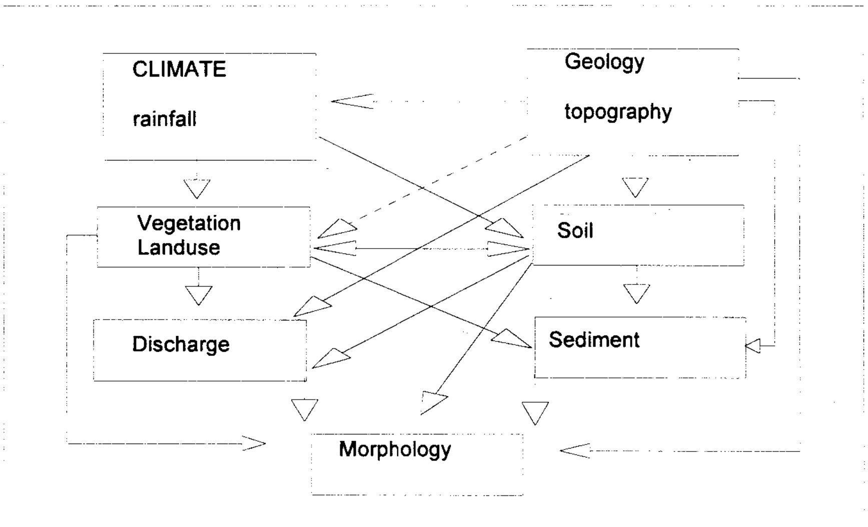

Figure 1.1 Variables in a catchment influencing the dynamics and morphology of the fluvial system. From Morisawa and Vemuri (1975)

A modification of Frissel's model has been proposed as a procedure for the classification of the geomorphological components of lotic ecosystems within selected South African river systems. This model is being developed as a Water Research Commission project and is comprised of six nested levels: the catchment, the zone, the stream segment, the channel reach, the morphological unit and the hydraulic biotope (Table 1.1). The development of the hydraulic biotope scale component within this hierarchy forms the basis of the research presented in this thesis and provides the essential link between geomorphology and ecology. The morphological unit and associated hydraulic biotopes provide the basic building blocks of the system whilst the catchment and its sub zones control the driving forces. The channel network, composed of segments and reaches, provides the link between the two. This system not only allows a structured description of spatial variation in stream habitat but also provides a scale based link between the channel and the catchment so as to account for catchment dynamics. The hierarchical model provides the spatial framework of physical features upon which process models of catchment hydrology, flow hydraulics and sediment transport can be based.

1.3.3 A hierarchical geomorphological model for South African river systems

The brief historical review of the literature relating to river classification given above forms the basis of a management tool for South African rivers. Of particular significance is the realisation that, in the traditional or conventional sense of the word, there are very few "true" classifications of rivers because this implies the identification and grouping of objects at the same spatial scale. When one links the longitudinal and lateral variables within the catchment, which interact somewhat inconsistently through space and time to produce a hierarchical network making up a river system, any attempt at river classification is made extremely difficult. The geomorphological model proposed here is the first stage of a classification, whereby it provides the framework for the description of the various components of the fluvial system, at any scale. To date this model has been applied to three South African catchments, the Sabie River (Wadeson & Rowntree, 1994), the Buffalo River (Rowntree & Wadeson, 1995a) and the Tugela River (Rowntree & Wadeson, 1995b). The following discussion introduces the various components of the hierarchical model, the model's practical application is demonstrated in Chapter Five.

Table 1.1. The hierarchical structure with definition of terms.

THE HIERARCHY	DEFINITION OF TERMS USED.
Catchment	The land surface which contributes water and sediment to the specified stream network.
Response zone	Areas within the catchments which can be considered as homogeneous with respect to flood runoff and sediment production.
Segment	A length of channel along which there is no significant change in the imposed flow discharge or sediment load.
Reach	A length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occur.
Morphological unit	The basic structures comprising the channel morphology for example pools, riffles, runs, rapids, waterfalls etc.
Hydraulic biotope	The habitat assemblage with a characteristic range of temporarily variable hydraulic and substrate characteristics which can be associated with the morphological units.

The catchment

The catchment is defined by the topographic divide except where groundwater is a major component of streamflow. The development and physical characteristics of a stream system are dependent upon the geological history and climate of its drainage basin (Hack, 1957; Schumm & 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).

The zone

Within large catchments there is much heterogeneity with respect to topography, climate, geology, vegetation cover, soils and landuse 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.

The segment

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, where a segment is a length of channel along which there is no significant change in the imposed flow discharge or sediment load.

The reach

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. For the purpose of this model, a reach is defined as a length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occur within identifiable channel patterns. Reach characteristics determine the possible direction of the response to changes in flow and/or sediment load, in particular whether it acts as a source, transfer zone or sink for sediment. These include valley gradient, geology, local side slopes, valley floor width, riparian vegetation and bank material.

The morphological unit

This level of the hierarchy involves the identification of individual morphological units and related 'hydraulic biotopes' within the reach. The morphological units are the basic structures recognised by fluvial geomorphologists as comprising the channel morphology and are formed from the erosion of bedrock (rapids, waterfalls, plunge pools etc.) or from the deposition of alluvium (sand or gravel bars, riffles, pools etc.). The characteristics and range of morphological units in a reach moderates the ecological impact of a change in flow/sediment regime as they determine the available habitat at any given discharge. The relationship of a given sedimentary feature to its larger-scale (pool/riffle or reach) environment is also important in understanding its dynamics (Laronne & Carson, 1976; Jackson & Beschta, 1982), so that a description of the different morphological features in a reach is an important input into sediment models.

Ecological habitat or 'hydraulic biotope'

The development of the hydraulic biotope concept and its role in the hierarchical model form the basis of this thesis. The hydraulic biotope may be defined as a spatially distinct in-stream flow environment characterised by specific hydraulic attributes (Wadeson, 1994). This level of the hierarchy provides the link between catchment geomorphology and lotic ecology. It is the key component to be considered in conservation programmes which strive to maintain the ecological integrity of fluvial environments.

1.4 RESEARCH AIMS

If a hierarchical geomorphological classification is to be a useful tool for river basin management and river conservation, there is a need for a scale based link between the physical characteristics of the fluvial environment and the associated lotic ecology. The apparent complexity of this task has meant that many earlier classifications have failed to provide a successful union between these two components and therefore have limited application.

The fundamental aim of this research is to develop a link between river ecology and geomorphology through what this author has termed 'the hydraulic biotope concept'. Quite simply this is the theory that there is an association between the relatively stable morphological units recognised by geomorphologists and the temporally and spatially unstable aquatic habitats recognised by river ecologists. An outline of the research framework used to develop this link is given here.

The initial impetus for the research was a recognition that ecological habitats do not equate to morphological units despite them often having common terminology. This led to a review of the ecological literature and discussion with lotic ecologists. These inputs indicated the problems of intuitive classification and the importance of velocity and depth as habitat descriptors. It was soon realised that hydraulic indices may be more appropriate to describe conditions of flow because they combine variables and allow comparison between features of different scales. A number of pilot studies were initiated to test ideas. Preliminary results indicated the potential of hydraulic indices as classificatory values for the characterisation of hydraulic biotopes (habitats). A detailed study was initiated in the Buffalo River to test ideas more rigorously. Throughout this process discussion with ecologists were continuing. This meant that the theory, definitions, identification etc. were being continuously refined and applied where possible.

Figure 1.2 outlines the sequence of aims which have arisen in response to the development of the hydraulic biotope concept. These will be addressed within the framework of the research programme.

- **Review the habitat terminology used in the ecological literature**
  - *Determine the validity of the use of the term 'habitat' to describe ecologically significant flow environments*
  - *Develop a common language for communication between geomorphologists and ecologists.*
- **Develop an objective technique for the recognition of hydraulic biotopes**
- **Review the hydraulic literature of open channel flow**
- **Carry out pilot studies to determine the validity of using scale independent hydraulic indices**
  - *Consider variations in discharge*
  - *Consider variations in scale*
  - *Considers variations in substratum*
- **Carry out a detailed sampling programme within the Buffalo River**
  - *Consider variations in discharge*
  - *Consider variations in scale*
  - *Consider variations in substratum*
  - *Consider micro- and macro- hydraulic characteristics*
- **Determine the ecological significance of hydraulic biotopes within the Buffalo River**

Figure 1.2 Research aims

1.5 RESEARCH OUTLINE

This section outlines the structure of the thesis and the development of the underlying research philosophy.

1.5.1 Chapter 1: General Introduction

For the development of a hierarchical geomorphological classification system it was first necessary to to identify the needs of various potential users. Early on it was realised that if the framework did not include a link to the biotic components of the physical landscape, it was likely to have limited application for scientists, managers and conservationists.

1.5.2 Chapter 2: The Hydraulic Biotope Concept

An ecological literature review with a geomorphological focus attempts to identify a scale of features that has ecological significance and is easily incorporated within a geomorphological framework. This review identifies hydraulic biotope features as 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, being the smallest scale at which geomorphologists can work and possibly the coarsest acceptable to ecologists studying population/community dynamics (Rowntree, 1995). This review also highlights a number of problems:

- Problems of nomenclature exist for the description of hydraulic biotope scale features.
- Hydraulic biotopes tend to be identified subjectively.
- Hydraulic biotopes are temporally and spatially unstable and not normally recognised in conventional geomorphological research.
- The use of depth, velocity and substrate as hydraulic biotope descriptors are scale dependent and non transferrable.

This chapter also attempts to provide solutions to some of these problems:

- A standardised terminology is introduced.
- An objective technique for hydraulic biotope recognition is presented.

- An idea is presented that suggests a morphological unit may have a specific association of hydraulic biotopes, an important concept for the transference of data between streams.

1.5.3 Chapter 3: Channel Hydraulics for Ecologists

For the resolution of the fourth problem identified in Chapter Two, there is a need for a relatively detailed review of the hydraulic literature as it may relate to aquatic ecology. This chapter illustrates the potential capacity of dimensionless indices such as the Froude number and the Reynolds number as universal indicators of the hydraulic conditions being experienced within hydraulic biotopes. This chapter also emphasises the importance of the micro flow environment, particularly as it relates to bottom dwelling organisms.

1.5.4 Chapter 4: Pilot Studies

There are a number of issues which need to be considered for further development of the hydraulic biotope concept. The two hydraulic indices which characterise average flow conditions within a column of water are the Froude number and the Reynolds number . Preliminary research is carried out in a number of different environments to assess the validity of utilising these indices as universal hydraulic biotope descriptors. Because of the assumption that the hydraulic indices are scale independent and that hydraulic biotope classification is determined by flow type and substratum, the following conditions are considered:

- A number of different spatial scales, that is; hydraulic biotopes of different reaches which have been similarly classified.

- A number of different flows, to account for the direction and progression of hydraulic biotope change with changing discharge.

- Within different sedimentological settings, to account for differences in hydraulic biotopes within different substratum.

1.5.5 Chapter 5: The Buffalo River

Results from the pilot studies of Chapter Four indicate that selected hydraulic indices may provide useful quantitative techniques for the classification and description of hydraulic biotopes. The scale independence of the Froude number makes it a useful value for comparison of hydraulic biotope classes at different spatial scales. Unfortunately a limitation of using the Reynolds number and the Froude number as descriptors of flow conditions within hydraulic biotopes is that they only account for the average conditions within a column of water. These conditions are likely to be particularly relevant to the distribution of fish, but unlikely to be of particular significance to bottom dwelling organisms who live within the micro-flow environment.

The Buffalo River was selected as a suitable river to carry out a detailed hydraulic survey at different spatial and temporal scales. This chapter presents information on the physical characteristics of the research catchment and applies the hierarchical geomorphological model as a framework for further development of the hydraulic biotope concept.

1.5.6 Chapter 6: Results and Discussion

This chapter considers the research findings of the detailed study in the Buffalo River, looking at both the average and near bed hydraulic conditions experienced within the hydraulic biotopes of a mountain stream. The aim of this chapter is to explore the relationships that exist within and between the micro- and macro-flow environments of various hydraulic biotope classes. These relationships are complicated by the inclusion of temporal and spatial variations of scale. This chapter also considers the relationships that may exist between hydraulic biotopes and morphological units.

1.5.7Chapter 7: The Ecological Significance of Hydraulic Biotopes within the Buffalo River

This chapter attempts to relate the research findings from selected reaches of the Buffalo River with past ecological studies carried out within the catchment. The aim of this chapter is to investigate the ecological significance of hydraulic biotopes within the Buffalo Catchment.

1.5.8 Chapter 8: Conclusions

CHAPTER TWO
THE HYDRAULIC BIOTOPE CONCEPT

2.1 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.* (1990, 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*" (authors italics).

A pervasive theme in the more recent literature concerned with lotic ecology is the use of hydraulic simulation models for the characterisation of riverine habitats. This is evidenced by the organisation of the First International Symposium on Habitat Hydraulics (1994) and the considerable effort being put into this subject by scientists throughout the world. 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 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 the IFIM procedure 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 appproach 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) 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 this author 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; and 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., 1995). 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 (Reice, 1974; Dudgeon, 1982; Mc Auliffe, 1983; Wevers & Warren, 1986), behavioural ecology of fishes and aquatic invertebrates (Smith & Li, 1983; Hart, 1981).

It was felt by this researcher that the ideas of Frissell *et al.* (1986) were theoretically sound but difficult to put into practice within a classification system. An important limitation of this system is the inability to transfer depth, velocity and substate data from one site to another to compare features at the 'microhabitat' scale. The research presented in this thesis 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. Section 2.2 presents a series of questions or problems which have been addressed within this thesis. These questions are not necessarily presented in the sequence within which they were resolved, but rather the idealised sequence for resolution.

2.2 RESEARCH QUESTIONS

2.2.1 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 thesis has as its focus areas within the stream which are of an approximate scale of $10^{-1}m^2$. 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, 1995) 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.com.* has suggested the use of the term 'hydraulic biotope' to avoid the possible implication that physical habitat incorporates water quality 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, 1994).

2.2.2 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 thesis they are referred to as classes of the hydraulic biotope.

2.2.3 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 prominant 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 2.1 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 2.1 represent a miniscule portion 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.

Table 2.1 The use of hydraulic biotope terms, and the extent to which they are defined. (● = no definition ; ■ = definition given.)

AUTHOR	POOL	RIFFLE	STICKLE	RIPPLE	RUN	FLATS	BACKWATER	WATERFALL	CASCADE	GLIDE	CHUTE	RAPID	STONES IN	CURRENT	STONES OUT	CURRENT
Allen (1951)	■	■	■	●	■	■			■			●				
Tebo (1954)	●	●							●							
Harrison & Elsworth (1959)	■	■	■	●	■	■			■			●	●			
Chutter (1970)			■		■				■				●		●	
Hynes (1970)	■	■			●						●					
Platts (1979)	●	●														
Savage & Rabe (1979)	●	●							●	●						
De Leeuw (1981)	■	■						■		■						
Moyle *et al.*(1985)	●	●			●					●						
Pridmore & Roper (1985)	●	●			■		●									
Frissel *et al.* (1986)	●	●														
Grossman & Freeman (1987)		■			■											
Bisson *et al.*(1988)	■	■					■		■	■						
Boutton et al.(1988)		■														
Anderson & Morison (1989)	■	■			■		■	■	■	■		■				
Hogan & Church (1989)	●	●								●						
Barmuta (1990)	●	●														
de Moor (1990)	●	●							●							
Reice *et al.*(1990)	●	●														
Barbour (1991)	●	●			●					●						
Shield *et al.*(1991)	●	●														
Gore *et al.*(1992)	●	●			●											
King *et al.,pers.com* (1992)	■	■			■		■	■	■	■	■	■				

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.

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.

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).

Run:

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.

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 velocity : depth ratio to prevent surface disruption.

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 run. 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.

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 35cm.

There is general agreement for the recognition of backwaters.

Cascades:

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.

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.

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.

Glide:

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 10cm and gradient 1 - 3 degrees.

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.

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.

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 approximately the same time as carrying out a literature review, this author carried out informal discussions with lotic ecologists who were actively involved in field research. As a supplement to these discussions, a seminar paper was presented to to the local ecological community in 1993. The main aim of these discussions was to ascertain what where the most commonly used terms to describe instream flow environments, and to try and 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.

2.2.4 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 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. For the development of a South African classification it was felt that perhaps the system of Bisson *et al.* (1981) would not be entirely appropriate as the classification had to be of equal value for small and large streams, and for vertebrates and invertebrates. The ideas of these authors were considered and formed a framework for further development.

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. This author managed to obtain common consensus from the researchers present for the naming and description of ecological significant hydraulic biotopes common within South African rivers (Table 2.2). 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.

Table 2.2 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 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.

A particularly noticeable feature about the definitions of hydraulic biotope terms given in Table 2.2 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 2.2 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 entire 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; Tharme & King, in prep), application of the concept to other rivers (Padmore & Newson, 1994; Arthington, *pers.comm*) and further development within South Africa (this thesis).

As was originally hoped, 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, 1995). 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 this author. One of the aims of this meeting was to try 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 discusssion 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 2.3.

Table 2.3 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 size, all variables deemed to be of ecological significance.

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 wheras a sand bed less than 1000 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 2.4.

Table 2.4 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

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 2.3) and incorporating substratum (Table 2.4) a new table of hydraulic biotope terms and definitions was produced (Table 2.5).

Table 2.5 The revised definition of hydraulic biotopes (from Citrusdal workshop, Rowntree, 1995)

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 dead zone 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 both upstream convergence and downstream convergence.
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. 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.

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

Detailed examination of the literature together with discussion with lotic ecologists, highlights an immediate problem when referring to hydraulic biotopes: the fact that their recognition is 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 recognition.

The logical progression from hydraulic biotope definition at the Citrusdal workshop, was the development of an objective technique for hydraulic biotope recognition. By combining flow type and substrate class in a matrix (Figure 2.1) 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 recognition 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 2.1 The hydraulic biotope matrix (after Rowntree, 1995)

The following series of photographs (Plate 2.1 a, b, c, d, e, f, g, h, i, j, k) 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.

Plate 2.1a Backwater hydraulic biotope

Plate 2.1b Slack water hydraulic biotope

Plate 2.1c Pool hydraulic biotope

Plate 2.1d Glide hydraulic biotope

Plate 2.1e Chute hydraulic biotope

Plate 2.1f Run hydraulic biotope

Plate 2.1 Riffle hydraulic biotope

Plate 2.1h Rapid hydraulic biotope

Plate 2.1i Cascade hydraulic biotope

Plate 2.1j Waterfall hydraulic biotope

2.2.6 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 these flow patterns have been conventionally defined, using such characteristics as critical 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 Three) 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 values. 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 within this thesis.

2.2.7 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 with low flow velocities and good depth during base flow conditions may become a run 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 difficult 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 question 2.2.7 more adequately. 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 a 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 occuring within the hydraulic biotope. If this is so, similarly classified features should demonstrate consistent hydraulic characteristics, irespective of discharge. This theory is tested to some extent in this research in both pilot studies and the detailed study of the Buffalo River. Unfortunately as the development of the matrix occured late in this study, hydraulic biotopes were largely intuitively recognised. It is felt that this does not allow definitive statements to be made about the validity of the matrix at this stage.

2.2.8 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 ($>10^{-1}m^2$) that sampling tends to occur. It is the belief of this author that this term is still semantically incorrect because most sampling strategies only *assume* different community structure within the different selected flow and substratum conditions. It is 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, 1995). 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, 1995) It is recognised that this method is in the early developmental stages and requires considerable refinement and testing. Detailed studies presented later in this thesis 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 design within this thesis attempts to address this issue.

2.3 THE HYDRAULIC BIOTOPE AND FLUVIAL GEOMORPHOLOGY

Fluvial geomorphology is the branch of science that attempts to find some systematic order in the wide array of landforms shaped by rivers and tries to understand the processes responsible for their development (Kellerhals & Church, 1989). The eight major variables that directly influence river morphology are width, depth, velocity, discharge, channel slope, roughness of bed material, sediment load and sediment size (Rosgen, 1994). In an ecological context, the morphology of a river directly determines the prevailing distribution of depth, velocity and substrate, in other words it provides the physical framework within which the hydraulic biotope exists.

River morphology or more specifically channel bedforms can be recognised at a number of different scales (Allen, 1968; Jackson, 1975; Grant *et al.*, 1990). Using the nomenclature of Grant *et al.* (1990) the following bedforms may be recognised. 'Individual particles', these are self explanatory and are those particles which dominate the channel. 'Subunits' or 'ribs' are at a scale where individual particles form a morphological sequence such as step / pool (McDonald & Banerjee, 1971; Koster, 1978; Whittaker & Jaeggi, 1982; Ashida *et al.*, 1984, 1986a, 1986b; Kishi *et al.*, 1987), a bedrock step (Hayward, 1980; Whitaker, 1987a, 1987b), or as a result of large woody debris (Heede, 1972;

Swanson *et al.*, 1976; Marston, 1982). 'Channel unit' or 'swells' (Kishi *et al.*, 1987) are at a scale where subunits may be interspersed by large pools and include pools, riffles, rapids, cascades and isolated steps (Grant *et al.*, 1990). 'Reaches' are the coarsest scale and can be defined by their longitudinal profile, planform morphology or valley side slopes.

Church (1992) states that features such as riffles, pools, cascades and rapids may be classified as intermediate channel bedform features. These bedforms are believed to constitute the optimum conditions for ecological diversity by providing spawning and rearing habitats for a range of fish species. Furthermore the hydraulic diversity created by heterogeneous substratum provides refuge, feeding opportunities etc for a number of aquatic organisms. In keeping with the findings of Grant (1990) and Church (1992), the 'channel unit' or 'intermediate channel bedform' is considered to be the scale most appropriate for providing a link between channel morphology and aquatic ecology. This scale of feature is termed the 'morphological unit' within the classification hierarchy of Wadeson & Rowntree (1994) and is the nomenclature used within this research. The following review of geomorphological literature focuses on this scale of channel morphology.

Conventional geomorphological literature makes a clear distinction between channel form features commonly found in alluvial (depositional) and bedrock (erosional) streams. The former tend to dominate lowland areas in many parts of the world whilst the later dominate many of the highland areas. South Africa finds itself in a relatively unique situation with a complex mix of both alluvial and bedrock morphology, particularly in the lowland areas. This relatively unique situation has brought about the introduction of some new terminology to describe channel morphology and morphological associations. It is important to note here that a preconceived idea by this researcher was that the fluvial geomorphological literature was considerably more precise and rigorous in the classification and definition of channel form features. Only while attempting to converse with members of the ecological community was it realised that fluvial geomorphology is often just as 'woolly' in the description of morphological units, with researchers often relying on intuition. This thesis does not attempt to address this problem but simply draws attention to the need for it to be addressed, particularly in the South African context where so many of the morphological units do not fit the traditional literature.

Before entering into any discussion concerning the possible relationship between the morphological unit and the hydraulic biotope, a relatively broad review of the geomorphological literature needs to be presented to introduce the morphological unit within two geological settings, alluvial and bedrock channels. Within these broad sedimentary settings reference is made to the associated hydraulic biotopes referred to in Table 2.5.

2.3.1 Alluvial channels

Channels that flow through sediments which they have previously deposited are termed alluvial channels. These channels are able to modify their form because they moved the sediment that makes up their bed and banks. Consistent relationships exist between discharge and the width, depth and velocity, these are termed hydraulic geometry. The actual form of the channel banks and bed is influenced by the size and strength of the material of which they consist (Church, 1992). Fluvial studies commonly emphasise 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.

In a stable natural channel, with erodible banks and bed, transmission of the flow and bank stability must be maintained simultaneously. There is thus an approximate or dynamic equilibrium between erosion and deposition. The topography of the channel bed is composed of forms created through the interaction of stream flow and debris transport. Three general classes of alluvial channels are recognised - sand bed, gravel bed and boulder bed channels, each of which have different associations of hydraulic biotopes (Table 2.6).

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 (Simons & Simons 1987). The microscale alluvial features associated with sand beds (ripples, dunes, plane beds and antidunes) adjust their form 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, are important in sand bed channels as they determine the channel cross section and hence flow conditions across the channel. The constantly changing environment associated with channel braiding is likely to provide less favourable conditions for the river ecology than more stable anastomosing sections which have been anchored by vegetation growth. These features are also relatively dynamic, with significant reshaping and shifting of bars occurring during major flood events.

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, 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 (Rowntree & Wadeson, 1995 and Chapter Four).

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 for organisms to maintain themselves. These hydraulic conditions were observed by Rowntree & Wadeson (1995). If flow occurs within riparian vegetation along the channel margin, it may provide a more favourable hydraulic environment and provide food and refuge.

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, the common spatial transition is the threshold change from headwater gravel-bed channels to downstream sand-bed channels (Yatsu 1955, Shaw and Kellerhals 1977). South African experience would suggest that this is the exception rather than the norm. Many rivers visited during the course of this research exhibited complex transitions involving relatively large substratum common in the upper reaches (cobbles and boulders) situated over and behind bedrock controls in the lowland reaches (Tugela River, Buffalo River, Great Fish River and the Sabie River).

The longitudinal profile of a gravel bed river is broken into a series of irregular steps of alternating steep and gentle reaches which the fluvial geomorphologist recognises as riffles and pools (Figure 2.2), features characteristic of both straight and meandering channels. There are a number of well documented techniques for their objective classification including the use of bed material size (Leopold *et al.*, 1964; Folk, 1968), water surface slope (Yang, 1971), average velocity over average depth (Wolman 1955; Dolling, 1968) and bed topography (Richards, 1976; O'Neill & Abrahams, 1984). 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. This is the pattern of flow characteristics familiar to river ecologists who necessarily avoid sampling during flood events.

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. This dynamic is well recognised by geomorphologists and may have important implications for ecological processes.

Within the South African fluvial environment, gravel bed reaches do occur (Dollar & Rowntree, 1995) and are often comprised of the classic riffle-pool morphology described in the literature, however relatively speaking, this type of fluvial environment is rare. 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. Riffle features are often situated on top of bedrock controls which form topographic high points within the lowland channel, alluvial pools are damned behind them. These features appear to be relatively stable at low to intermediate flows while flows approximating the annual flood have been observed by Rowntree (pers com) to transport material in the median size range (medium size cobbles).

As illustrated in Table 2.6, ecologists and geomorphologists generally agree in their identification of riffles, but differ with respect to pools. In part this can be attributed to the flow reversals noted above wherein pools vary in their flow characteristics and sediment dynamics as discharge varies whereas riffles are more uniform. In addition, ecologists recognise a transition between these features, namely the run. This hydraulic biotope has flow characteristics intermediate to those of the pool and the riffle, but spatially may be an extension of the riffle as sediment infilling occurs in the pool morphological unit.

It is important to note that geomorphologists recognise distinct physical features - the zone of deposition or bar (riffle) and the zone of scour between (pool), whereas ecologists recognise hydraulic biotopes that are determined by the flow hydraulics associated with these features. As discharge changes, so do the flow hydraulics. As the riffle is drowned out and pool velocity increases, the run may extend longitudinally into the low flow pool and riffle. Thus hydraulic biotopes are partly discharge dependent whereas the morphological unit is not.

One further point of interest concerning riffle-pool sequences as recognised by geomorphologists is that they are depositional 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 and therefore a change in available hydraulic biotopes. 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 easily modified by a change in the flow regime.

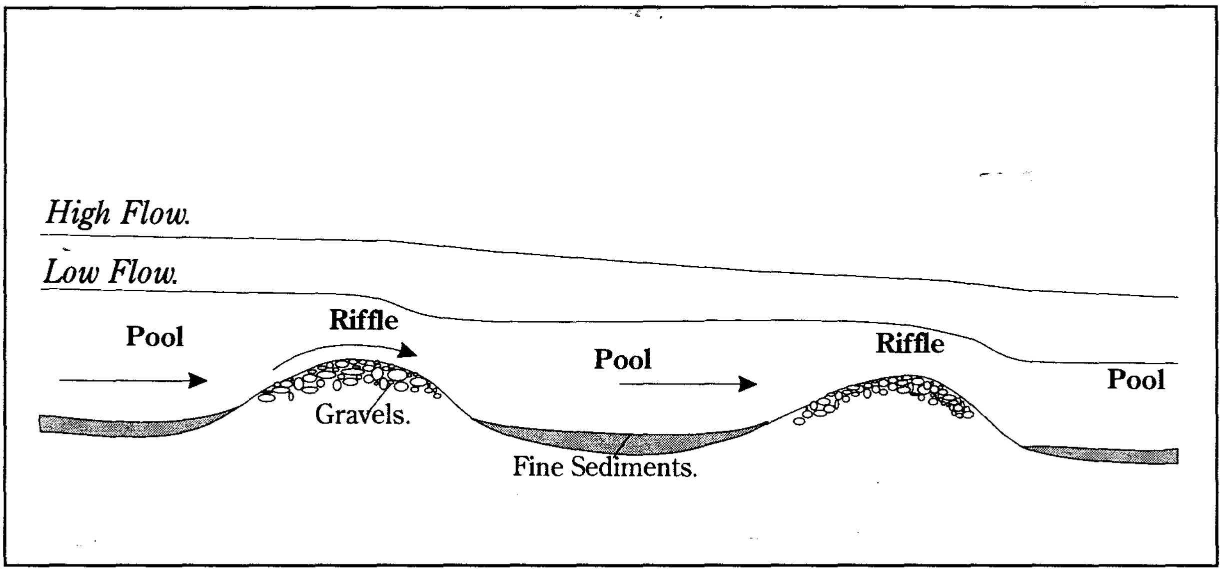

Figure 2.2 Characteristic profile of pools and riffles, showing depth changes with increasing stage

Cobble and boulder beds

The dominant morphological unit associated with 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). As a result, 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), where the boulder and cobble fractions make up the major features of channel morphology which remain stable except in rare flood events.

Hydraulic biotopes that have been associated with this morphological unit are rapids, waterfalls, pools 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 resistant geology. Because of the vertical rather than lateral flow components, pools in boulder beds are likely to have significantly different hydraulic characteristics than pools in sand or gravel beds and therefore should be identified as a separate hydraulic biotope. It is recommended that the term cascade rather than waterfall be retained for hydraulic biotopes associated with step features in cobble and boulder beds. When morphological cascades dominate the channel they are considered as 'small channels' (Church, 1992) and are considered 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 brown trout and large mouth 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).

Another morphological unit commonly associated with boulder and cobble beds is the plane bed described by Montgomery and Buffington (1993). This channel morphology is describe as a stretch of river channel which lacks well defined bedform. These features are quite distinct from both step-pool and pool-riffle channels in that they lack rhythmic bedforms, they appear to occur naturally at gradients and relative roughness intermediate between these other two morphologies. Montgomery and Buffington (1993) suggest that plane bed morphology reflects a channel capable of mobilising bed material at bankfull thresholds conditions but does not possess sufficient lateral flow convergance to cause pool development. The 'flashy' flow regime associated with many of the semi arid rivers of South Africa (high intensity-low duration rainfall events) may in part account for the dominance of this morphology in many headwater streams.

2.3.2 Bedrock channels

Bedrock channels are distinguished by the absence of alluvial sediment, except in isolated scour holes. They are defined as channel segments which lack a coherent bed of active alluvium. In addition to consolidated rocks, they may include cohesive fluvial deposits now undergoing dissection. Bedrock sections most commonly form the headwater tributaries in otherwise alluvial channel networks, but may also occur in any channel reach where steep gradients inhibit the deposition of sediment.

Channel morphology within these rivers is primarily determined by geological controls. The gradient of bedrock channels exhibits no necessary correlation with discharge and sediment characteristics, in contrast to the strong correlations found for alluvial channels. Gradients are determined by the distribution of bedrock resistance to erosion along the channel and the erosional history of the channel network. The rate of erosion of bedrock channels is determined jointly by the bedrock resistance and the hydraulic regime (discharge, sediment load, and size distribution of supplied sediment; Howard 1987).

Many bedrock channels have straight long-profiles, but where the network intersects resistant strata rapids and waterfalls are common. At the small scale, bedrock characteristically forms a series of pools and steps. The pools found within bedrock channels are significantly different from those found in alluvial features. Whereas alluvial pools are scour features between riffles in a depositional environment, bedrock pools are the result of the spatial heterogeneity in geological resistance and often form as erosional features below a resistant strata, for example plunge pools below waterfalls. Potholes may also form in fast-flowing streams where overflow is concentrated at one location for a long enough period. Pools also form behind resistant strata that form hydraulic controls across the channel, as mentioned previously, a common feature in many South African rivers. The flow hydraulics within a bedrock pool depend on its shape, itself largely the result of bedrock resistance; flow patterns will be less predictable than in an alluvial pool.

It is apparent that the ecological definitions for waterfalls are generally clearly defined, although as noted previously, terms like cascade and waterfall are often used to describe a number of different physical features within the fluvial environment with little regard for the essential physical processes underlying their formation. They are applied equally to both boulder bed and bedrock channels. To avoid confusion the use of the term waterfall should be confined to bedrock features; where these occur in a step like succession the term cataract may be appropriate.

There is little agreement between ecologists and geomorphologists in the definition of rapids. It has been observed in the field that many ecologists include irregular rapid flow with white water over a bedrock channel in the riffle category. Geomorphologically, rapids and riffles are clearly distinguished as erosional and depositional features respectively.

2.3.3 Bedrock controlled or mixed channels

Bedrock channels and alluvial channels with either fine (sand) or coarse (gravel) beds commonly coexist in many drainage basins of the world. 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 (E. Transvaal); the Tugela River (Kwa-Zulu Natal) and the Olifants River (W. 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 gradient. Deposition 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 (E. Transvaal) where riffle type features occur over bedrock (as discussed in section 2.3.1), downstream of alluvial pools.

Table 2.6 The definition of selected morphological units and their associated hydraulic biotopes found within A) alluvial and B) bedrock channels.

A). ALLUVIAL CHANNELS

Morphological Unit	Definition	Hydraulic biotope Equivalent
Riffle *(Sand and Gravel bed channels)*	These are topographic high points in an undulating bed long profile. They are spaced 5-7 channel widths apart and are composed of coarser sediment such as pebbles (Leopold et al. 1964). At low flow , riffles have rapid, shallow flow with a steep water surface gradient, and act as a broad - crested weir.	Allen (1951) **Riffles, Stickles.** Harrison and Elsworth (1959) **Riffles, Stickles.** Chutter (1970) **Stickle.** De Leeuw (1981) **Riffle.** Pridmore and Roper (1985) **Run.** Grossman and Freeman (1987) **Riffle.** Bisson et al. (1988) **Riffle.** Boulton *et al.* (1988) **Riffle.** Anderson and Morison (1989).**Riffle.** King *et al.* (pers.comm. 1992) **Riffle.**
Pool *(Sand and Gravel bed channels)*	These are low points with sandy beds although scour at high discharges may expose coarse lag sediment, which is then covered by fine sediment during periods of low flow (Hack 1957, Lisle 1979). At low flow the pool is deep and slow flowing with a gentle slope.	Allen (1951) **Pools, Runs, Flats.** Harrison and Elsworth (1959) **Pools, Runs, Flats.** Chutter (1970) **Run.** De Leeuw (1981) **Pool, Glide.** Bisson et al. (1988) **Pool, Backwater, Glide.** Anderson and Morison (1989).**Pool, Run, Backwater, Glide.** King *et al.* (pers.comm. 1992) **Pool, Run, Backwater, Glide.**
Step-Pool or Cascade (Boulder bed channels)	These are characterised by large clasts organized into discrete channel spanning accumulations that form a series of steps separating scour pools containing finer material (Grant *et al.* 1990).	Allen (1951) **Cascades.** Harrison and Elsworth (1959) **Cascades.** Chutter (1970) **Cascades.** De Leeuw (1981) **Cascades, Waterfall.** Bisson et al. (1988) **Cascades.** Anderson and Morison (1989) **Cascades.** King *et al.* (pers.comm. 1992) **Cascades, Waterfalls.**

B. BEDROCK CHANNELS

Morphological Unit.	Definition.	Hydraulic Biotope Equivalent.
Waterfall.	This is a site at which water falls vertically; a cataract is a step-like succession of waterfalls (Selby 1985).	De Leeuw (1981) **Falls, Cascades.** Bisson et al.(1988) **Cascades.** Anderson and Morison (1989) **Cascades, Waterfalls.** King et al. (pers.comm.1992) **Waterfalls, Cascades.**
Pool	These form as erosional features below a resistant strata (plunge pools), they may also form behind resistant strata lying across the channel.	Allen (1951) **Pools, Runs.** Harrison and Elsworth (1959) **Pools.** Chutter (1970) **Run.** De Leeuw (1981) **Pool, Glide.** Bisson et al. (1988) **Pool, Cascade, Glide.** Anderson and Morison (1989).**Pool.** King *et al.* (pers.comm. 1992) **Pool, Run.**
Step-Pool or Cascade (bedrock)	Water flows directly on bedrock, individual steps are more uniform than in boulder cascades and coincide with rock structure. (Grant *et al.*, 1990).	Allen (1951) **Cascades.** Harrison and Elsworth (1959) **Cascades.** Chutter (1970) **Cascades.** De Leeuw (1981) **Cascades, Waterfall.** Bisson et al. (1988) **Cascades.** Anderson and Morison (1989) **Cascades.** King *et al.* (pers.comm. 1992) **Waterfalls.**
Rapid	These are part of the long profile in which the flow of water is broken by short steep slopes. Rapids may be completely drowned by the flow at high discharges when turbulence at the water surface is the only evidence of the underlying profile irregularity (Selby 1985).	Allen (1951) **Cascade.** Harrison and Elsworth (1959) **Cascade.** Chutter (1970) **Cascade.** Anderson and Morison (1989) **Rapids.** King et al. (pers.comm.1992) **Chutes, Rapids.**

NB: The list of morphological units given above is far from comprehensive. Definitions are given for 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 Table 5.4.

2.4 SUMMARY

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 recognition 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 (Table 2.6) 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.

2.5 WHERE TO FROM HERE?

Having defined various classes of the hydraulic biotope, and having developed an objective technique to identify them, the next stage in the research is to address the following questions:

- Do hydraulic biotopes, identified using the flow matrix principles, have any hydraulic significance?

- Do hydraulic biotopes, identified using the flow matrix principles, have any ecological significance?

CHAPTER THREE
CHANNEL HYDRAULICS FOR ECOLOGISTS

3.1 INTRODUCTION

An important link can be made between geomorphology and ecology within the hierarchical geomorphological model, more specifically between morphological units and hydraulic biotopes. The review of literature together with consultation with ecologists suggests that it is the spatial and temporal variations in flow hydraulics associated with the different features that provides this link. Previous attempts to define hydraulic biotopes in terms of depth, velocity and substrate failed because values could not be transferred between channels of different scales.

The following review represents a relatively detailed 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.

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).

3.2 THE MACROENVIRONMENT

3.2.1 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 some point on 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 (often measured at 0.6 depth from the surface.
Shear velocity (V_*):	a measure of shear stress (force acting parallel to the flow).
Kinematic viscosity (ν):	the ratio of dynamic viscosity to density

3.2.2 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 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). 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.

How the above variables change throughout a catchment as discharge changes can be investigated by linking information from a number of sites within a stream system. This "downstream" hydraulic geometry is only valid if the discharges used for comparison from site to site are of the same recurrence interval.

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 3.1), 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.

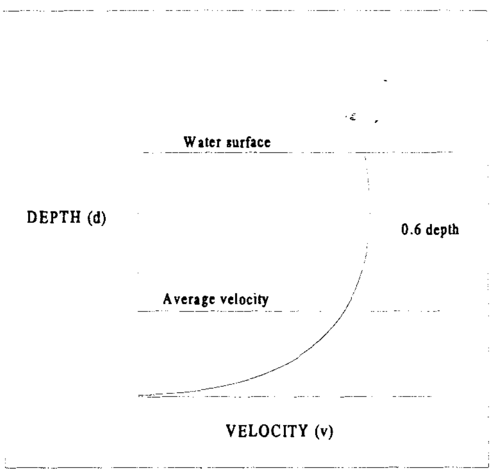

Figure 3.1 A 'typical' velocity profile

In the centre of broad rapid streams the velocity profile may show the maximum velocity at the free surface (Figure 3.2). 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.

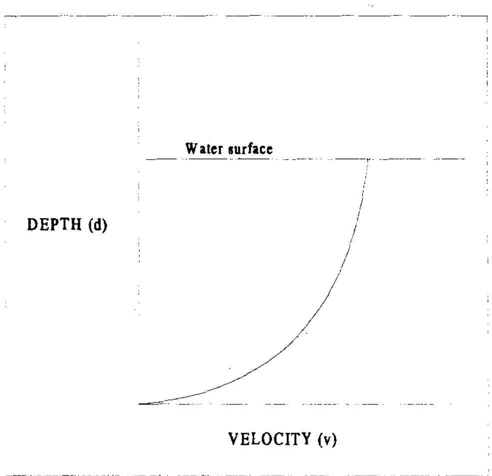

Figure 3.2 Velocity profile of a broad, rapid stream

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 3.3) are sometimes apparent.

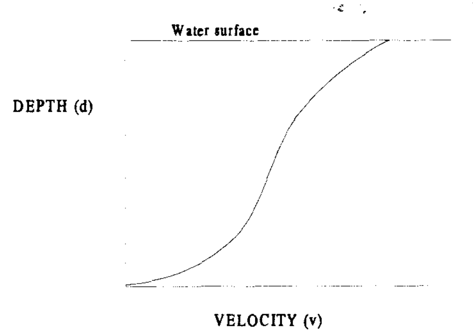

Figure 3.3 Velocity profile of a shallow, steep mountain stream

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 then is the point at which velocities are measured if only one reading is taken (Gordon *et al.,* 1992).

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.

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 "superelevated". 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).

3.2.3 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, pp67). 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:

$$Re = VL/\nu \qquad \textbf{\textit{equation 3.1}}$$

where V = velocity ($m.s^{-1}$)
L = characteristic length (m) considered to be equal to the hydraulic radius (R)
ν = 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 to 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:

$$Fr = V/\sqrt{gL} \qquad \textit{equation 3.2}$$

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).

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

$$V_c/\sqrt{gD_c} = 1 \qquad \textit{equation 3.3}$$

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 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 and is often described as rapid, shooting or torrential.

In the mechanics of water waves, the critical velocity $\sqrt{g}D$ 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 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.

3.2.4 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.

3.2.5 Types of flow

Figure 3.4 presents a summary of the different types of flow:

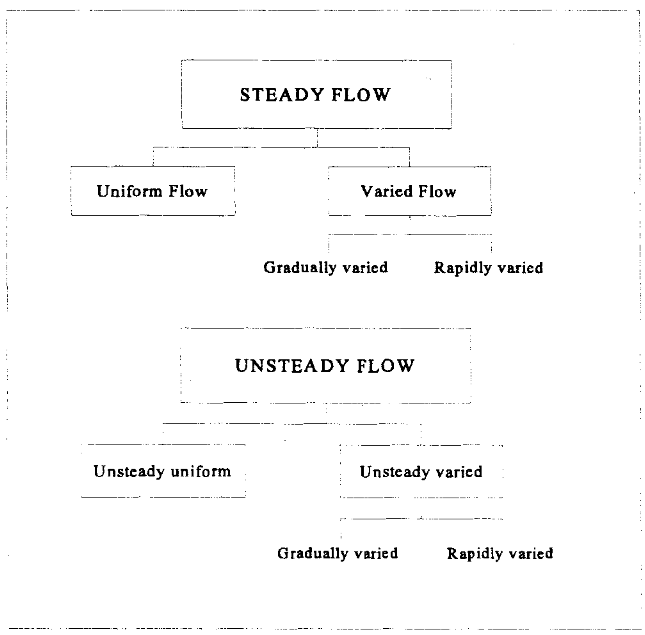

Figure 3.4 Summary diagram of different flow types

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 3.4 (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 at a cobble bed pool, the flow is gradually varied.

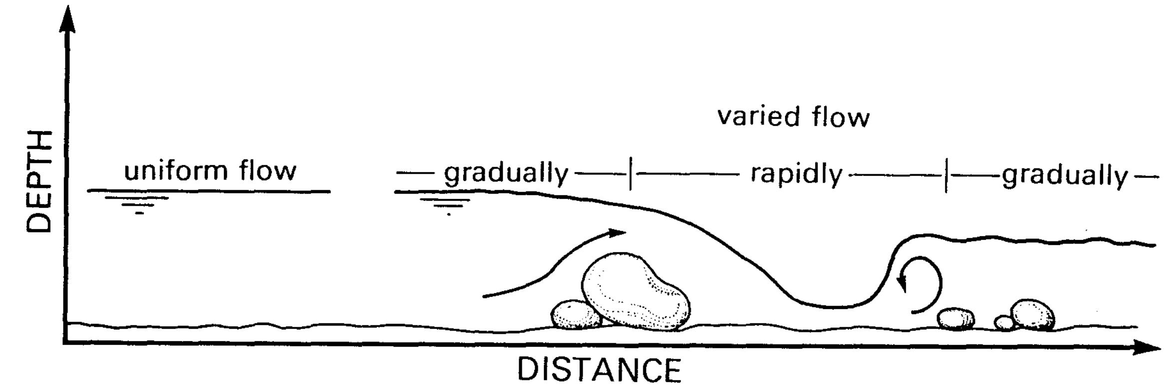

Figure 3.5 Classification of open channel flow.

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.

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 dissipators 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):

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.

It should be noted that hydraulic jumps are not possible if the upstream flow is subcritical (Froude > 1).

Flow in natural channels is typically varied, unsteady, turbulent and subcritical. However, uniform, steady and laminar conditions 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".

3.3 THE MICROENVIRONMENT

3.3.1 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 streambed 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 3.6). 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 $\approx$ 500 000

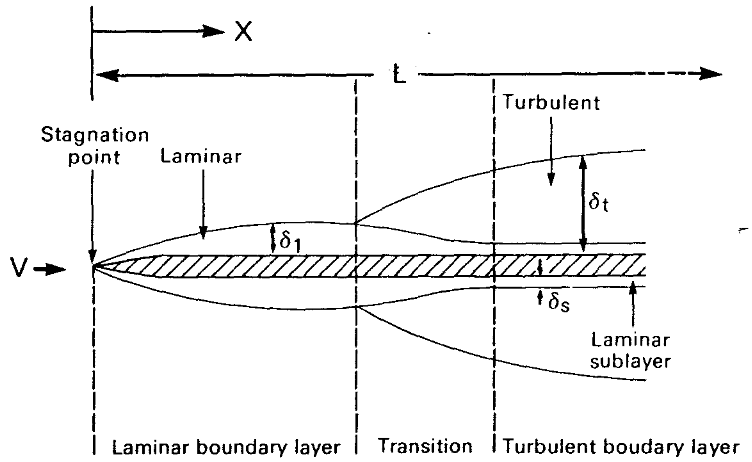

Figure 3.6. Boundary layer formation across the top of a sharp flat plate (L is the "characteristic length", V is the approach velocity, x the distance from the leading edge and δ the boundary layer thickness (for l, laminar; t, turbulent and s, viscous sublayer regions). From Gordon *et al. (1992).*

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 at the channel boundary.

3.3.2 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

$V_* = \sqrt{gds}$ ***equation 3.4***

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 inability to calculate water surface slope.

Shear velocity can be more accurately derived from the velocity profile obtained from field measurements where

$$V_* = \frac{5.75}{\tan\alpha} \quad \text{and} \quad \tan\alpha = \frac{V_1 - V_2}{\log Z_1 - \log Z_2}$$ ***equation 3.5***

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

Again there are a number of problems associated with the calculation of shear velocity using this method because it requires adequate depth of water (< 0.75m) for multiple velocity measurements and it assumes a log linear velocity profile. As indicated earlier in this chapter, the presence of large substratum on the stream bed or overhanging vegetation in contact with the water will cause considerable variability in the velocity profile.

A third method for the calculation of shear velocity requires 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 3.6***

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 thesis because of the problems of shallow water and highly variable bed topography.

3.3.3 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:

$$\delta = 11.5\, \nu / V_*$$ ***equation 3.7***

where ν 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).

3.3.4 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 3.8***

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

$$Re_* = V_* k/\nu$$ ***equation 3.9***

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.

3.3.5 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.

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, but the classification is based on measurements of bed topography rather than flow itself.

The classification of flow as given by Morris (1955) and Davis and Barmuta (1989) are not directly comparable with the flow types presented in the hydraulic biotope matrix (Figure 2.1). The flow types described in the hydraulic biotope matrix refer to the condition of flow at the surface of the water rather than those near the bed and makes no distinction between those flows that are hydraulically rough or hydraulically smooth at the boundary.

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 (λ).

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 3.7, Plate 3.1). Two different lengths of rod were necessary in this study because of the occasional presence of very large substratum.

For the purpose of this research, two bed profiles were taken at each point of interest along a transect, one parallel to the flow, the other at right angles to it. In each case the frame was held close to the bed with the rods vertically upright and the frame horizontal. The clamps were released and the rods were allowed to fall freely to the streambed. Once the rods were settled they were re-clamped and the resultant profile traced onto waterproof paper.

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. The lack of a well defined technique in the literature meant that whatever method was selected for this research, it had to be consistent throughout. For this thesis 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 3.7. 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.

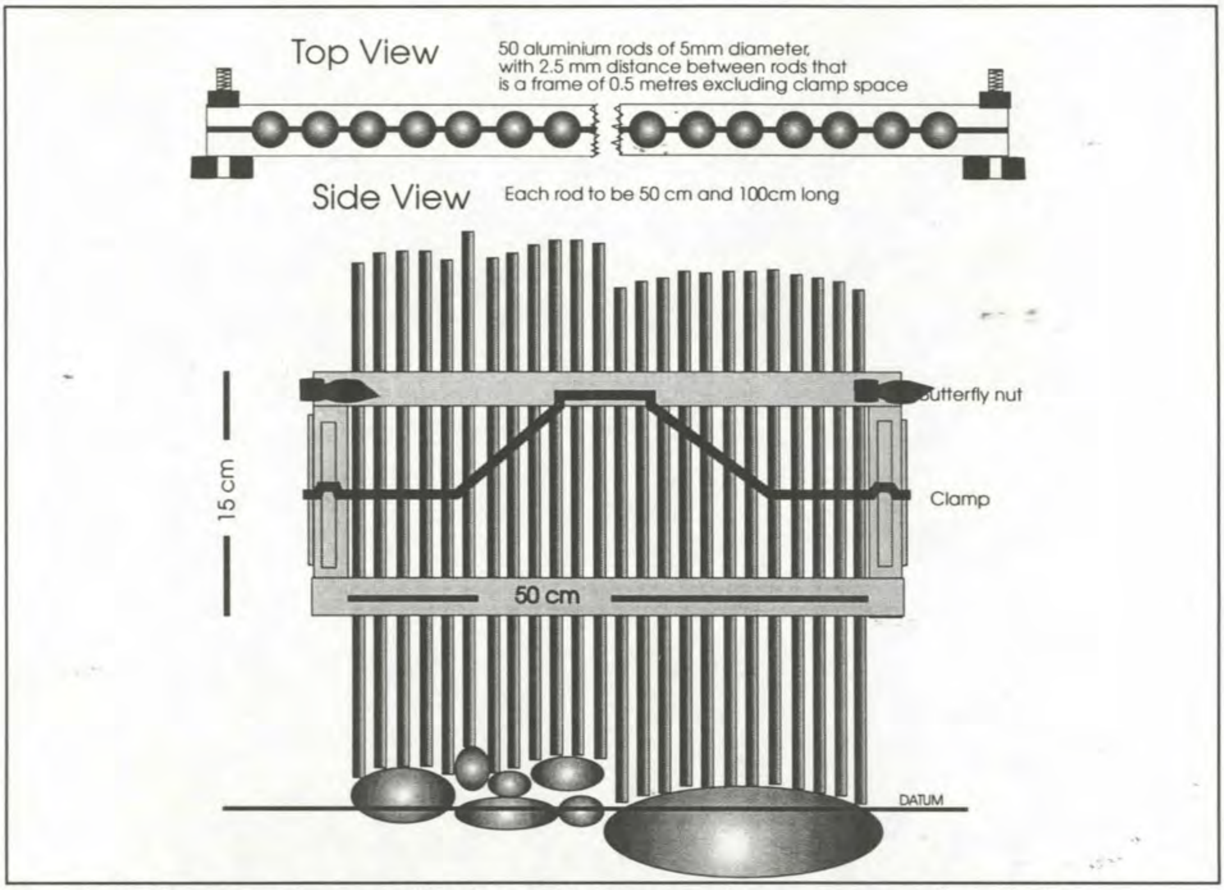

Figure 3.7 Diagram to show specifications of the frame used to measure roughness height.

Plate 3.1 Photograph of frame used to measure roughness height.

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 3.8). 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).

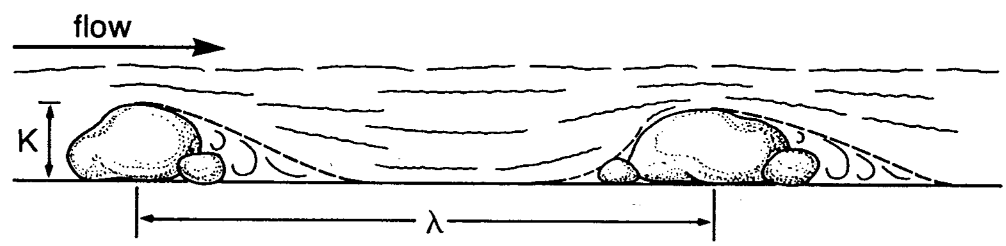

Figure 3.8 Diagrammatic illustration of isolated roughness flow patterns (from Gordon *et al., 1992).*

Wake interference flow

Roughness elements are closer together and the eddies from the elements interact, causing intense turbulence (Figure 3.9). 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).

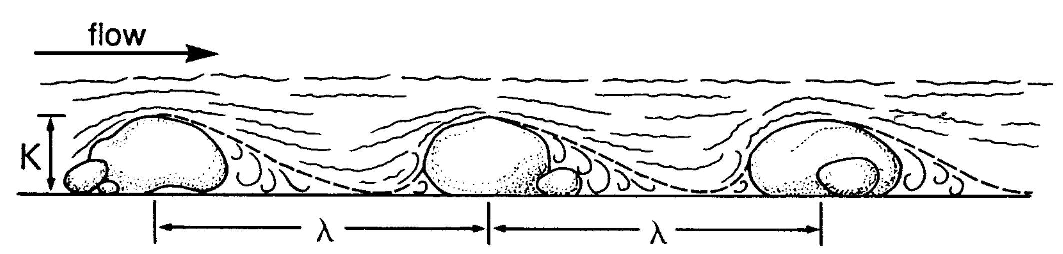

Figure 3.9 Diagrammatic illustration of wake interference flow patterns (from Gordon *et al., 1992).*

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 3.10). 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).

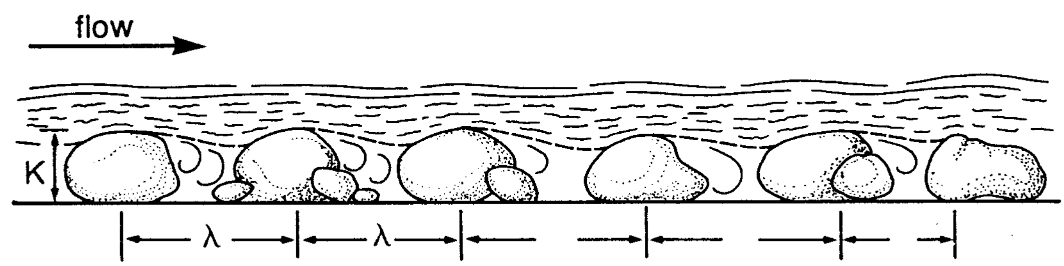

Figure 3.10 Diagrammatic illustration of skimming flow patterns (from Gordon *et al., 1992).*

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.

Exposed roughness flow (Chaotic flow)

Elements protrude through the water surface and flow conditions become very complex as water flows over and around these large obstacles (Figure 3.11). 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).

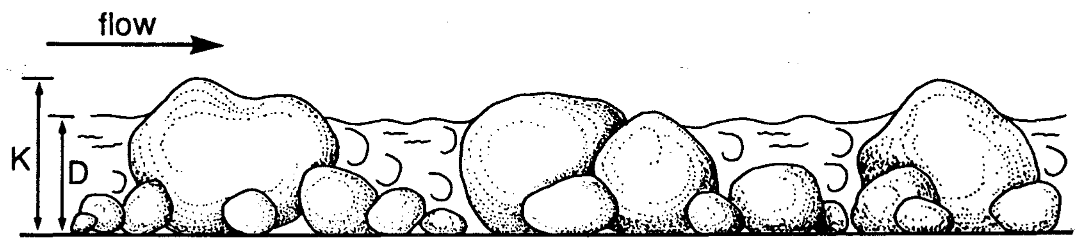

Figure 3.11 Diagrammatic illustration of exposed roughness flow patterns (from Gordon *et al.*, 1992).

3.4 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 3.12). These flow types are largely based on measures of bed topography and as such are unlikely to show good relationships with the hydraulic biotopes described in Chapter Two, which are defined according to surface flow conditions.

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. The remainder of this thesis has as its focus the testing of these hypotheses.

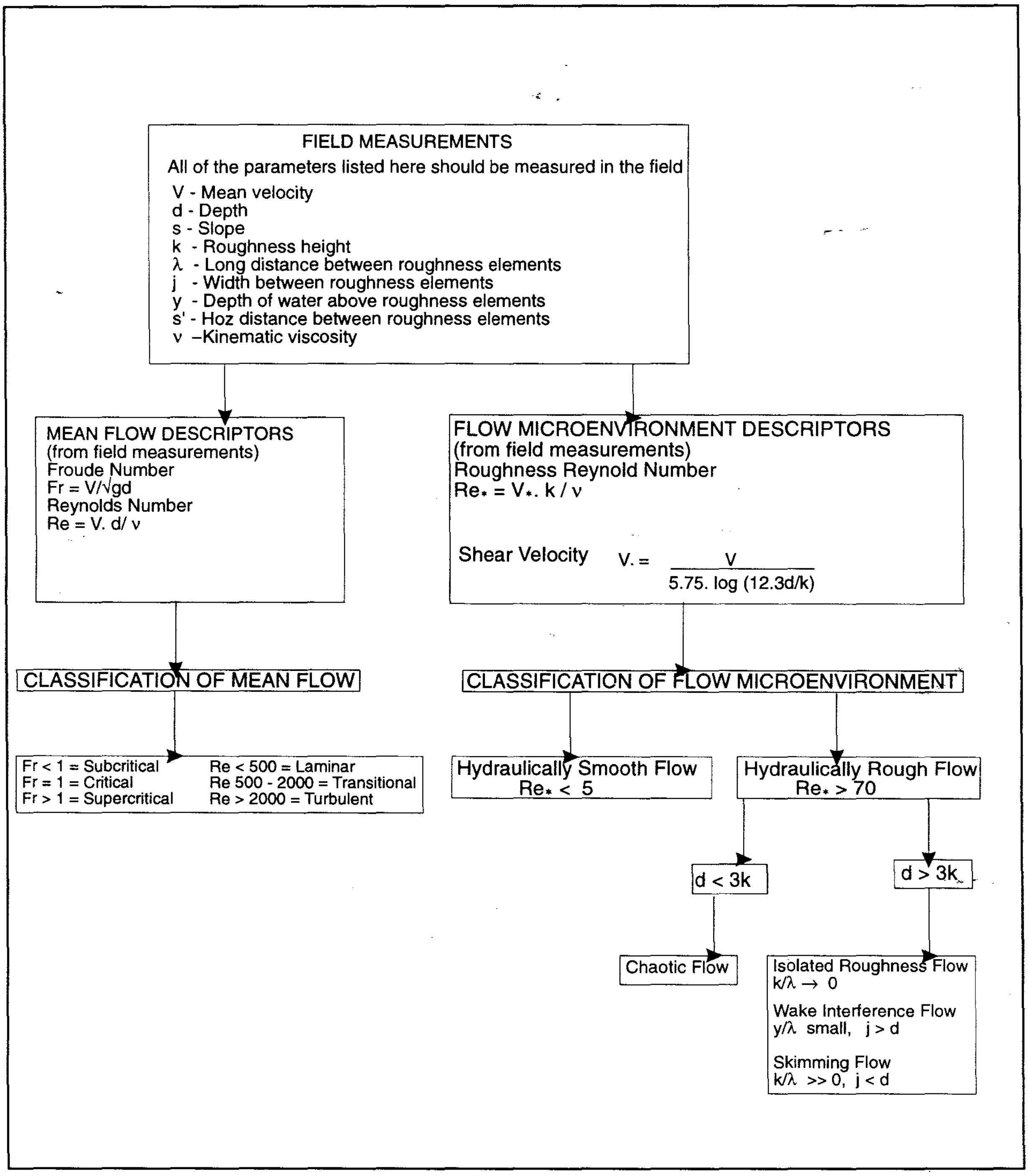

Figure 3.12 The classification of flow, from Davis and Barmuta (1989).

CHAPTER FOUR
PILOT STUDIES

4.1 INTRODUCTION

A review of the hydraulic literature (Chapter Three) suggests that the Reynolds number and the Froude number, two dimensionless numbers that characterise mean motion or flow down a river channel due to gravity, may be useful indices for the characterisation of different flow environments. As described in Chapter Three, 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 velocity, variables commonly collected during ecological surveys.

Although a number of researchers have referred to the potential usefulness of these simple mathematical indices for the characterisation of different flow environments (Statzner *et al.*, 1988; Davis & Barmuta, 1989), there have been few attempts to use them to classify spatially distinct environments (hydraulic biotopes) recognised by limnologists. Recently a study in New Zealand by 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.

This chapter presents preliminary investigations into the potential use of simple hydraulic indices to characterise the spatial and temporal variability of hydraulic biotopes within three South African rivers, each representing discrete sedimentary environments. The three river systems selected for this research were the Great Fish River in the Eastern Cape (gravel bed), the Olifants River in the Western Cape (sand bed) and the Molenaars River in the Western Cape (boulder bed). Comparisons are made with the research results from a gravel bed river in New Zealand (Jowett,1993). The data represented here has either been published (Wadeson, 1994) submitted for publication (Rowntree & Wadeson, 1995b) or submitted as a report.

4.2 THE GREAT FISH RIVER, EASTERN CAPE, SOUTH AFRICA[1]

4.2.1 Introduction

The transfer of water from areas of surplus to areas of deficit have long been recognised by the DWAF (1986) as the only practical solution to the redistribution of the water supplies in South Africa. Motivation for the development of an inter-basin transfer between the Orange River (Orange Free State) and the Great Fish River (Eastern Cape) was initiated by Dr Lewis in 1928 in his role as the Director of DWAF. The idea was to harness the water of the Orange River and its tributary the Caledon River and store this water in two of the largest dams of their kind in the southern hemisphere; the P.K. Le Roux dam and the Hendrik Verwoerd dam. The Orange - Fish tunnel was opened in 1977.

From the large dams of the Orange Free State, water is pumped through tunnels to the Great Fish River catchment to be locally stored in three smaller dams. Once the water is in the Great Fish River catchment it is still under the control and management of the DWAF and is released according to the irrigation and domestic requirements of the various receiving areas of the Eastern Cape.

The once irregular seasonal flow of the Great Fish River has now become perennial but varies according to flow regulation; this provided a good range of flow conditions within a relatively short time span for the initial testing of the hydraulic biotope concept.

4.2.2 Aims

The aims of this study were to investigate the potential use of the hydraulic indices Reynolds number (Re) and Froude number (Fr) to characterise the temporal and spatial variability of hydraulic biotopes within a mixed bed channel and to compare the results from the Great Fish River with the findings of Jowett (1993) in New Zealand.

4.2.3 Study area

The Great Fish river extends 650 km from its headwaters in the Tandjiesberg mountains west of Cradock, to the Indian Ocean 150 km east of Port Elizabeth (Figure 4.1). The Great Fish River had a naturally seasonal flow regime with the river being reduced to a series of unconnected pools during the dry season (April - October). The river flows within an arid catchment, and has a mean annual rainfall range from 350mm to 550 mm (O'Keeffe & De Moor, 1988). The river is extremely important locally as a source of water for both farmers and rural inhabitants and is of traditional significance as a natural boundary between the RSA and the Ciskei homeland.

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[1]Results presented in this section have been published by Wadeson (1994).

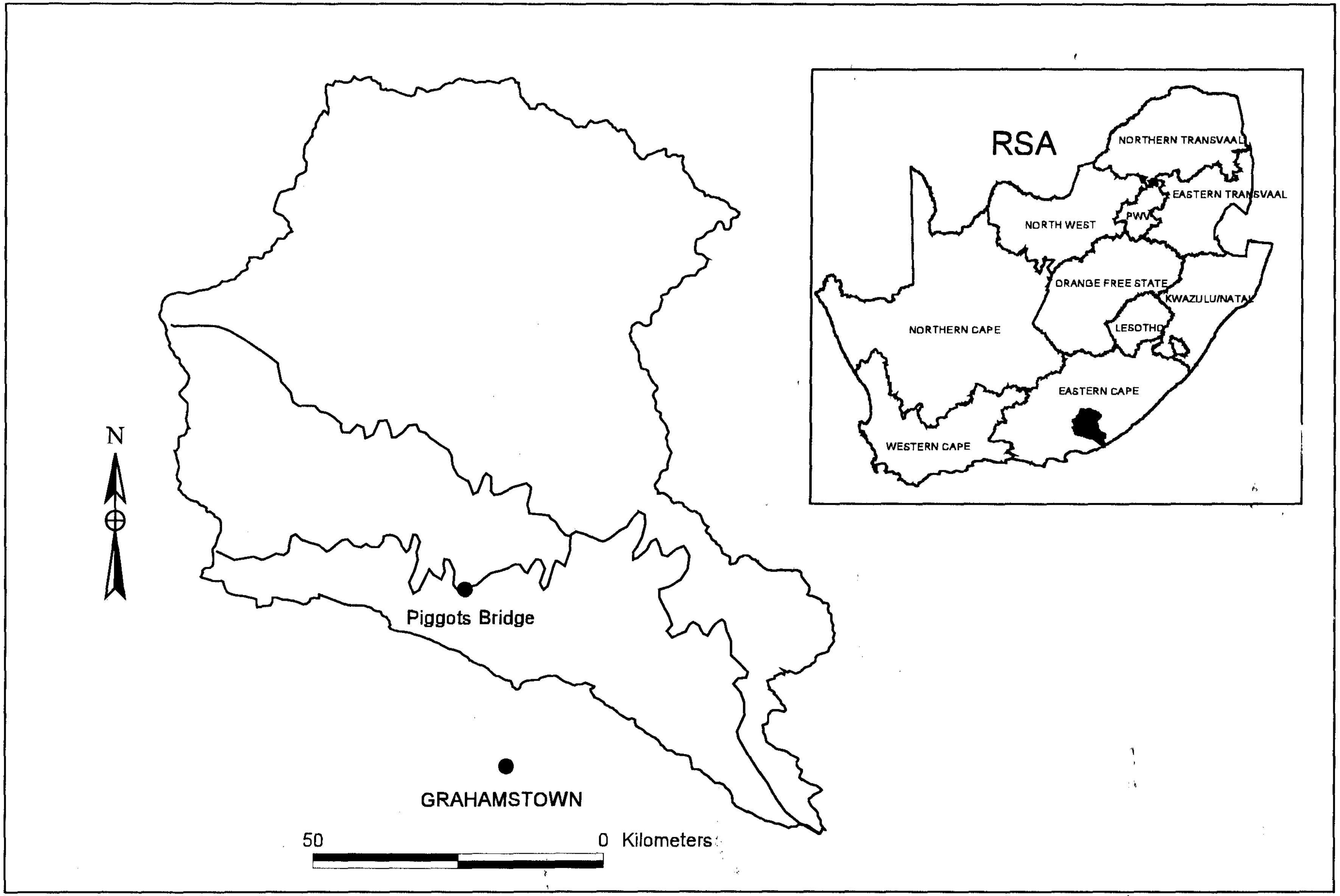


Figure 4.1 The Great Fish River catchment

Prior to the transfer of water from the Orange River, the middle reaches of the Great Fish River were characterised by poor water quality (TDS above 2000 mg-1). Water transfer has resulted in reductions in ion concentrations of between 10% and 77% (O'Keeffe & De Moor, 1988). The predominant geology of the catchment includes sandstones and mudstones of the Beaufort series (accounting for high natural salinity) and Ecca shales. This geology also accounts for the dominant weathering products in the channel bed, namely pebbles, gravels and coarse sands.

As a result of the transfer of water from the Orange River system, the once irregular seasonal flow has now become perennial with a 500% to 800% increase in the mean annual runoff in the upper catchment (O'Keeffe & De Moor, 1988). In contrast to this, the increased irrigation demand in the lower reaches of the river has produced little change in the mean annual discharge, although seasonal variations are quite different.

Data was collected from the area Pigott's Bridge which is situated in the flat, lowland area of the Great Fish River catchment. This was a site visited by a large number of South African ecologists in February 1993. These ecologists arrived at a common consensus for the classification of the various hydraulic biotopes present at the particular flow condition experienced at the time (approximately $5m^3s^{-1}$). Hydraulic biotope classification during this visit was based on an intuitive awareness of the flow and substratum characteristics.. The hydraulic biotopes recognised were run, transition zone, riffle, run and pool. These hydraulic biotopes were assumed to extend across the width of the channel (Figure 4.2) hence the classification was applied at the transect rather than the point scale. In this early study the hydraulic biotope classification was largely determined by the geomorphological classification of morphological units and there was no attempt to reclassify hydraulic biotopes as discharge changed.

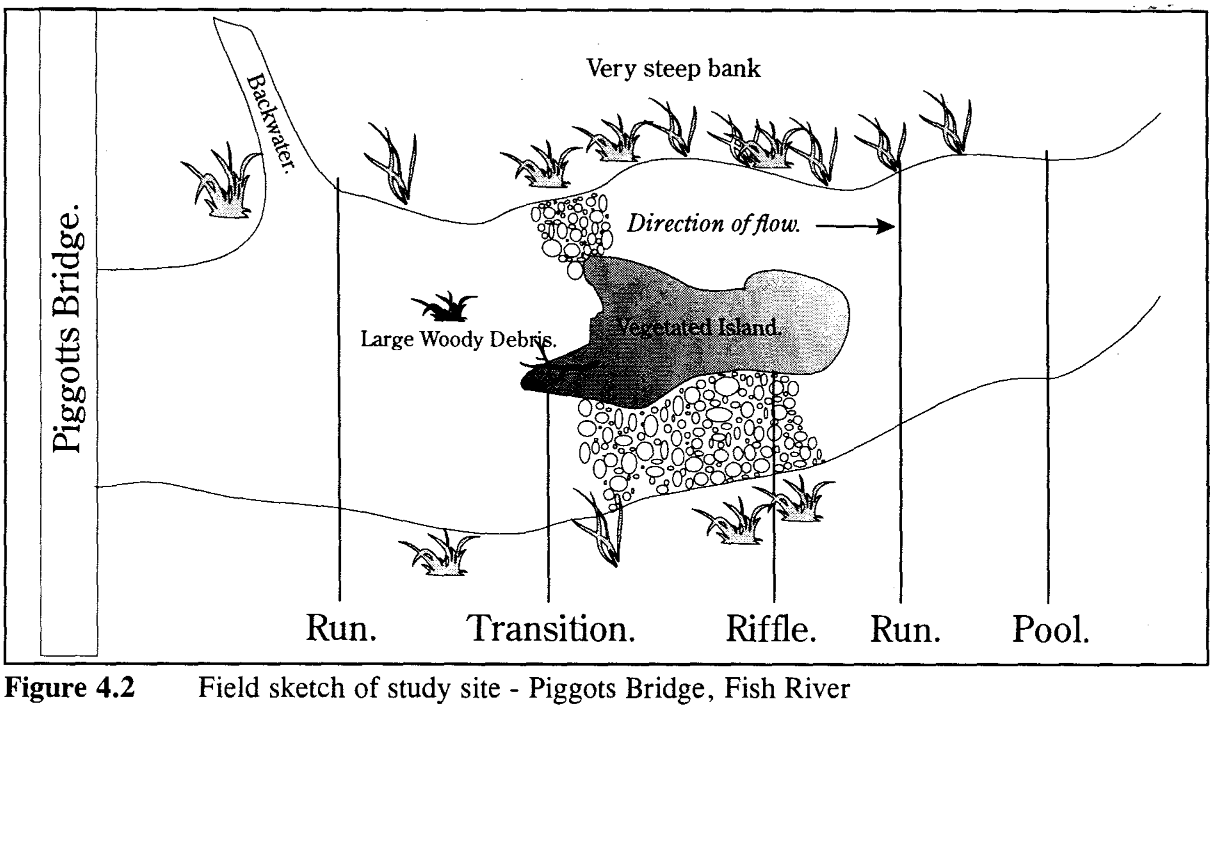


Figure 4.2 Field sketch of study site - Piggots Bridge, Fish River

The reach consists of a series of riffle-pool features (morphological units) in an alluvial channel which is deeply incised in a wide flood terrace. The most upstream hydraulic biotope (run) is situated in a pool morphological unit which has a substratum dominated by large cobbles and small boulders which are interspersed with sand. The transition and riffle hydraulic biotopes are both situated in a riffle morphological unit which has a substratum dominated by cobbles with local pockets of sand. Further downstream, the run and pool hydraulic biotopes are both situated in a pool morphological unit which is dominated by a sand substratum.

4.2.4 Methods

Data collection

During the course of 1993 the site was visited five times at different discharges. At each of five different hydraulic biotopes along the river channel, a tape measure was strung between two fixed points. At two metre intervals a water depth above roughness elements (substratum) was recorded, and velocity measured at 0.6 depth below the water surface (Chow 1959). These data were used to estimate Reynolds and Froude numbers for each two metre cell of the cross section. Unfortunately conditions during each visit did not always allow the collection of a complete data set for the five different hydraulic biotopes. 16 out of a possible 25 data sets were collected (Table 4.1).

Table 4.1 Available data sets for five hydraulic biotopes at five discharges.

Discharge ($m^3. s^{-1}$)		15.5	8.9	5.2	4.8	3.4
RUN	Average Velocity ($m.s^{-1}$)	0.69	0.47		0.33	
(Site 1)	Average Depth (m)	0.82	0.59		0.46	
TRANSITION	Average Velocity ($m.s^{-1}$)	1.15	0.84		0.45	
(Site 2)	Average Depth (m)	0.54	0.35		0.26	
RIFFLE	Average Velocity ($m.s^{-1}$)	1.49	1.02		0.80	0.65
(Site 3)	Average Depth (m)	0.68	0.32		0.21	0.20
RUN	Average Velocity ($m.s^{-1}$)		0.58	0.48	0.47	0.37
(Site 4)	Average Depth (m)		0.66	0.50	0.49	0.46
POOL	Average Velocity ($m.s^{-1}$)		0.41		0.33	
(Site 5)	Average Depth (m)		0.93		0.81	

Data Analysis

Two simple techniques for exploratory data analysis were carried out. Box plots were used to show whether any patterns of distribution exist for the Froude and Reynolds numbers, both temporally (at different discharges), and spatially (across hydraulic biotopes). This analytical technique is particularly useful for studying symmetry, checking distributional assumptions, and detecting outliers.

The Kruskal-Wallis test was used to examine whether there is a significant difference between the Reynold numbers of different hydraulic biotopes and between the Froude numbers of different hydraulic biotopes. This test is the nonparametric equivalent of ANOVA, but is more appropriate when the assumptions of normality and equal population variance are not met (Mc Grew & Monroe, 1993). In this test, values from all samples are combined into a single overall ranking. The rankings from each sample are summed, and the mean ranks of each sample are then calculated. The test examines whether the mean rank values are significantly different.

4.2.5 Results

Aggregate discharge data

The first level of analysis grouped all data together irrespective of discharge for each hydraulic biotope as identified during medium flow conditions in February 1993. The variability of Reynolds numbers within and between hydraulic biotopes is shown in Figure 4.3a, and that of Froude numbers is shown in Figure 4.3b.

It can be seen from Figure 4.3a that there is a large variability of the Reynolds number within each hydraulic biotope and that there is a considerable degree of overlap between the various hydraulic biotopes. The Reynolds number does not appear to be a useful means of distinguishing hydraulic biotopes. A Kruskal-Wallis one way analysis procedure confirms the hypothesis that the Reynolds numbers for the five hydraulic biotopes (at a combination of discharges) come from the same population (Table 4.2).

Table 4.2 Reynolds vs Hydraulic biotope (Kruskal-Wallis one way analysis).

HYDRAULIC BIOTOPE	SAMPLE SIZE	AVERAGE RANK
Run.	56	94.1
Transition.	30	100.3
Riffle.	25	86.4
Run.	51	82.4
Pool.	20	100.9

TEST STATISTIC = 3.36 SIGNIFICANCE LEVEL = 0.50

In contrast to the Reynolds number, Figure 4.3b shows that the Froude number can be used to differentiate between hydraulic biotope classes. There is a continuum of Froude number distribution from a run, to run-riffle interface, to riffle, back to a run, and finally down to a pool. This distribution shows marked differences in the range, quartiles and medians for the various hydraulic biotopes.

To test the hypothesis that the Froude numbers for five hydraulic biotopes (at a combination of different discharges), come from the same population group, the Kruskal-Wallis one way analysis procedure was carried out (Table 4.3). The test results indicate that this hypothesis must be rejected, that is the Froude numbers for five hydraulic biotopes are significantly different.

Table 4.3 Froude vs Hydraulic biotope (Kruskal-Wallis one way analysis).

HYDRAULIC BIOTOPE	SAMPLE SIZE	AVERAGE RANK
Run.	56	71.5
Transition.	30	137.1
Riffle.	25	144.5
Run.	51	81.7
Pool.	20	37.8

TEST STATISTIC = 78.31 SIGNIFICANCE LEVEL = 0.0

In his study in New Zealand, Jowett (1993) used discriminant analysis to select the variable, or set of variables, which best distinguished between three hydraulic biotope types (riffle, run and pool). Results showed that the Froude number together with velocity/depth ratio and slope, were major components of highly significant ($P<0.001$) first and second discriminant factors. Froude numbers of 0.18 and 0.41 separated pool/run and run/riffle habitats respectively; these discriminating values are marked on Figures 4.3b and 4.4b.

If we compare the results of Jowett (1993), with those found in the Great Fish River a number of interesting observations can be made. The classificatory values from New Zealand appear to be generally applicable to the Great Fish River if one uses the median Froude values of the various hydraulic biotope classes for aggregate discharge data (Figure 4.3b). Within each hydraulic biotope class the Froude numbers are highly variable, indicating that each class is made up of cells which, if classified in isolation, would be assigned to a range of different classes. This is particularly true for the riffle which includes cells with low Froude numbers typical of runs and pools. The pool class is seen to be far more homogeneous. It should be noted that very few riffle cells have Froude numbers in the super critical range, an important observation if one refers to the previous definition of a riffle by King et al. (*pers.comm.* 1992). Contrary to their intuitive definition, results here show that riffles may be characterised by sub-critical flow.

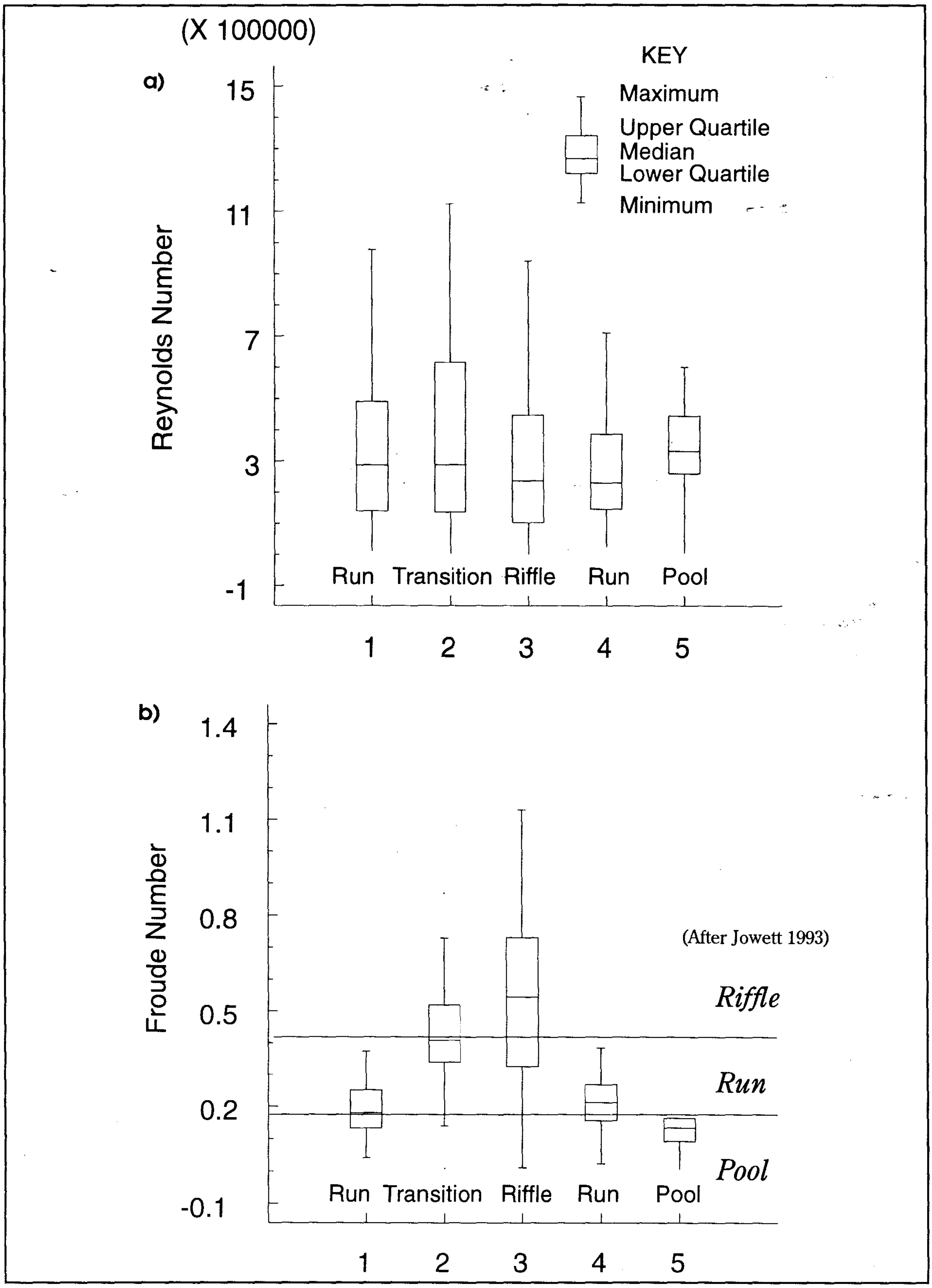


Figure 4.3 Box plot showing the variability of Reynolds number (a.) and Froude numbers (b.) when discharges are combined for individual hydraulic biotopes.

Disaggregated discharge data

At the second level of analysis, the data sets were separated by hydraulic biotope and discharge in order to examine temporal changes of the hydraulic indices and hence to see whether or not the hydraulic biotope classification for a transect changed.

An examination of the box plot for Reynolds number against discharge at each hydraulic biotope class (Figure 4.4a) shows that there is considerable overlap of data between the various classes and between the various discharges. At the highest discharges, sites are easily distinguished even though variability is high within each. One consistent pattern of the data distribution is a progressive decline in the range of values for Reynolds number as discharge decreases at each site. In other words there are degrees of turbulence which may be important for the classification of hydraulic biotopes.

An examination of the box plot for Froude values against discharge at each hydraulic biotope class (Figure 4.4b) shows that although there is some overlap of Froude values across both discharge and hydraulic biotopes, there is a much clearer pattern of distribution than there is for Reynolds number. The quartile ranges tend to overlap within the various hydraulic biotope classes at different discharges, but less frequently across the hydraulic biotopes. As with Reynolds number there appears to be a clear pattern of declining variability with decreasing discharge for all classes except riffles.

If we again compare the classificatory values from Jowett (1993) as marked on Figure 4.4b, we can make some interesting observations. Looking at median values, riffles consistently classify according to New Zealand results; that is riffles do not seem to change their characteristics of mean flow (Froude number) as discharge changes. At the lowest flow however, there is an increase in run type cells within the riffle. The median values for the first run suggest that it may have been mis-classified at medium flow, when according to Jowett's criteria it is a pool. Transition areas appear to be well classified at higher flows, but become runs as discharge decreases. The idea that a hydraulic biotope class will change with discharge is consistent with ecological thinking but, as the results here suggest, the relationships may be quite complex.

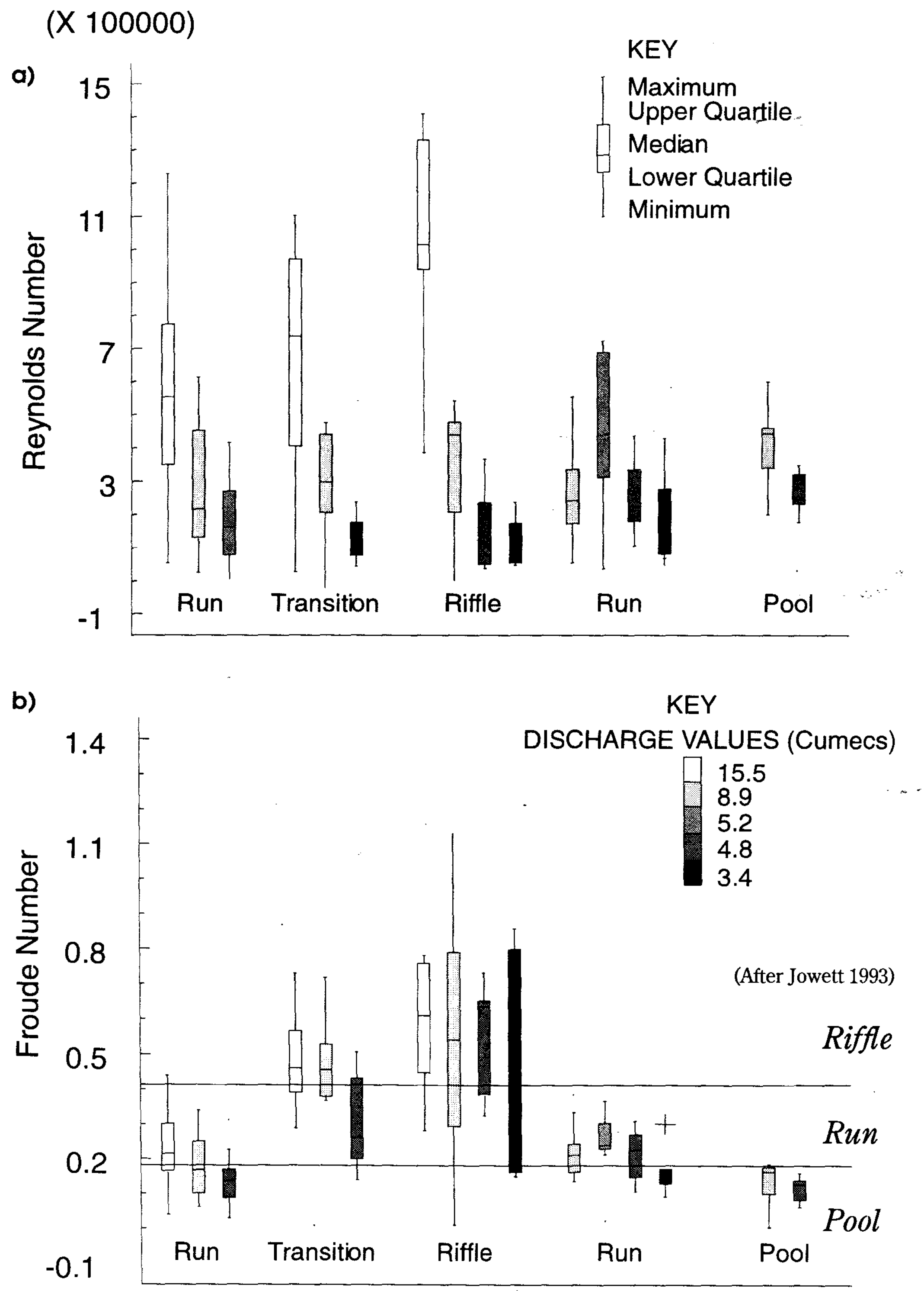


Figure 4.4 Box plot showing the variability of Reynolds number (a.) and Froude numbers (b.) across hydraulic biotopes and at different discharges within hydraulic biotopes.

4.2.6 Discussion

The results of this limited study indicate that the Reynolds number of mean flow, on its own, is of little value for the quantitative classification of hydraulic biotopes. The Reynolds number may, however, remain a useful indicator of flow characteristics for a given hydraulic biotope class. Of note was the declining variability of flow turbulence for all hydraulic biotopes as discharge decreased, indicating that the hydraulic environment became more spatially uniform as flow diminished. Pool environments had a lower variability than any other hydraulic biotope class at the same discharge, confirming the point made by Hynes (1970) who suggested that the hydraulic consistency within a pool makes it a relatively poor environment in terms of species variety.

As shown previously by Jowett (1993) for New Zealand streams and confirmed in this paper, the Froude number is a good discriminator of hydraulic biotopes identified from their visual characteristics. Comparison of median Froude numbers with Jowett's discriminators helped to highlight the change in the hydraulic biotope classification as discharge varied at each site.

As with the Reynolds number, within site variability of Froude numbers was again seen to be an important characteristic of the hydraulic biotopes. Riffles have a high variability, which does not appear to be discharge related, whereas runs and pools have a much lower variability which decreases further at low discharges. The maintenance of a high variability in the riffle class can be related to the low ratio of depth to bed roughness, which increases further as discharge decreases.

The good agreement found between the results from New Zealand rivers and the Great Fish River in South Africa supports the use of the Froude number as a classificatory tool for the definition and categorisation of hydraulic biotope classes. There is obviously considerable scope for further research into the temporal and spatial variability of hydraulic biotope characteristics. Firstly, the research needs to be extended to include the range of hydraulic biotope classes described above for both alluvial and bedrock channels. Secondly, if hydraulic biotopes are to be equated to meso-scale morphological units as proposed by this author, the within hydraulic biotope variability in terms of the range of cell by cell micro-habitats needs to be addressed. Hydraulic biotopes should be classified in terms of both median values and variability so as to incorporate Hynes' (1970) contention that the greater the variability in the flow hydraulics, the richer the hydraulic biotope is likely to be in terms of the stream benthos.

Findings from the exploratory research carried out here indicate that the scale of the hydraulic biotope is considerably smaller than the morphological unit. This points to a need for a cell by cell classification of hydraulic biotopes rather than a general classification of transects. Research findings also indicate that at a point hydraulic biotope classification is likely to change in response to discharge, this needs to be accounted for by a re-classification of hydraulic biotopes at each new flow condition.

If we are to continue to assume that the hydraulic biotope has ecological significance in terms of biotic distribution, we need to consider the potential associations between hydraulic biotopes and the near bed flow conditions.

The results presented in this study indicate that the ambiguity that exists in the classification of fluvial features, particularly within lotic ecology, can be overcome by the use of some simple mathematical indices such as the Froude number. If hydraulic biotopes can be defined in terms of both hydraulic and geomorphological variables, the ability for ecologists to predict long term change in stream environments should be greatly enhanced.

4.2.7 Ecological links

This research suggests that the most important link between the hydraulic biotopes recognised by lotic ecologists and the morphological unit recognised by fluvial geomorphologists is the hydraulics of flow. A study carried out by O'Keeffe and De Moore (1988) compared the ecological conditions in the Great Fish River, pre- and post- inter basin transfer. These authors discovered substantial differences in the invertebrate communities of riffles as a result of water transfer with only 33% of the identified taxa being common to both pre- and post- transfer surveys. The authors suggested that changes in invertebrate species can be attributed to more permanent flow and increased erosional habitat.

The results of the preliminary research outlined in this study indicate that the change in the discharge regime may create a more variable hydraulic environment and therefore an increased diversity of available hydraulic biotope classes. It would seem possible that the invertebrate response to changes in the flow conditions are more specifically a result of changes in the available hydraulic biotopes.

An interesting observation of O'Keeffe and De Moore (1988) is the specific response of invertebrates that reside in morphological riffles. The response of these aquatic organisms indicate how these morphological units form a vital component of the lotic environment, and how riffles represent weak ecological links in river systems. This can be explained by the fact that riffles represent topographical high points within the long profile of the channel bed and are therefore extremely susceptible to changes in discharge.

4.3 THE OLIFANTS RIVER, WESTERN CAPE, SOUTH AFRICA[2]

4.3.1 Introduction

The Olifants River in the Western Cape is presently regulated by two major impoundments which store water for use in extensive irrigation schemes in the semi-arid lower catchment (Figure 4.5). The Clanwilliam Dam acts as a holding reservoir for the lower Bulshoek Dam from which irrigation releases are made. Abstractions upstream from the Clanwilliam Dam could in future be met by releases from a planned impoundment in the upper catchment. Proposals have been made to manage flows below Clanwilliam Dam to encourage spawning of the endemic Clanwilliam yellowfish (*Barbus capensis*) which is under threat from alien fish predation (Skelton, 1977).

Present and future flow regulations in the Olifants River impact directly on the discharge regime in the downstream channel. Coincidental with changes in flow discharge are changes in flow characteristics associated with aquatic habitats: flow depth, wetted perimeter and velocity (Statzner *et al.*, 1988). Related changes in flow competence impact on bed mobility and sediment transport (Richards,1982). Whilst discharge changes are experienced more or less uniformly over considerable lengths of the channel, the impact on flow characteristics will vary locally depending on the channel characteristics, the form of the channel cross-section and perimeter resistance.

Hydraulic biotopes recognised in gravel bed channels such as the Great Fish River include pools, runs and riffles. In these channels the perimeter remains relatively stable except during infrequent high magnitude discharges, whereas in sand bed channels, the characteristic substratum of the Olifants River downstream of Clanwilliam Dam, 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.

During December 1993, a series of experimental releases from Clanwilliam Dam 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. The results of this study have management implications not only for the Olifants River, but also for other sand bed rivers.

[2] This is an abridged version of a paper submitted for publication by Rowntree and Wadeson (1995b).

4.3.2 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.

4.3.3 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. 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). Morand (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 hydraulic biotopes as shown in Figure 4.6. 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.

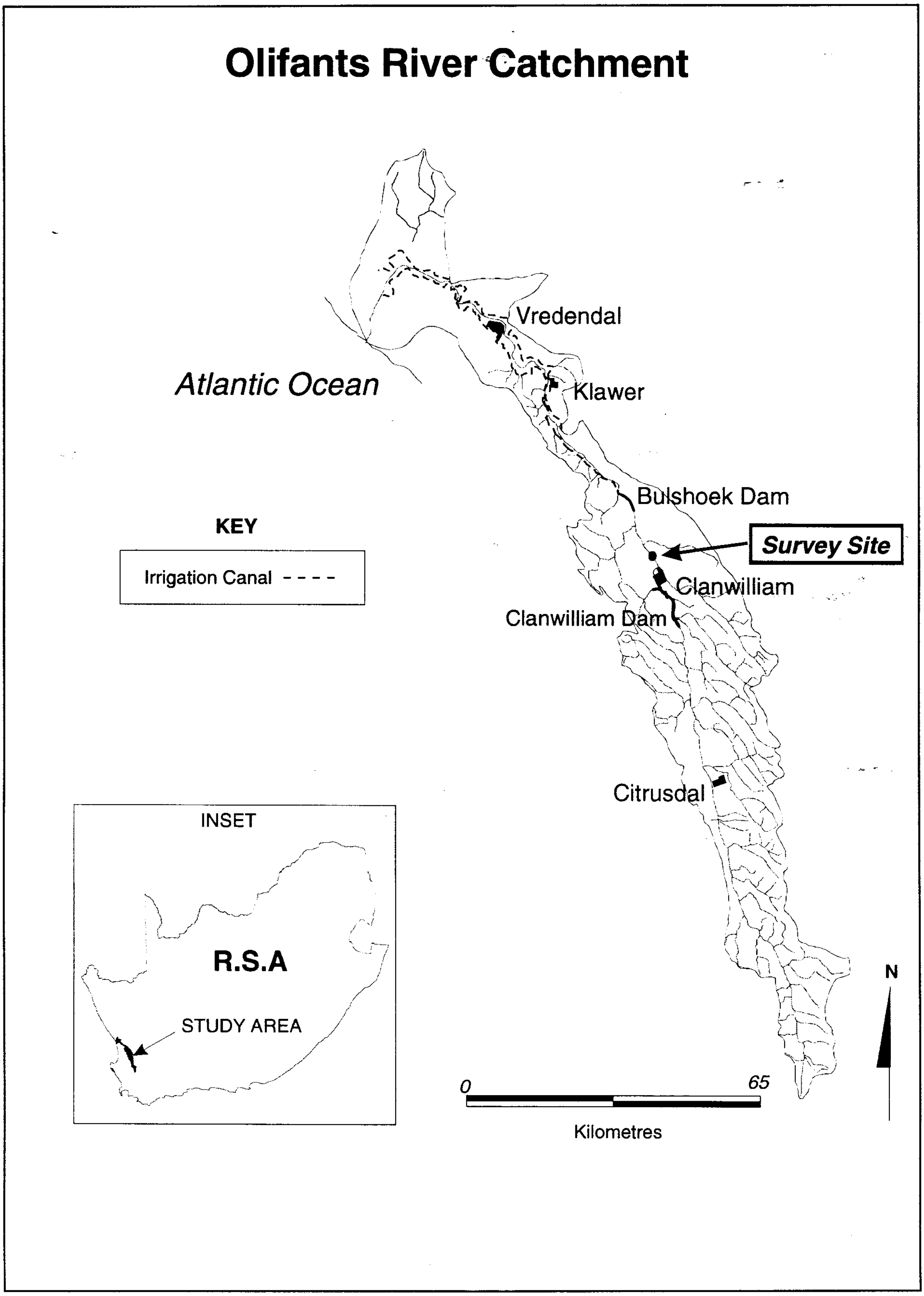


Figure 4.5 The Olifants River Catchment showing the location of the survey site below Clanwilliam Dam

4.3.4 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 4.6. 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.

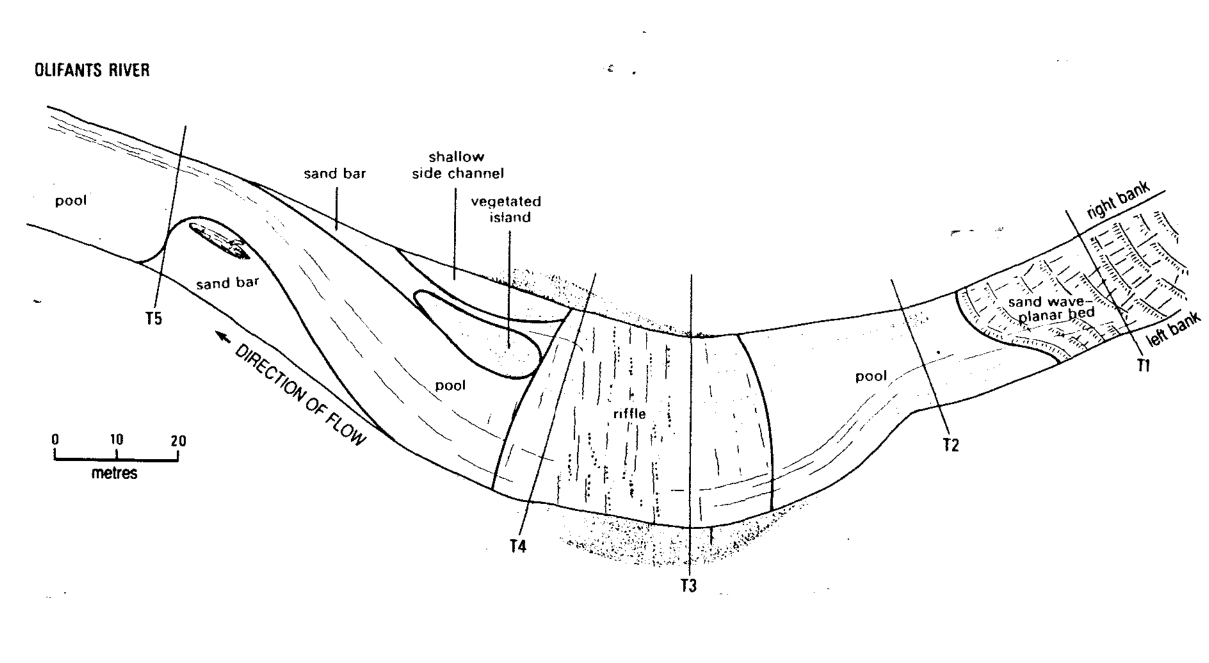


Figure 4.6 Plan view of Olifant River study site

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 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 4.4.

Table 4.4 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 Planar bed	5.16	8.35	10.88	9.73
2 Pool	5.16	8.10	10.71	10.06
3 Riffle	5.16	8.02	10.71	10.39
4 Riffle	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 2.1. 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 4.7 and 4.11 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 4.8).

Changes in width, mean depth and mean velocity with discharge were analysed using hydraulic geometry diagrams (Figure 4.9). Trend lines were drawn in by eye. Equivalent plots for mean hydraulic characteristics are given in Figure 4.10 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 4.12.

4.3.5 Results

The study site can be subdivided into three broad morphological units as indicated on Figure 4.6 - riffle, pool and planar bed. 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 4.7. The two pools (Transects 5 and 2) and the sand wave/planar bed (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.

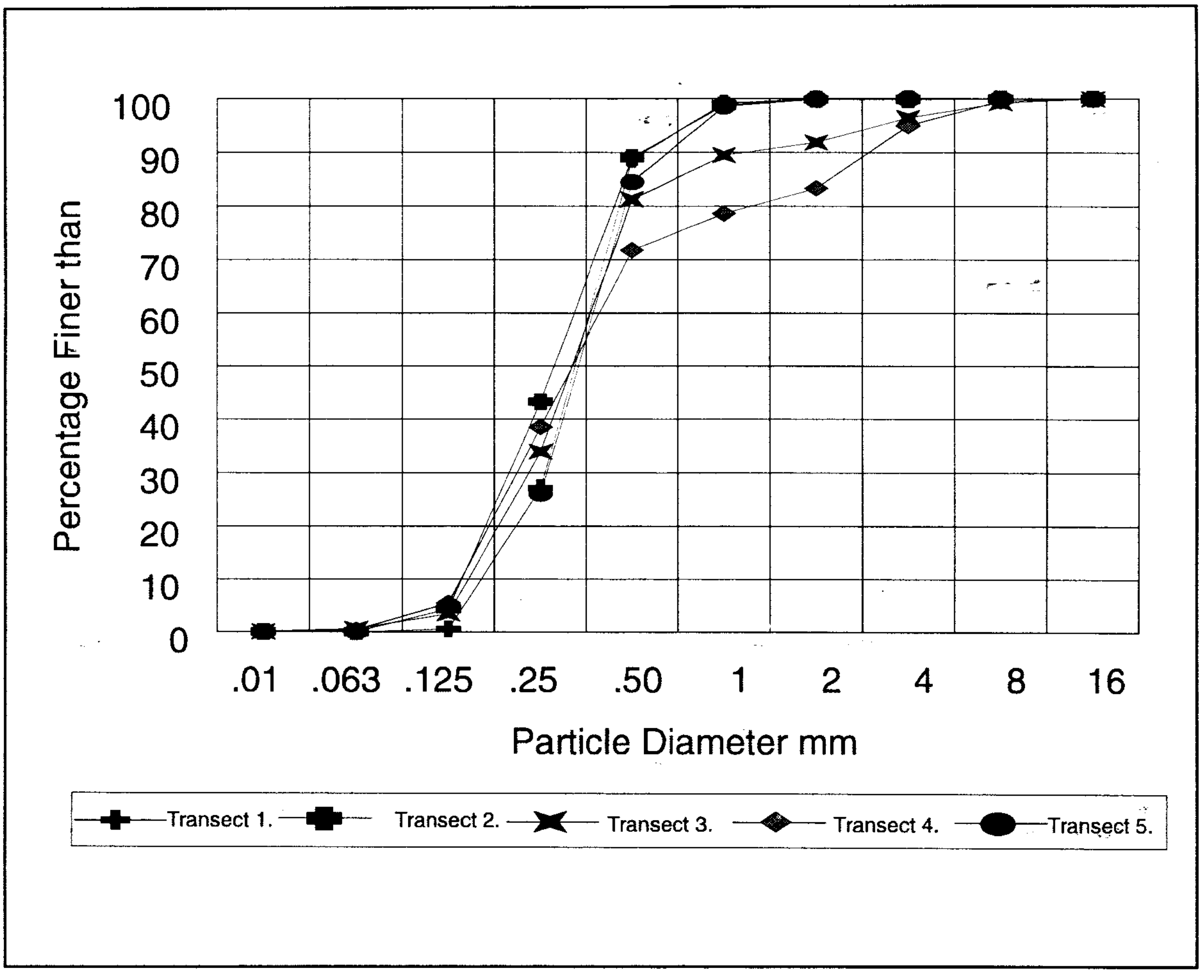


Figure 4.7 Particle size distribution of bed material at the five transects

Channel adjustment to discharge

Transect 1. Planar bed.

Figure 4.8a 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 4.8b). 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 4.8c 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.

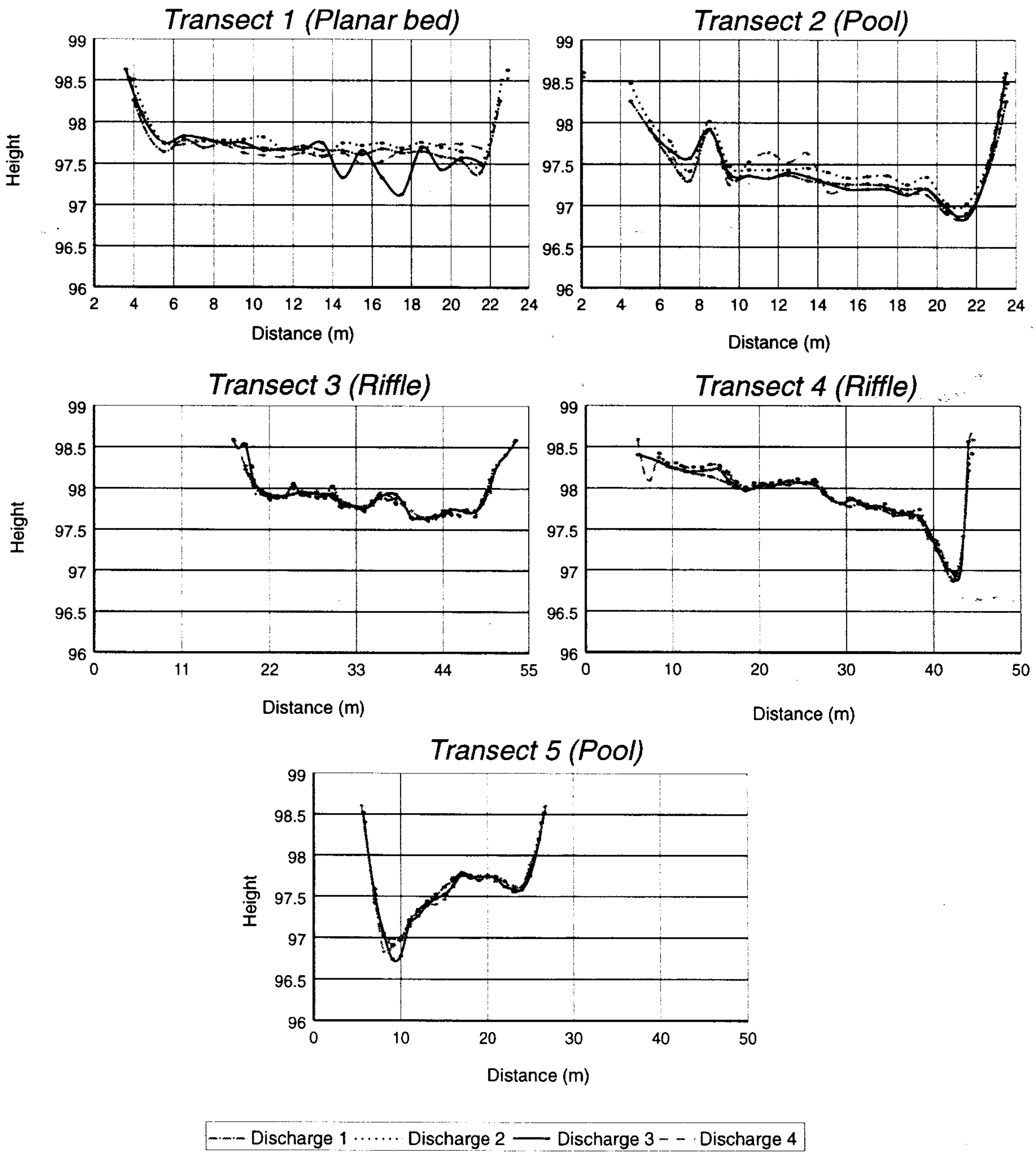


Figure 4.8 Changes with channel cross section with changes in discharge

Flow adjustment to discharge (hydraulic geometry)

Hydraulic geometry describes the adjustment of the flow variables width, depth and velocity to changes in discharge. Figure 4.9 shows the hydraulic geometry for the five transects surveyed in the Olifants river.

Transect 1. Planar bed.
From Figure 4.9a 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 velocity was the greater. There was a small but perceptible increase in width.

Transect 3 & 4. Riffle.
It can be seen from Figure 4.9d (Transect 4) that adjustment to an increasing discharge over the riffle 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 riffle showed a response transitional between the riffle 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.

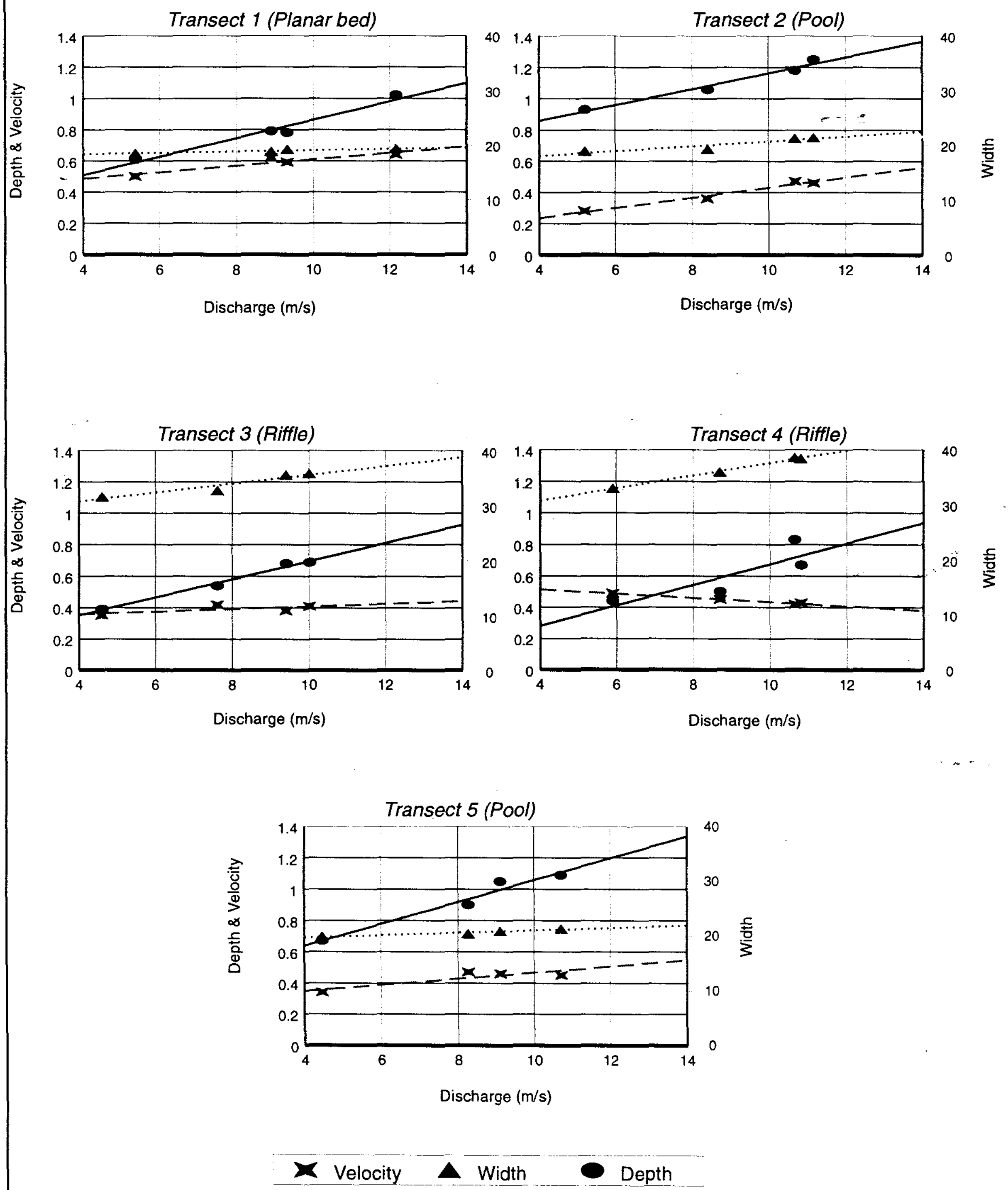


Figure 4.9 Hydraulic geometry, showing changes in width, depth and velocity with discharge

Flow hydraulics and sediment transport

Variation in hydraulic variables and sediment transport are illustrated in Figure 4.10. The variation in the particle size distribution of the material transported as bed load can be seen from Figure 4.11. 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 planar bed/sand wave. Over the riffle, Froude numbers decreased. This decrease was particularly pronounced at Transect 4 and is related to the reduction in velocity with discharge.

Transect 1. Planar bed.

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 4.11a) 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 4.10b and 4.10e. From Figure 4.11b and 4.11e 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. Riffle.

Sediment transport rates over the riffle remained low through all discharges. This site had a high stability and few changes were observed over the range of discharges experienced. The two riffle 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 into the riffle where it formed small dune features over the armoured surface.

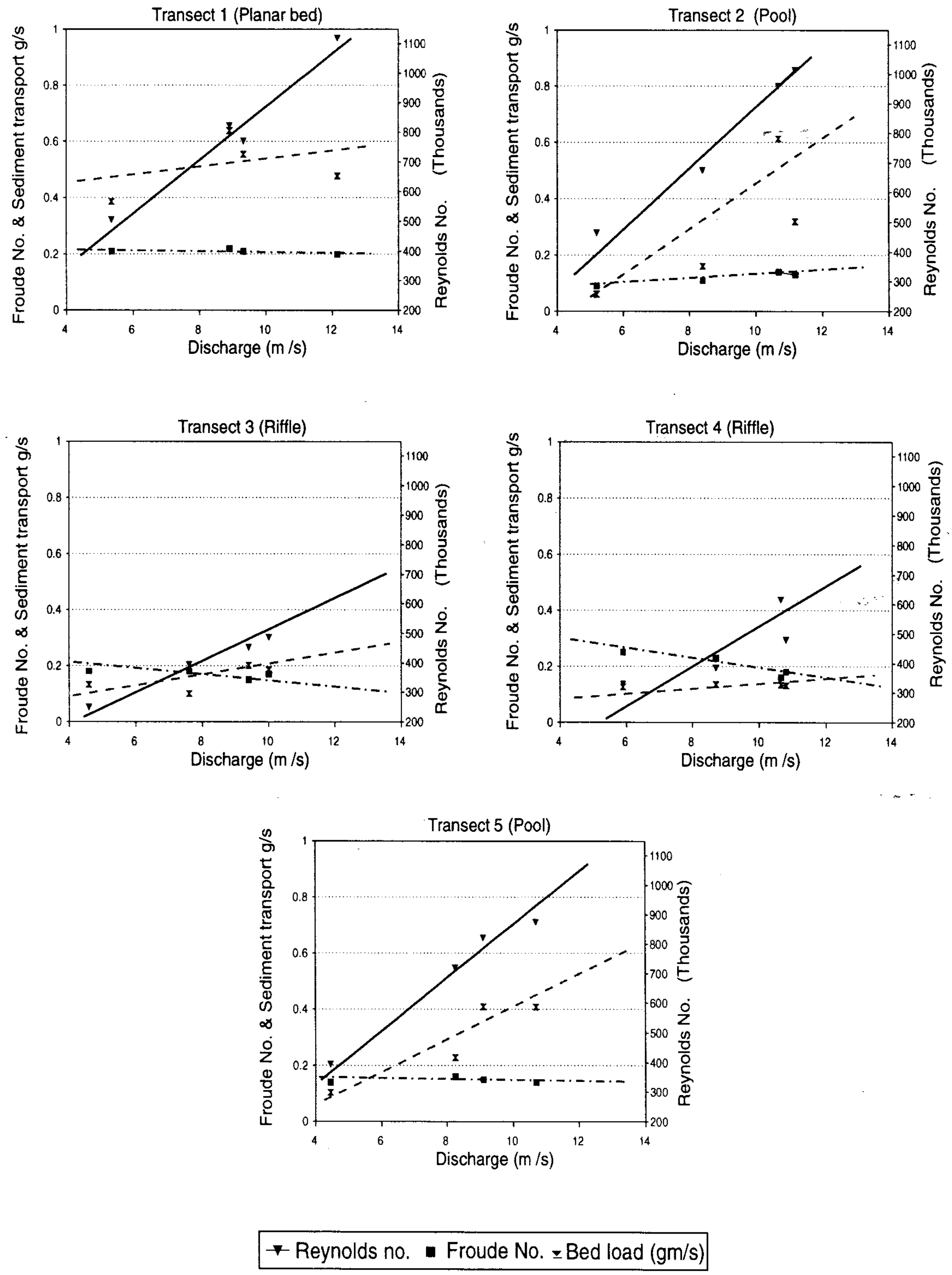


Figure 4.10 Changes in hydraulic indices and bedload transport with discharge

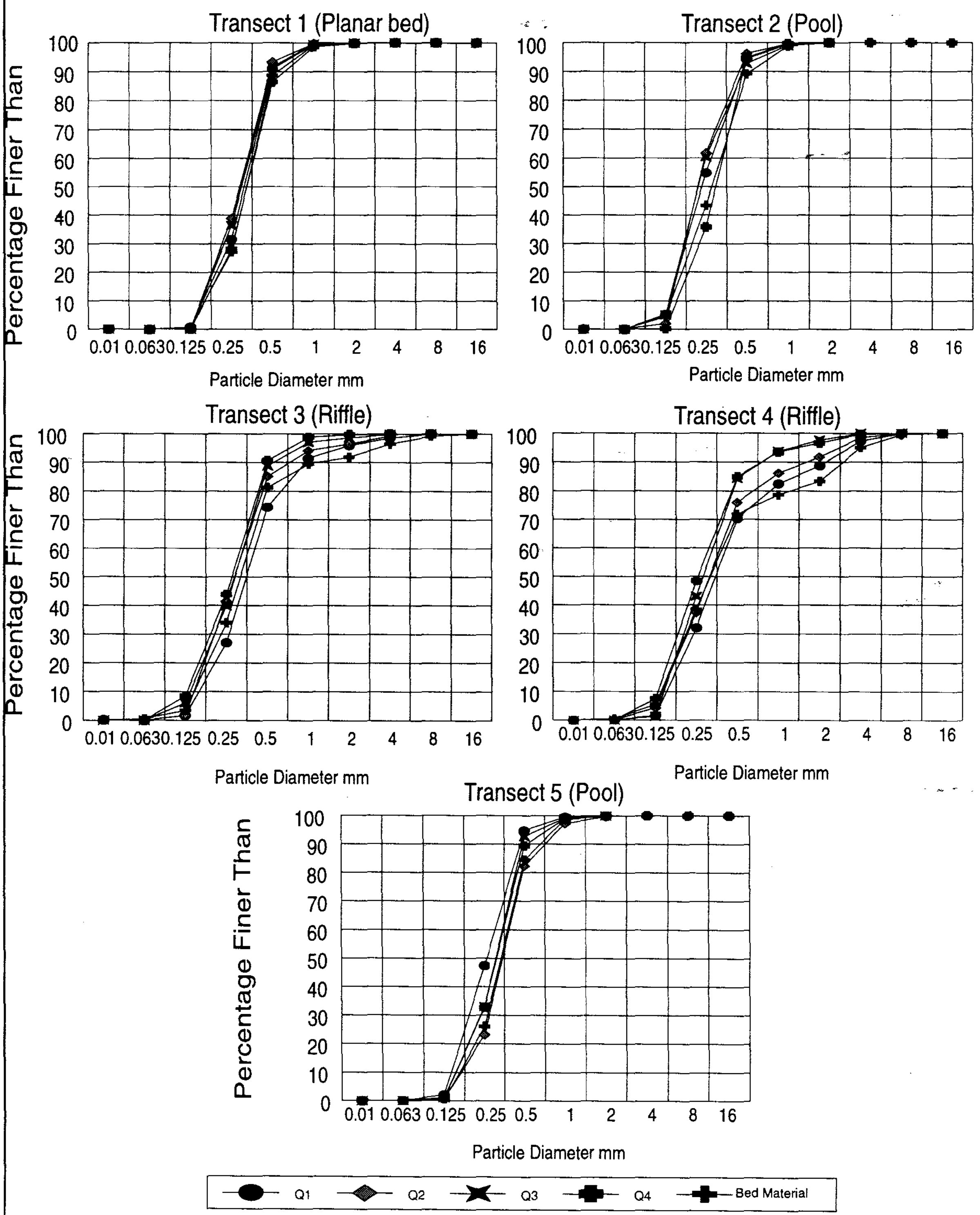


Figure 4.11 Particle size distribution of the bedload

The relationship between sediment transport rate and flow discharge is both site dependent and temporarily dynamic. The riffle 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 4.5. 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.

Table 4.5 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		

Hydraulic biotope classification

Transect 1. Planar bed.

Field classification of hydraulic biotopes placed 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 4.12. 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. Riffle.

Although the morphological unit at Transect 3 was classified as a riffle, 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 4.12 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.

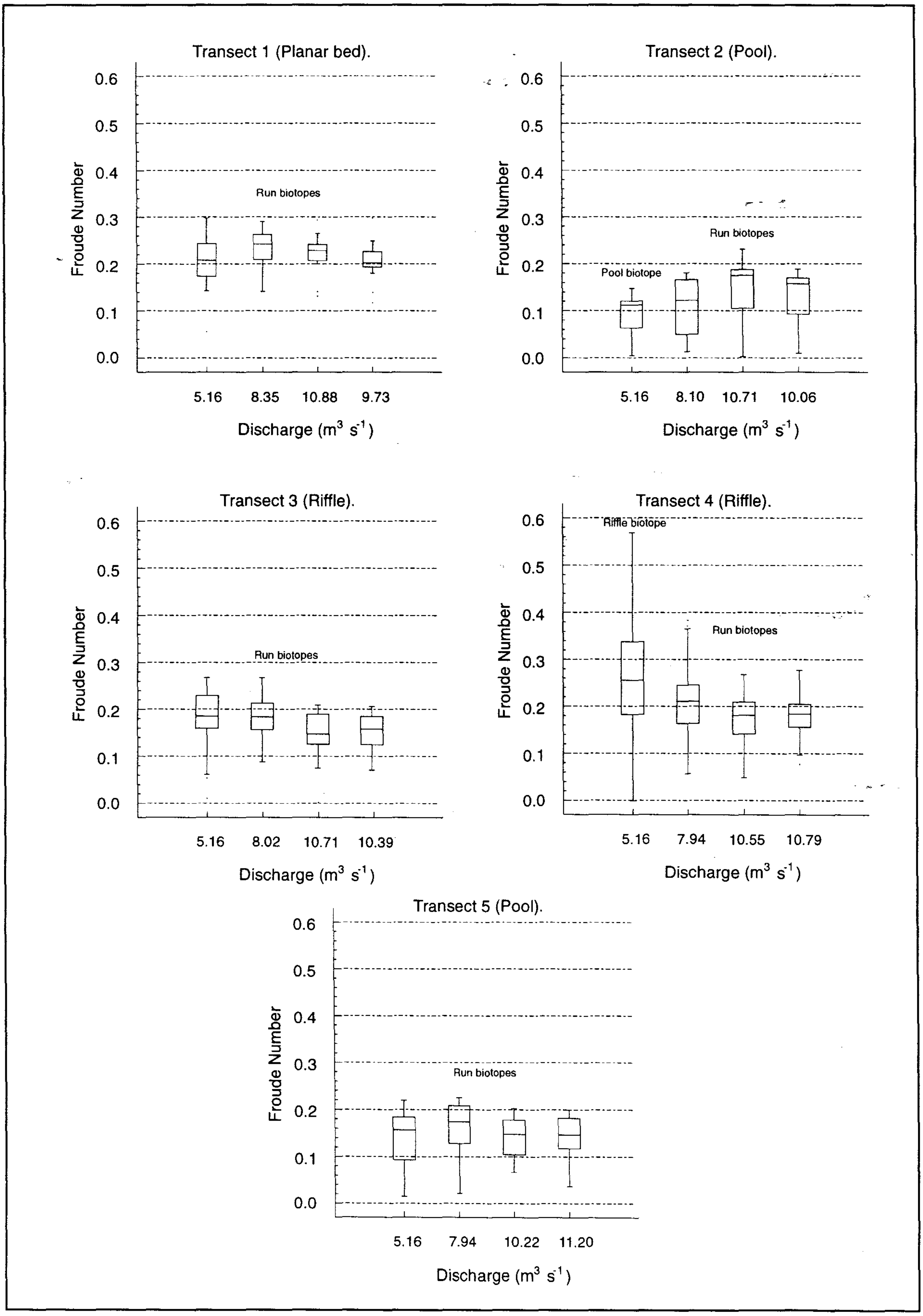


Figure 4.12 Hydraulic biotope classification based on cell Froude number

4.3.6 Discussion

Hydraulic biotopes were defined earlier as spatially distinct in-stream flow environment 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: planar bed, pool and riffle.

Transect 1 - planar bed

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 - Riffle

Increased flow over the riffles 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 riffle 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. Riffles 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 riffles 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.

4.3.7 Conclusion

The Olifants study was initiated to carry out further research into the development of the hydraulic biotope concept. This study allowed an assesment 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 riffle is consistent with findings elsewhere (Wadeson 1994, 1995). 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, riffles the least. Riffles tended to loose 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 riffles 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.

Given the changes described above, flow regulation within the range of discharges studied is likely to have a serious impact on aquatic life, impacts that would be compounded by any further discharge increases. An assessment of the nature of these impacts is beyond the scope of this paper and would require an in-depth ecological assessment. It can be concluded, however, that an assessment of the impacts of flow releases, be they for irrigation or yellow fish spawning, must take into account the associated changes in hydraulic biotope characteristics and relate these to the flow requirements of the different stages of the life cycles of downstream biota.

There is a limited understanding in South Africa as to how sand bed channels respond to changing flow environments, sediment inputs and so on. 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.

4.4 THE MOLENAARS RIVER, WESTERN CAPE, SOUTH AFRICA.

4.4.1 Introduction

A criticism of the use of hydraulic indices describing mean flow is that there is no consideration given to the micro flow environment in which many of the aquatic communities live, either on or near the channel bed. In addition there is little understanding as to how the mean and micro flow environments can be related to one another and what these relationships might mean for the biota. A review of hydraulic literature (Chapter Three) indicates that exploratory investigations into the micro-flow characteristics of the hydraulic biotope concept need to be quite selective because of intense data requirements and corresponding time constraints.

An opportunity was presented in October 1993 to carry out a relatively detailed study of the hydraulic biotope characteristics of selected reaches of the Molenaars River in the Western Cape, South Africa. This study provided an opportunity to focus on the spatial variation of hydraulic biotopes across reaches. Furthermore this study provided a useful opportunity not only to test the concepts already developed in the Great Fish River and Olifants River, but also to design a research framework to address the problems of micro flow hydraulics within the hydraulic biotope concept.

4.4.2 Aims

The specific aims of this research were:

- To ascertain whether the hydraulic biotopes found within four separate reaches could be characterised using selected hydraulic indices describing the mean and near bed flow environments.

- To determine the degree of homogeneity of hydraulic variables used to characterise hydraulic biotopes in four separate geomorphological reaches.

- To analyse the findings of a detailed sampling programme so as to obtain guidelines for similar research involving the collection of detailed hydraulic data.

4.4.3 The study area

The catchment of the Molenaars River is situated some 60 km north east of Cape Town in the winter rainfall region of the Western Cape (Figure 4.13). The river rises in the Du Toits Kloof area east of Paarl and is relatively short and steep, flowing within a laterally confined valley. As the river flows eastwards it combines with the tributaries of the Elands river, immediately below the Huguenot tunnel, and somewhat later the Tierstel river. The Molenaars River eventually becomes the Bree River, with which it has its confluence near the town of Worcester. The local relief consists of mountainous terrain geologically dominated by Table mountain sandstones, very similar to that found in the Olifants catchment.

In October 1993 a detailed survey of selected upper reaches of the Molenaars River was carried out as a co-operative research effort with members of the University of Cape Town's Fresh Water Research Unit (Dr Jackie King, Ms Rebecca Tharme and Ms Geordie Ratcliffe). The upper reaches of the river are of particular ecological significance because of a high biotic diversity, and of geomorphological significance because of diverse channel morphology. These may both be under threat due to the proximity of the N2 motorway (Johannesberg - Cape Town). This motorway is at present being upgraded to a dual lane highway and so there is a high potential for environmental degradation.

Following the completion of a desk study reach analysis, four research sites were selected along the Molenaars River between the Elands River and Tierstel River confluences. Each site was considered to be in a separate geomorphological reach, consisting of different channel gradients and likely to have different associated patterns of morphological units.

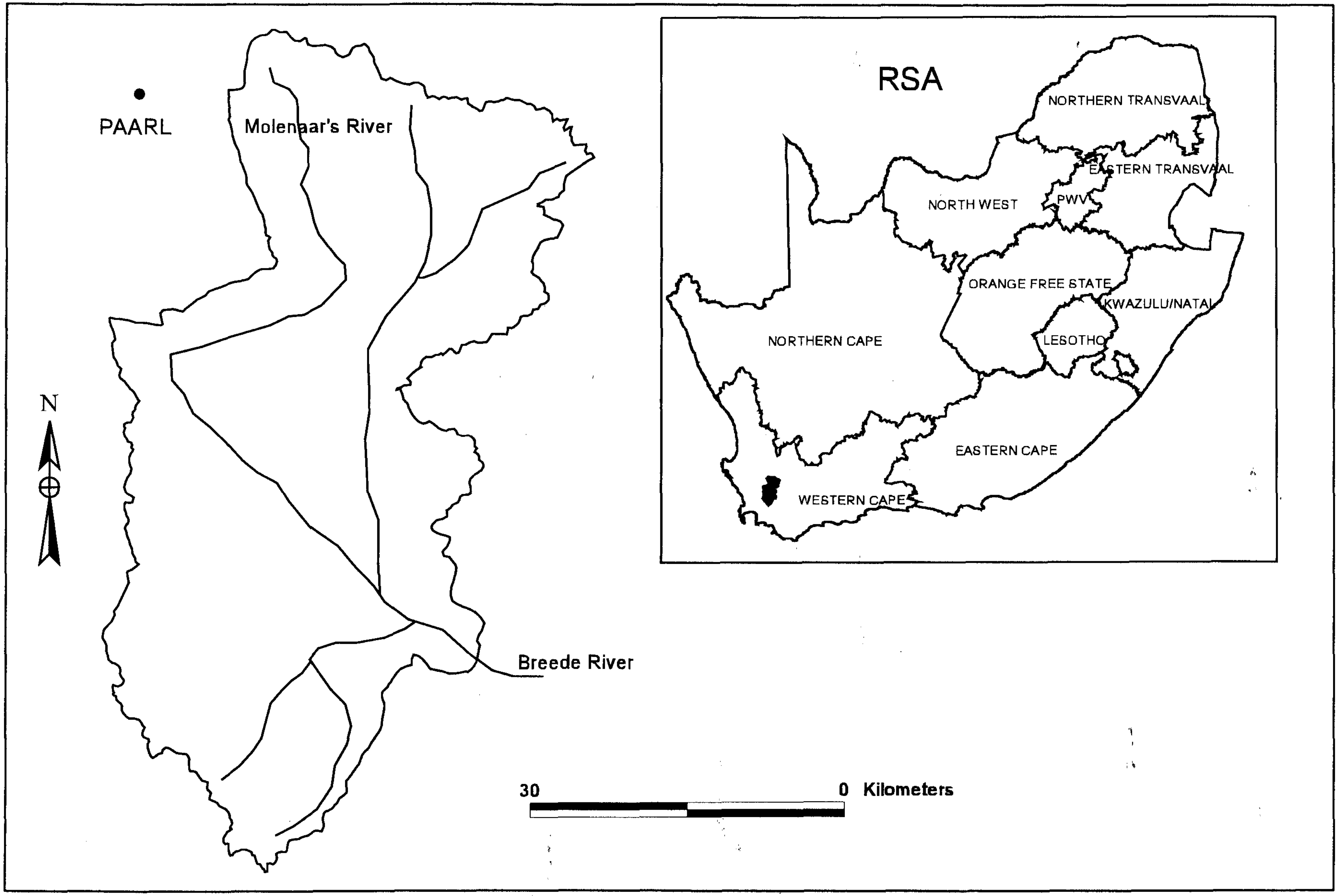


Figure 4.13 The Molenaars River Catchment

4.4.4 Methods

Reach Analysis

As defined in section 1.3.3, a reach is recognised as 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 types occur. The method used to demarcate reach boundaries is outlined in Appendix Three.

There are a number of limitations to this aspect of the research. These include a high degree of subjectivity in data collection. The field catalogue (Appendix Two) assumes a fairly broad understanding of geomorphological concepts. The overriding consideration in the choice of sites for data collection tends to be ease of access, this generally means that the point of access are locally disturbed and therefore atypical of the reach. To overcome this problem surveys are completed at least 100m upstream of the access points.

The area of interest within the Molenaars River is a fourteen kilometre stretch extending from the Huguenot tunnel to the first road bridge crossing the river along the existing highway; using the reach analysis outlined in Appendix Three, it was determined that the river could be divided into four geomorphological reaches (Figure 4.14). It was assumed that the selection of a sampling site within each reach would provide a diverse geomorphological, and associated hydraulic/ecological, environment.

The demarcation of reaches using the above technique was checked against 1:6000 aerial photographs which had been further enlarged and mapped at a scale of 1:1700.

Site Selection

A specific sites was selected within each reach based on the following criteria:

- It had to be representative in terms of general channel morphology, riparian vegetation, channel pattern etc.
- It needed to be easily accesible for the transportation of survey and flow equipment to the site.
- It needed to be relatively undisturbed in terms of bridges, weirs, canals etc.

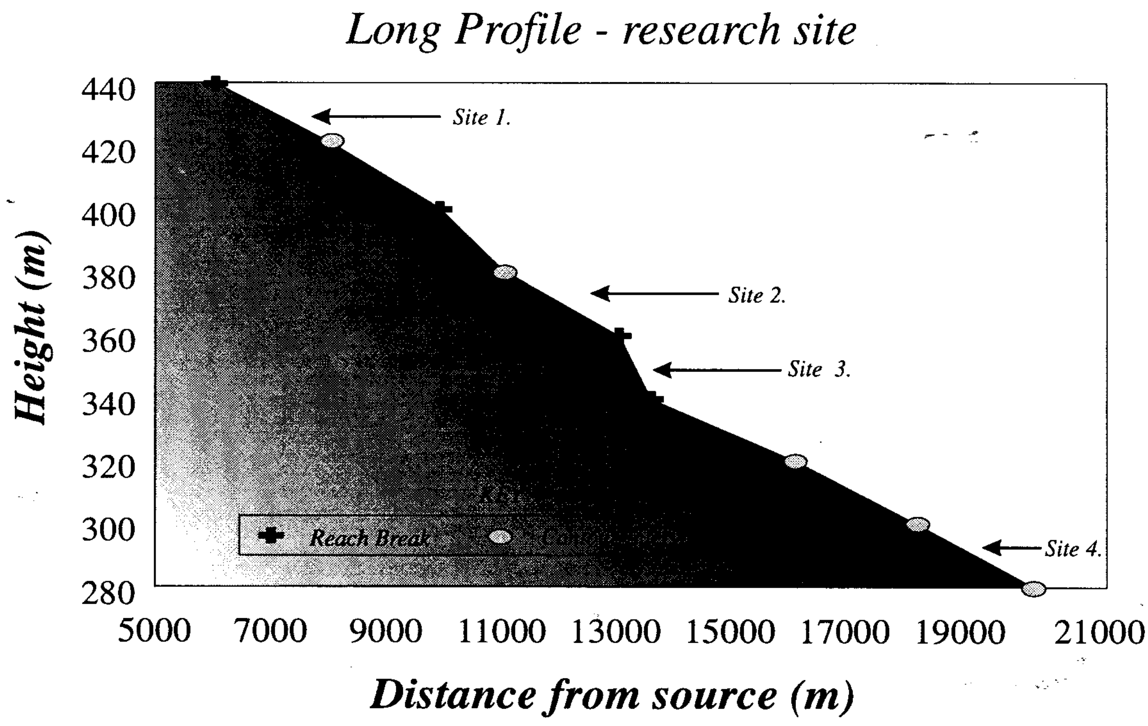


Figure 4.14 Long Profile of research area in the Molenaars River.

Data collection

At each site a reach analysis was carried out using the form in Appendix Two. A detailed plan survey was also carried out at each site using a Kartii plotting table with theodolite.

In order to carry out a detailed survey of these reaches each site was divided into 11 cross sections perpendicular to the active channel at approximately 10 metre intervals. Each cross section was divided into a number of 2.5 metre cells, the start and end of which represented sampling points within the channel. Average channel width was 23 metres and therefore a total of 404 sampling sites were selected for detailed data collection within 4 separate reaches.

Data collected at each sampling site included water depth, water velocity at 0.6 depth from the surface and in some cases 0.2 and 0.4 depth. A description was made of substratum type using a revised version of the Wentworth scale (Table 2.4). An estimation of percentage cover of substratum within a 0.5m^2 grid was carried out. The *b* axis length of each clast found within the 0.5m grid was measured. The embededness of the substratum was subjectively assesed and a classification of the morphological unit and hydraulic biotope class made.

Hydraulic biotopes were intuitively classified in the field using the concepts and ideas which are formalised in Figure 2.1. The following hydraulic biotope classes were recognised; pools, backwater pools, runs, riffles, chutes and cascades.

Data analysis

A subjective analysis of reach forms was carried out to ascertain the spatial variability of channel morphology, this allowed for a general description of the geomorphological characteristics of the reaches and provided a broad physical framework within which hydraulic biotopes could be nested. Hydraulic biotopes were characterised using Froude numbers, Reynolds numbers and 'roughness' Reynolds numbers, calculated from the point velocity, depth and the median *b* axis values of substratum data. The spatial variation of data values for both combined and separate reaches was portrayed using box and whisker plots .

The relatively large data set for this study (400+ points) allowed for a more rigorous statistical analysis than that carried out in previous research. Variables were tested for normality and where appropriate, were transformed (Table 4.6).

Table 4.6 Descriptive statistics for three variables before and after transformation

	Reynolds No (Re)	Transformed (Re)	Froude No (Fr)	Transformed (Fr)	'roughness' Reynolds No (Re*)	Transformed (Re*)
Mean	83062	4.55	0.15	0.34	17137	3.35
Std Devtn	121609	0.65	0.17	0.18	39293	1.18
Skewness	5.09	-0.73	2.16	0.97	4.60	-0.96
Kurtosis	41.84	0.45	5.22	0.92	25.12	0.53

Univariate analysis of variance (ANOVA) was used to examine the differences in Froude number, Reynolds number and 'roughness' Reynolds number between different hydraulic biotopes. Discriminant analysis was used to determine the variable or group of variables which best distinguished between the different hydraulic biotopes.

Limitations

The presence of five researchers in the field, all with different levels of experience in the recognition of hydraulic biotope classes, produced some error in the identification of different hydraulic biotope classes. One result of this was the tendency for researchers to classify a hydraulic biotope as a run if they were not sure.

The use of *b* axis length is often used as a surrogate for roughness height (Gordon *et al.*, 1992) it is recognised however that this value may not be ideal for the calculation of 'roughness' Reynolds number (Equation 3.9). The value of *b* axis length may not be a good indicator of roughness height because of such aspects as shape, packing, substratum orientation etc.

4.4.5 Results

Geomorphology

Site 1. (most upstream site below the Huguenot Tunnel)

This site was situated in a reach directly below the Elands river confluence and had an average gradient of 0.01. The Elands river is likely to have a significant impact on the Molenaars River due to the relatively large inputs of water and sediment and would probably be considered a segment boundary in terms of the classification hierarchy of Wadeson & Rowntree (1994). The research site is in the upper section of this new reach and is a highly disturbed site which is laterally confined (rather atypical of the reach in general). Downstream the river flows in a relatively wide valley within a well defined floodplain as illustrated in Plate 4.1 and Figure 4.15. The morphological units associated with this reach are typical of an unconfined channel and the reach may be classified as a response reach which has a relatively low gradient which is transport limited, that is there is a tendency for the accumulation of alluvium. The morphological units include bars, pools and riffles. These units tend to be relatively stable even though the material forming the bed may be transported annually. The size of the largest bedload material in this channel is considerably less than the bankful flow depth. Overbank deposits consist of coarse grained sand and appear to be quite considerable. These large sand deposits can be explained by the loss of energy the river would experience in this reach as it flows over a relatively flat gradient in a laterally unconfined valley as opposed to the steep, narrow and confined channel of the upstream reach.

The geology of this site is an important determinant for the demarcation of reach boundaries. The upstream boundary of reach one is defined by the transition of quartzitic sandstone to coarse porphyritic granite. The downstream boundary is a breccia fault across this coarse porphyritic granite.

The reach has an irregular channel pattern with a combination of both point and alternate irregular bars. There are a number of incidences of encroaching vegetation on emergent bars. Substratum consists of a full range of the sediment classes but is dominated by larger material such as cobbles and occasional boulders. The substratum shape is spherical and rounded and compaction is moderate (little overlapping and can be dislodged).

Reach disturbance can be considered as high, the valley consists of both agricultural land and indigenous vegetation interspersed with exotics (particularly *Acacia mearnsii;* Black Wattle). The riparian zone consists of mainly indigenous species but there is considerable intrusion by exotics. Some of the local disturbances include borrow pits, road\bridge building and the bulldozing of flood berms, all immediately below the survey site.

Plate 4.1 Overview of site 1

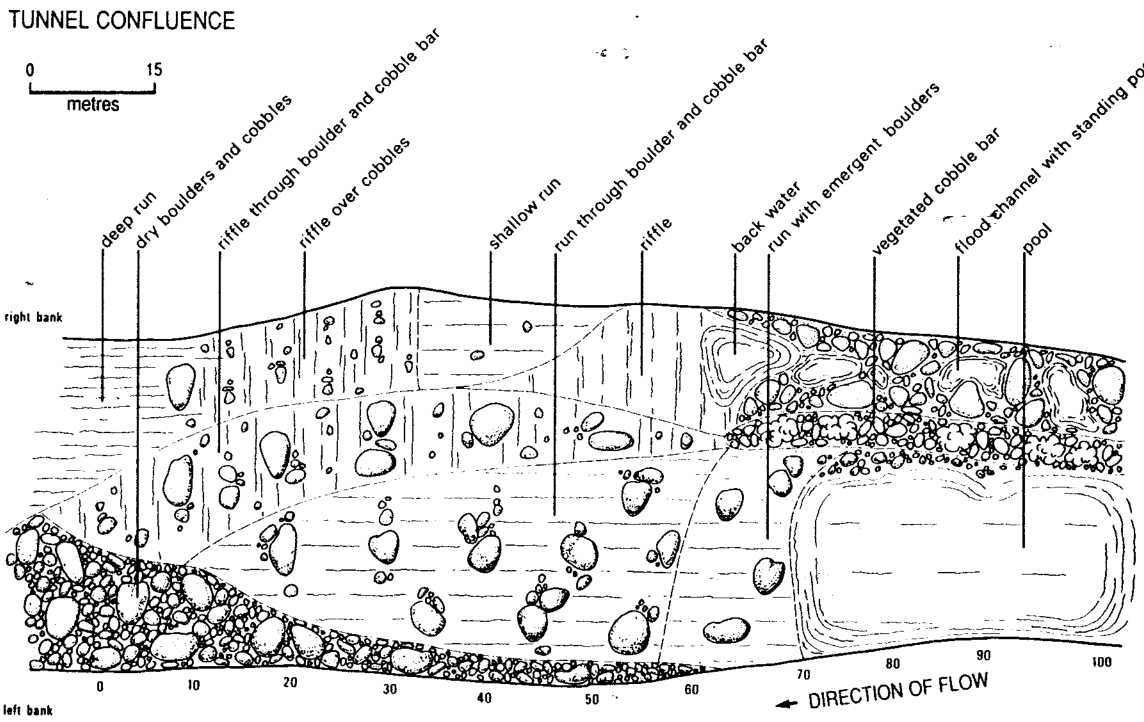


Figure 4.15 Plan view of site 1.

Site 2. (Upstream of Klip river confluence)

This reach extends from the farm Oude Kraal (upstream) to the Klip River confluence and has an average gradient of 0.013. The research site is in the most downstream area of this reach, about 500m upstream of the confluence. This site is on a large meander bend veering to the left, forced by local topography on the right hand bank as illustrated in Plate 4.2 and Figure 4.16. The active channel within this reach is considerably wider than that found upstream and shallower at comparable discharges. At this particular site the channel widens further as a result of the lateral extension of the banks towards the downstream left hand side as the flow is deflected by Leeuklipkop. This lateral extension has caused the formation of a wide cobble bar across the meander bend. The river still flows within a wide unconfined valley, the presence of restraining topography (although only on one bank at this point) indicates the close proximity of the next reach boundary. The floodplain within this reach is well defined with well vegetated terraces. The morphological units associated with this reach are the same as the previous one. Bars, riffles and pools dominate but are considerably larger in areal extent to those found upstream. As with the previous reach, this area can be considered as a low gradient response reach which is transport limited.

The geological boundaries for this reach are a breccia fault within coarse porphyritic granite at the upstream end and another fault on the downstream side which is the transition from coarse porphyritic granite to quartzitic sandstone

This reach has a mildly sinuous pattern which consists of alternate irregular bars. The substratum is dominated by cobbles with the occasional boulder, these are spherical and rounded in shape. At low flow conditions the channel is divided in places by these cobbles which occur as bars. There are local pockets of gravel and sand behind obstructions. Compaction of the substratum is largely dependent on situation -in bars there is a low compaction (little overlap and easily dislodged) whilst riffles tend to have a moderate compaction.

Plate 4.2 Overview of site 2

The reach has a low level of disturbance with the presence of indigenous vegetation on both sides of the river with very few exotics, this applies for both the valley and riparian zone. The good vegetation cover on channel banks together with the moderately compacted beds enhances channel stability. The only other local disturbance here is the very close proximity of the national highway. This is going to have considerable influence on this reach in the future because of retaining walls for channel stability etc.

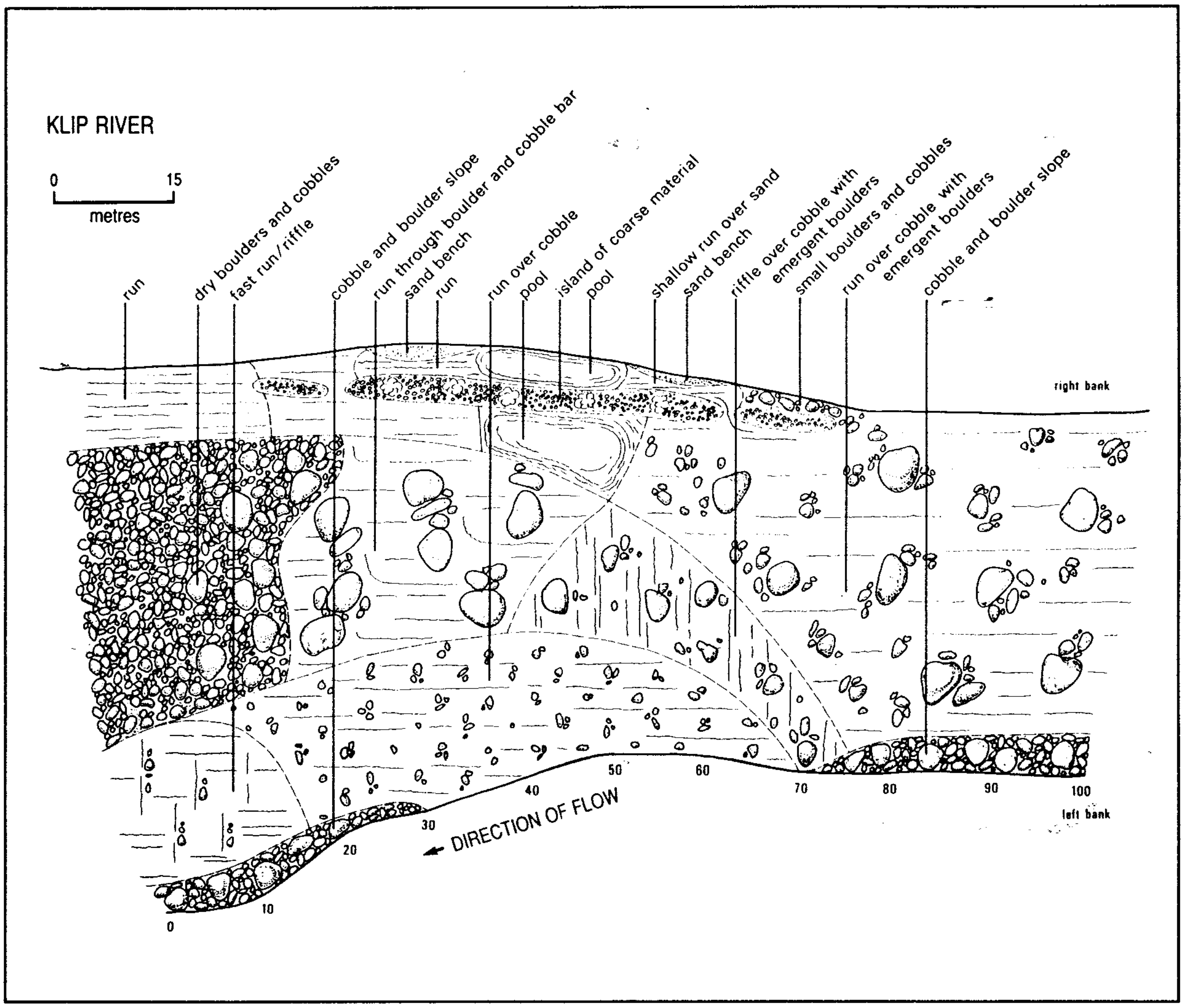


Figure 4.16 Plan view of site 2.

Site 3. (Leeuklipkop)

The third reach is situated immediately downstream of the Klip river confluence with an average gradient of 0.035. This reach is relatively short and steep with close, laterally confined valley side walls (Plate 4.3 and Figure 4.17). The research site is in the upstream area of this reach; its selection was largely determined by accessibility. The lateral confinement means that there is little room for a floodplain, instead there is a very narrow bench consisting of sand deposits. This section of the channel is a transport reach which has a high gradient, is resilient to change and is supply limited in terms of alluvium, that is any sediment arriving in this reach is moved through very quickly. The morphological units associated with this reach can best be described as rapid and cascade. The presence of large particle sizes (and bedrock) relative to flow depth, and the fact that it is a high energy environment in a steep gradient, means that energy dissipation in the flow is dominated by high turbulence and hydraulic jumps around large substratum. It seems likely that the more frequent, larger substratum will not be moved except in extreme events. The intermediate and smaller bedload material will be transported at bankful flows. Sand and finer material will likely be rapidly transported at most flows.

The geological influence on the reach boundaries in this section are the transition from coarse porphyritic granite to quartzitic sandstone at the upstream boundary, and a transition from this to alluvium at the downstream boundary.

This reach is a complex one both in terms of the morphology and the resultant hydraulics. The channel pattern is straight with the presence of a few mid channel bars which have been vegetated. Dominant substratum is boulders, bedrock and large cobbles, these are interspersed with smaller material but still mostly within the cobble size class. Alluvial material tends to be well rounded and spherical in this reach and is moderately compacted. Reach disturbance can be considered as moderate with the most important influence from the national highway and the presence of exotic vegetation.

Plate 4.3 Overview of site 3

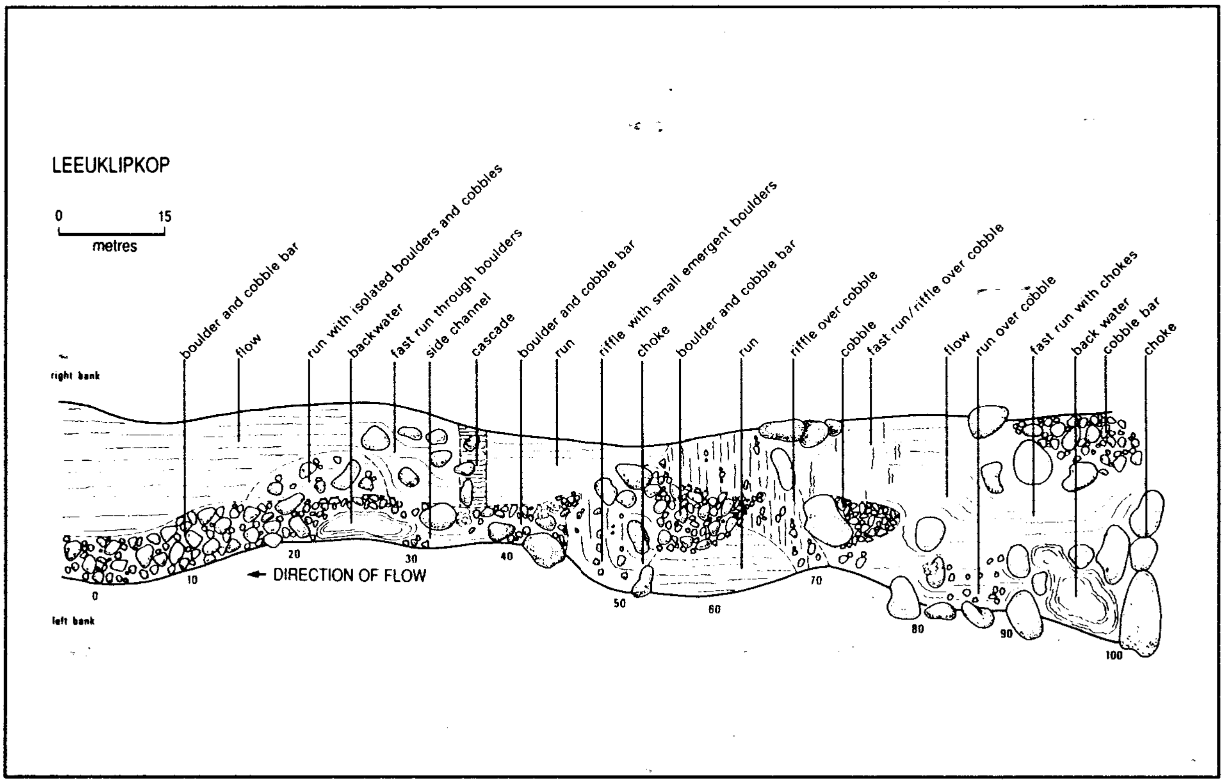


Figure 4.17. Plan view of site 3.

Site 4. (Upstream of N1 road bridge)

This final reach is situated immediately upstream of the present road bridge across the Molenaars River. The research site is approximately 5.5 km from the upstream reach boundary. The reach is characterised by a relatively narrow, deep channel within a wide valley and floodplain and has an average gradient of 0.008 (Plate 4.4 and Figure 4.18). The floodplain is well vegetated with exotics (*Accacia mearnsii*) and has a substratum dominated by cobbles embedded in coarse sand. There are many dry flood channels scoured within these deposits. As with site 1 and 2, the reach is characterised by low gradient, transport limited, morphological units - namely bars, riffles and runs. These units are at a different scale to those in upstream reaches and would appear to demonstrate different hydraulic characteristics. The pools tend to be deeper and larger in areal extent whilst the riffles are better defined, shallow, steeper units. Geologically this reach occurs within alluvium, the upstream boundary being the transition to coarse porphyritic granite.

The channel takes on a mildly sinuous pattern as it flows across a relatively wide floodplain. Bars tend to be irregular, well vegetated (Palmiet) and stable. Substrate sizes incorporate all classes with predominant size being determined by situation. Pools tend to have a layer of fine sand over large cobbles and the occasional boulder. Riffles consist of intermediate to small cobbles interspersed with gravels and sand. Vegetated bars consist mostly of sand and organics. Substrate shape of the larger particles tend to be disc like but well rounded. The shape of the substratum allows for a packed but unarmored bed which incorporates an array of size classes.

The reach can be considered as moderately disturbed with the dominant impact being the presence of exotic trees on one bank. The left hand bank is relatively undisturbed and extremely stable in many areas with dense stands of palmiet. The valley floor is in a similar condition with many exotics in areas but also large stands of indigenous species. Local disturbances must include the close proximity of the highway and the presence of the road bridge within this reach.

Plate 4.4 Overview of site 4

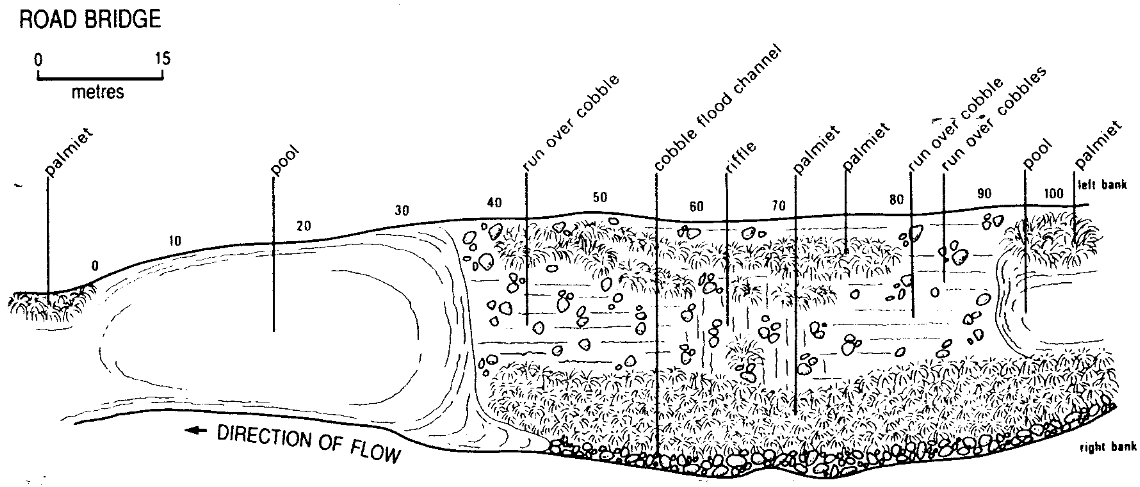


Figure 4.18 Plan view of site 4.

Data Analysis

Aggregate spatial data

The first level of statistical analysis grouped all hydraulic biotope data together, irrespective of situation within different reaches. The aim of this was to determine general patterns of data variability and the potential of hydraulic indices as classificatory values for hydraulic biotope classes.

Box plots

The box plots of figures 4.19a, 4.19b and 4.19c indicate the within and between hydraulic biotope variability of Reynolds number , Froude number and 'roughness' Reynolds number respectively.

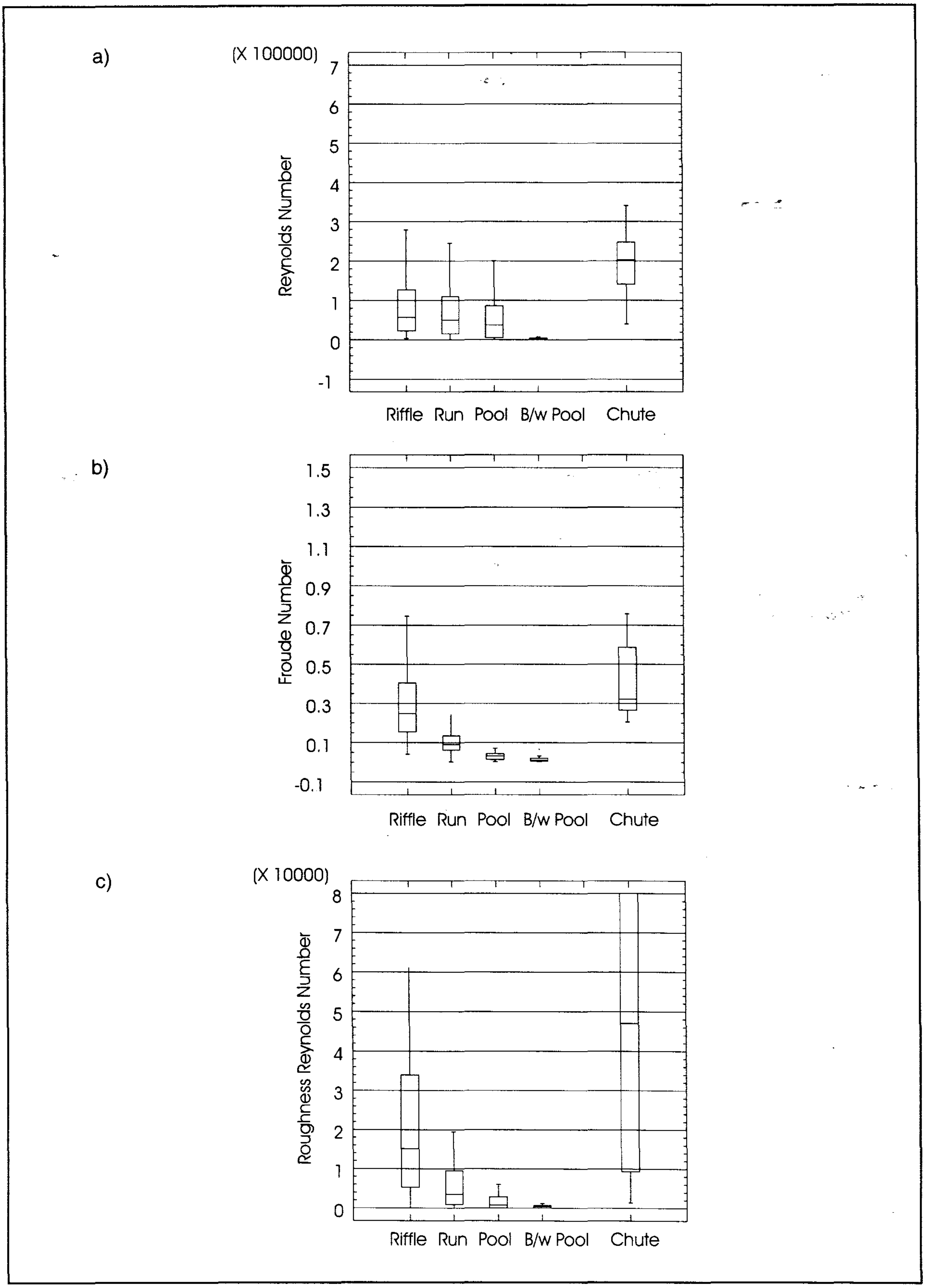


Figure 4.19 Box plots showing hydraulic variability of hydraulic biotope classes when data is combined for all sites.

A visual analysis of the box plots for Reynolds number indicates that the variability shows a progressive decline in the range of values from chute through riffle, run, pool to backwater pool. Cascades are ignored due to insufficient data (only 1 data point). Consistent with previous studies, there is considerable overlap of data between classes, this supports previous findings where the Reynolds number on its own was unlikely to be a good classificatory index for hydraulic biotopes.

The box plots showing Froude number variability follow the same pattern as in previous studies where there is a clear distinction between the variability of the different hydraulic biotopes with chutes showing the highest values and backwater pools the lowest. The pattern of Froude number distribution, within and between hydraulic biotopes, suggests that these features can be considered as separate environments in terms of the mean flow hydraulics.

Box plots showing 'roughness' Reynolds number variability demonstrate the same pattern as that for Froude number. This is significant because it suggests that hydraulic biotopes can also be considered as distinctly separate units with respect to the near bed flow characteristics.

ANOVA

Univariate analysis of variance or the *F* ratio test, is the standard parametric test of differences between three or more samples (Box *et al.*, 1987). The rationale of analysis of variance is to find out whether there is more variation between samples than within them. The test requires three null hypothesis i.e that there is no significant difference between (the Reynolds number, the Froude number and the 'roughness' Reynolds number) of separate hydraulic biotope classes. Table 4.7 demonstrates the results of this test for the three hydraulic variables.

Table 4.7 The ANOVA *F* statistic testing the probability that means are equal at a 0.05 confidence interval (n = 373, significance level = 0).

	***F* Statistic**
Reynolds number	27.354
Froude number	87.262
'roughness' Reynolds number	23.296

NB: The significance level measures whether the *F* ratio is significantly greater than 1. Small significance levels (less than 0.05) indicate that the response variable differs significantly across the level of the classification factor.

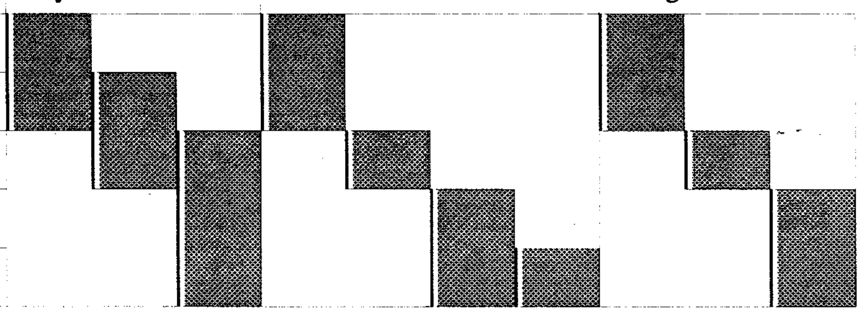
The null hypothesis must be rejected for all three instances, in other words there are significant differences between hydraulic biotope classes for each of the three hydraulic variables. It is not known from this analysis whether all classes are significantly different from each other, or whether only groups of classes are different. For example the test may be grouping runs, riffles and pools together but separating chutes and cascades. To overcome this problem a multiple range analysis can be carried out, this test compares all data separately. From the F statistic it would appear as though the most significant differences are to be found within the Froude number. These findings differ from those of previously studies where the Reynolds number was not significantly different between hydraulic biotopes at different discharges. The results indicate that it may be important to reconsider Reynolds number as a classificatory index, but because of the large overlap in variability, probably not on its own.

Multiple range analysis

A multiple range analysis for the means is a procedure that uses the least significant differences method to analyse whether there are significant differences between the hydraulic biotopes for each of the three hydraulic variables (Milliken & Johnson, 1984). Table 4.8 demonstrates the potential usefulness of this analysis by showing how classes are grouped for each hydraulic index (shaded blocks). To interpret the results consider shaded blocks in the vertical plane as constituting a group. For example backwater pools and pools can be considered as hydraulically the same as shown for all indices.

Table 4.8 Classification of hydraulic biotopes using multiple range analysis

Hydraulic Biotope Class		Reynolds No	Froude No	'roughness' Re
Backwater pool	n=106			
Pool	n=186			
Run	n=50			
Riffle	n=22			
Chute	n=8			



The *multiple range analysis* indicates that all hydraulic variables considered here may be important as quantitative measures for hydraulic biotope classification. The Froude number appears to remain the most useful single index because it separates the hydraulic biotopes into the most groups (4). The reason that not all hydraulic biotopes are recognised as separate entities can be attributed to the large overlap due to data variability within certain hydraulic biotope classes and to problems of hydraulic biotope identification. Results from the multiple range analysis do not clearly coincide with the results from the box and whisker plots, the reason for this is that the multiple range analysis data has been normalised while the box and whisker data has not.

The 'roughness' Reynolds number does not appear to be as good a classificatory index as the Froude number in this analysis, but appears to provide more conclusive reults than the Reynolds number. This observation is supported by the pattern of data distribution shown in the box and whisker plots.

The lack of consistency for hydraulic biotope classification using *the multiple range analysis* technique is not surprising considering the large variability of data within different classes. This result indicates that statistical analysis utilising a number of hydraulic variables together, may be better for the classification of hydraulic biotopes. This theory is put to the test by the use of discriminant analysis on Disaggregated data.

Disaggregated spatial data

The second level of statistical analysis separates the reaches and considers the similarities or differences between the Froude number and the 'roughness' Reynolds number of the hydraulic biotope classes found within them. A geomorphological assessment of the different reaches suggests that two broad sedimentary environments exist. Sites 1, 2 and 4 consist of river beds dominated by cobble while site 3 consists of a steep channel dominated by large cobbles, boulders and bedrock. It would be reasonable to expect patterns of data distribution for the hydraulic biotope classes of the different reaches to be divided into two broad classes concomitant with the sedimentary environments. The following multiple range analysis (Table 4.9) considers each hydraulic class separately.

Table 4.9 The classification of hydraulic biotopes by site using multiple range analysis at a 0.05 confidence interval (n = 364, significance level = 0)

Hydraulic biotope class			Froude Number		Roughness Reynolds Number	
RIFFLE	n = 5	Site 1	■		■	
	n = 7	Site 2	■		■	
	n = 8	Site 3	■			■
	n = 2	Site 4	■		■	
RUN	n = 11	Site 1	■		■	
	n = 10	Site 2	■		■	
	n = 5	Site 3		■		■
	n = 24	Site 4	■		■	
POOL	n = 35	Site 1	■		■	
	n = 58	Site 2	■		■	
	n =41	Site 3	■		■	
	n = 30	Site 4	■			■
B-WATER POOL	n = 40	Site 1	■		■	
	n = 41	Site 2	■		■	
	n = 12	Site 3	■		■	
	n = 13	Site 4	■			■

Chutes and Cascades

Statistical analysis of these hydraulic biotopes was not carried out because they occurred to infrequently across the four reaches. These hydraulic biotope features dominate site 3 which is a high energy environment in a steep gradient.

Riffles

The box plots of Froude number (Figure 4.20a) indicate that there are differences in the variability of this index within different sites but that the median value seems to remain relatively constant around 0.27. The higher variability for site 3 is consistent with what one would expect in a high energy environment dominated by large substratum. A *multiple range analysis* suggests that statistically there is no significant difference between the Froude values for the different reaches. These findings suggest that the Froude number is a useful scale independent index for hydraulic biotope recognition. These findings also suggest that the riffle class has been correctly recognised in the field.

The box plots of 'roughness' Reynolds number (Figure4.20b) show a relatively constant variation for sites 1, 2 and 4 but a notable difference between these and site 3. A *multiple range analysis* suggests that statistically there are two broad groups according to the values for 'roughness' Reynolds number : site 3 and the rest. This supports the idea of two separate sedimentary environments. This may also be explained by the requirements of a roughness height for the calculation of 'roughness' Reynolds number.

Run

Box plots for Froude number (Figure 4.21a) indicate that although there are differences in the hydraulic variability of this feature between reaches, the most obvious differences are between site 3 and the rest. A *multiple range analysis* suggests that statistically there are two broad groups according to the values for Froude number; site 3 and the rest. This is a disappointing result because it questions the scale independence of this index for hydraulic biotope recognition. Possible reasons for the results found here are that researchers may have mis-classified runs within the high energy environment of site 3, where their recognition is considerably more difficult than for other environments. The 'roughness' Reynolds number (Figure 4.21b) shows a similar pattern as that for the Froude number with a *multiple range analysis* for this index indicating that site 3 should be separated from the rest.

Pool and Backwater pools

The box plots for these hydraulic biotopes (Figures 4.22 & 4.23) show a minimal variability in both Froude number and 'roughness' Reynolds number . As one would expect, variability of the Froude number is higher in pools than in backwater pools. This clearly illustrates that they need to be considered as separate hydraulic environments. A *multiple range analysis* suggests that statistically there is no significant difference between the froude values for the different reaches in both classes.

Box plots of 'roughness' Reynolds number (Figures 4.22b & 4.23b) do not show any clear differences between the two hydraulic biotope classes. A *multiple range analysis* suggests that statistically there are two broad groups according to the values for 'roughness' Reynolds number : site 4 and the rest. This does not coincide with the findings of the box plots and can perhaps be considered as an artifact of transformation.

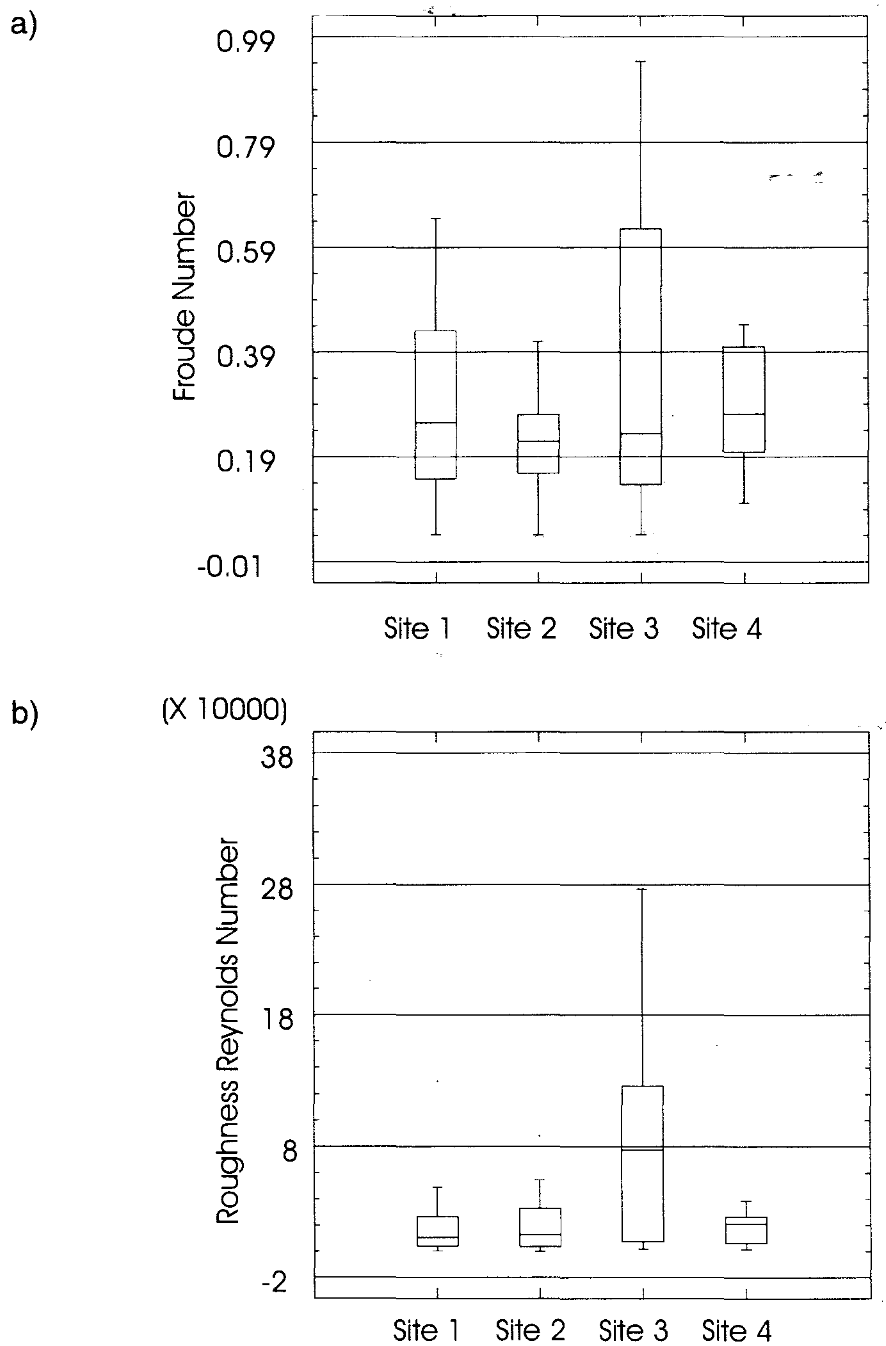


Figure 4.20 Box plots of Froude number and 'roughness' Reynolds number for the riffle hydraulic biotope class.

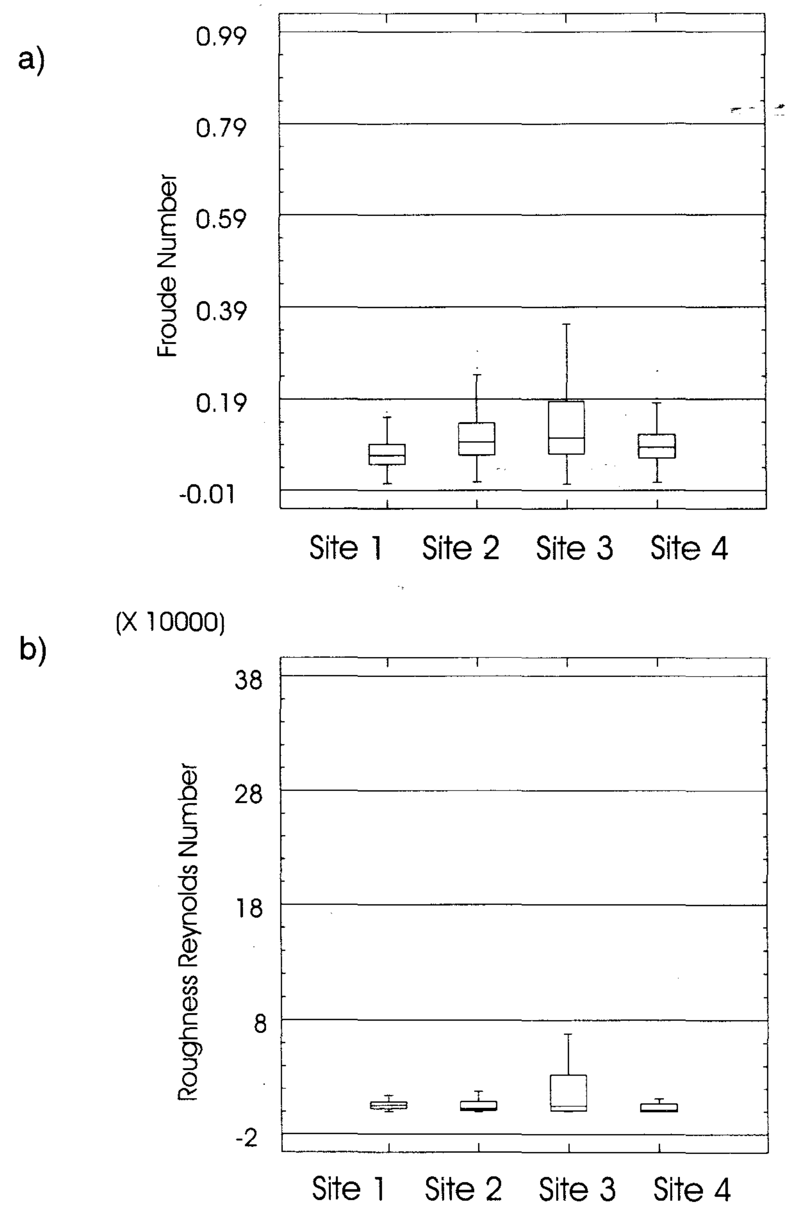


Figure 4.21 Box plots of Froude number and 'roughness' Reynolds number for the run hydraulic biotope class.

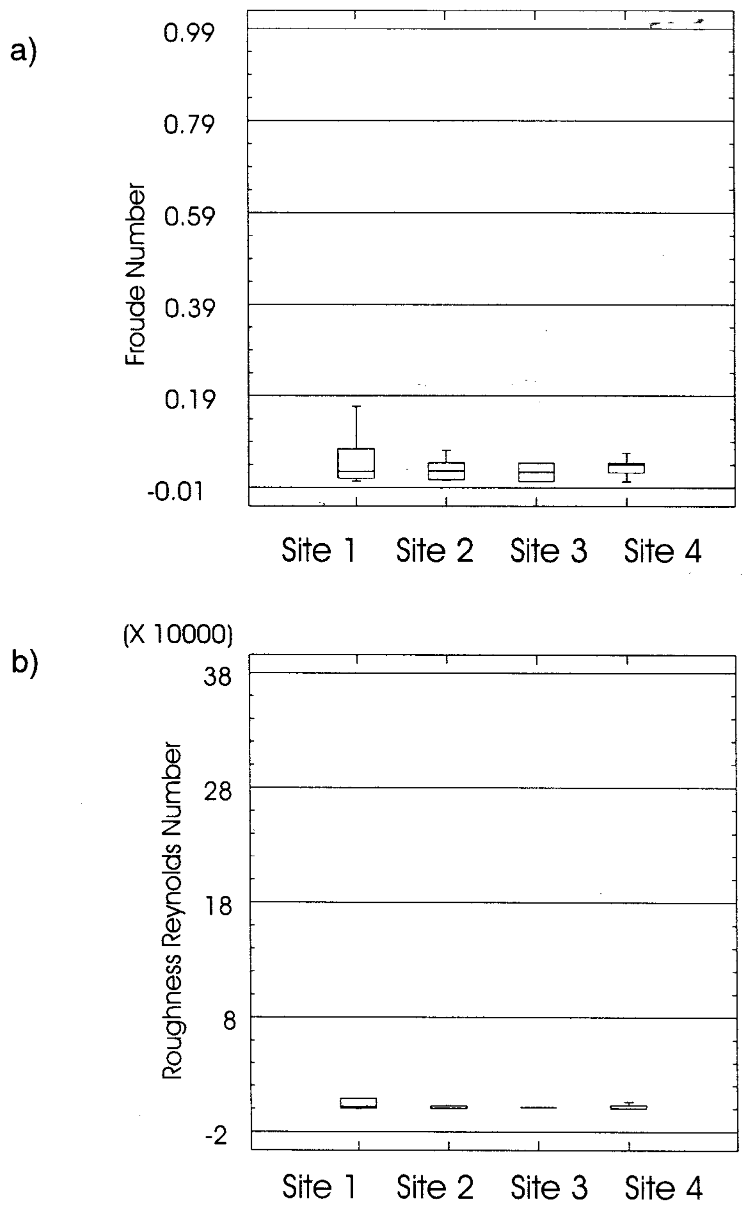
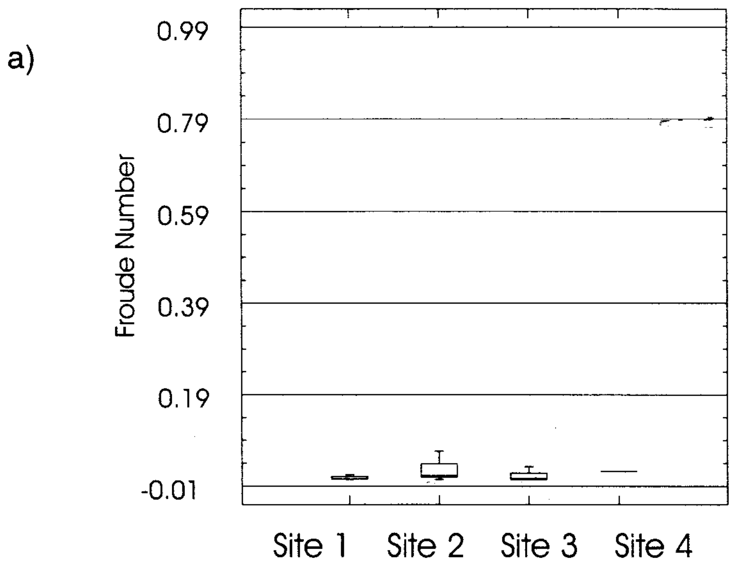


Figure 4.22 Box plots of Froude number and 'roughness' Reynolds number for the pool biotope class.



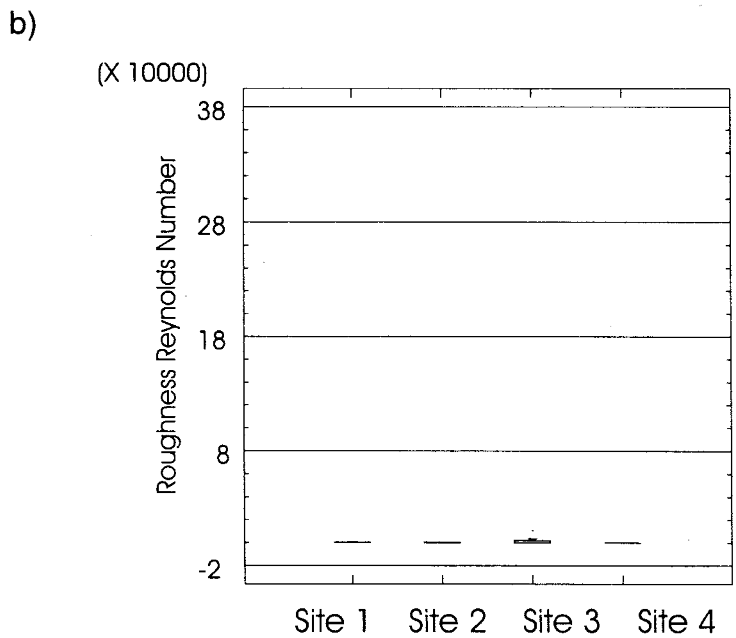


Figure 4.23 Box plots of Froude number and 'roughness' Reynolds number for the backwater pool biotope class.

Discriminant analysis

Discriminant analysis is a statistical technique which is useful when data is classified into two or more groups (hydraulic biotopes) and one wants to find one or more functions of quantitative measurements (hydraulic indices) that will help discriminate amongst the groups (Bolch & Huang, 1974). The procedure assumes that variables are drawn from populations with normal distributions.

Discriminant analysis was carried out for all data, irrespective of situation, in an attempt to find the best hydraulic index or group of indices to discriminate amongst hydraulic biotopes. Only Froude number, Reynolds number and roughness Reynold number were considered. The results of this analysis are given in Table 4.10

Table 4.10 The percentage of correct predictions of hydraulic biotope classification using various combinations of discriminant functions

Hydraulic biotope	n	Fr number	Fr number & Re number	Fr number & Re* number	Fr number, Re* number & Re number
RIFFLE	22	38 %	35 %	40 %	37 %
RUN	50	63 %	61 %	62 %	61 %
POOL	186	58 %	62 %	39 %	50 %
B/W POOL	106	72 %	77 %	77 %	77 %
CHUTE	8	38 %	50 %	50 %	63 %
Average		54 %	57 %	54 %	58 %

Results from the discriminant analysis indicate that the use of Froude number alone is a good classificatory index for hydraulic biotope recognition with an average success rate of 54 %. This success rate may be improved if we include the Reynolds number (57 %) and then improved only slightly if we add the 'roughness' Reynolds number (58 %). It must be recognised that these values are exaggerated by the unrealistic value of 100 % for cascades because there was only one data point present.

Discussion

The Froude number and 'roughness' Reynolds number clearly show that hydraulic biotopes can be considered as significantly different in-stream flow environments with regards their hydraulic characteristics. The Reynolds number is an important index for the characterisation of mean flow conditions within hydraulic biotopes, but does not appear to be as good a variable on its own for the recognition of different hydraulic biotope classes.

The 'roughness' Reynolds number is a hydraulic index which characterises flow conditions near the bed. This value accounts for substratum particles which protrude into the flow and for this reason is scale dependent and non transferable. The use of median particle size as a surrogate for roughness height in the calculation of the 'roughness' Reynolds number appears to be valid when looking for distribution trends of this value between hydraulic biotopes. It is suggested that where possible 'real' values for roughness height should be used, this takes account of such aspects as geology, shape and packing, and prevents bed disturbance.

Analysis of the various combinations of hydraulic indices as tools for the classification of hydraulic biotopes indicate that there is not a significant improvement in accuracy as more and more indices are added. This suggests that the easily obtainable Froude number on its own may be an adequate index for the quantitative classification of different hydraulic biotope classes. If a limited improvement in accuracy is required an inclusion of the easily obtainable Reynolds number is suggested followed by the 'roughness' Reynolds number .

The potential of these and other hydraulic indices needs to be tested more rigorously in a detailed study. It is envisaged that a detailed study would allow the incorporation of more precise methods for the collection of data. Such a study should also allow further testing of the potential for hydraulic indices to both classify and characterise hydraulic biotopes.

4.4.6 The use of the Molenaars data for site selection and research design

As highlighted previously, an important criticism of using the hydraulic characteristics of mean flow to characterise hydraulic biotopes is that this may not account for the hydraulic environment experienced by the majority of biota in the flow. Many aquatic organisms live on or near the bed. In this study of the Molenaars River, a *b* axis length for substratum was considered adequate as an approximation of roughness height (k). This value was used to calculate the 'roughness' Reynolds number so that exploratory data analysis could be carried out on that hydraulic index which represents flow conditions near the bed. An analysis of this data indicates that indices which characterise both the mean and micro flow environments may be useful quantitative values for hydraulic biotope classification. For this relationship to be explored more fully it is necessary to carry out a detailed hydraulic survey using more rigorous techniques for the determination of such variables as roughness height. Such a survey was planned for selected reaches of the Buffalo River, Eastern Cape.

Any detailed study of this nature is going to be expensive, time consuming and fraught with difficulties.

An analysis of the data presented here may provide valuable insight for site selection and sampling design, key issues that need to be considered before the initiation of a detailed study.

Site selection

Findings from the Molenaars study indicate that the first division between sites must be based on reach breaks. Each reach seems to have a characteristic pattern and type of channel form unit, these have particular hydraulic biotopes associated with them. Using this as the first criteria, each sample site in the Buffalo River is to be placed in a separate reach. To enable the findings of a limited survey to be placed within the bigger picture of the catchment, typical or representative reaches will be selected. The realisation of how time consuming a study like this may be, (the collection of mean flow data at a single discharge for four easily accessible sites in the Molenaars River took five qualified researchers one week), an important criteria for site selection in the Buffalo River is accessibility.

Sampling design

An important use of data obtained from the Molenaars River is that it may be manipulated to give an idea of how many sampling points one needs within each hydraulic biotope to account for a high percentage of the variability. To do this the Froude number was selected as being a good single indices for hydraulic biotope classification, this selection is based on the discriminant analysis results of this study (Table 4.9) together with findings from previous studies.

A cumulative means technique was used whereby Froude numbers were calculated for an increasing sample size. The purpose of this is to see at what point the mean values become relatively consistent having accounted for all the variability likely to be encountered.

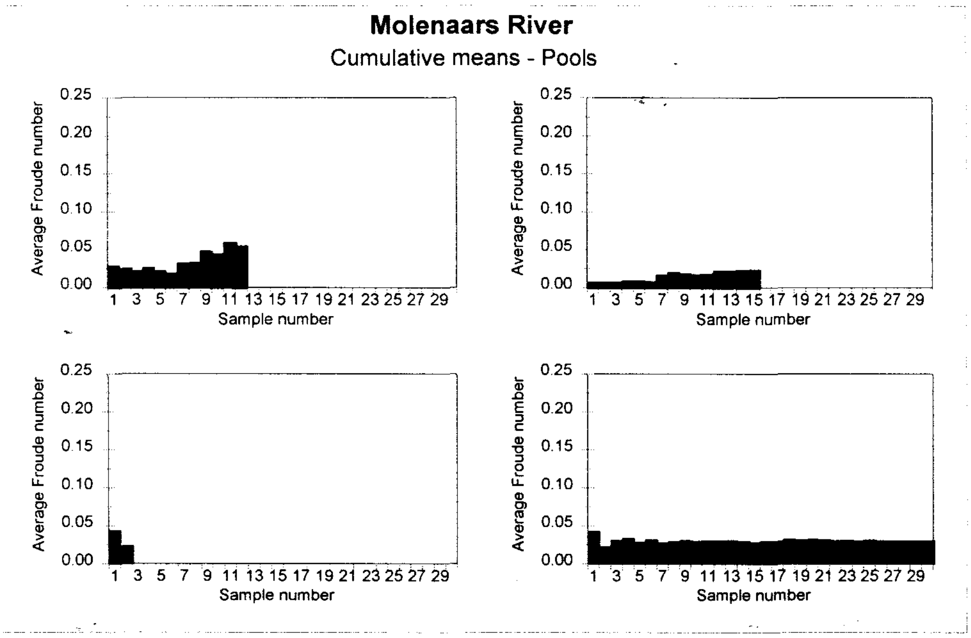


Figure 4.24 Cumulative means of the Froude number for pools at four different sites

Figure 4.24 shows cumulative means for pools. The results from sites 2 and 4 indicate a level of consistency around 7 sampling points. Site 1 did not stabilise at any number of sampling points. Site 3 does not have enough data points to assess sampling point requirements.

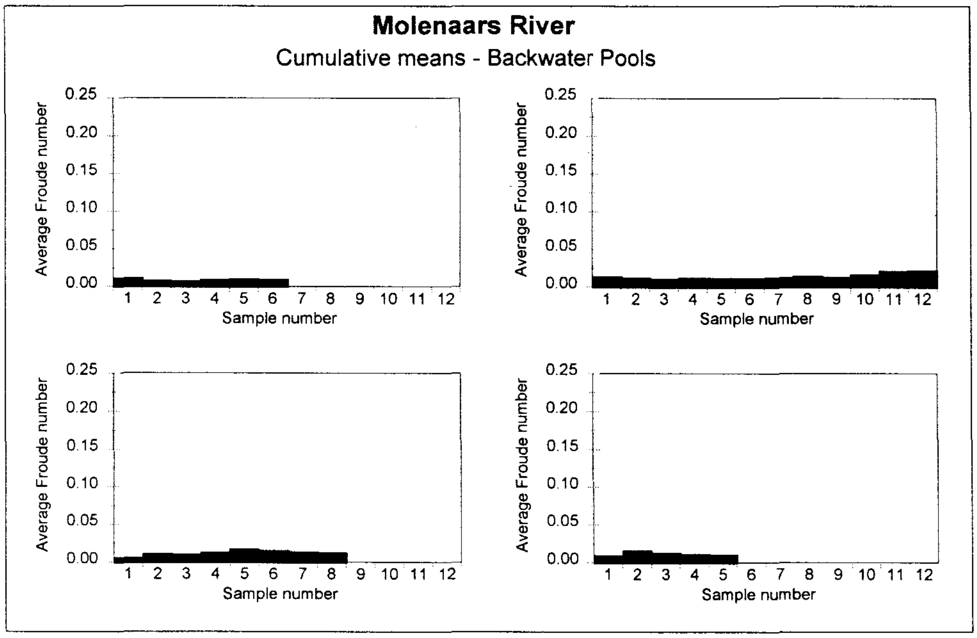


Figure 4.25 Cumulative means of the Froude number for backwater pools at four different sites

Figure 4.25 shows cumulative means for backwater pools. These results indicate that within all 4 sites a reasonable degree of consistency was reached within 3 or 4 sampling points.

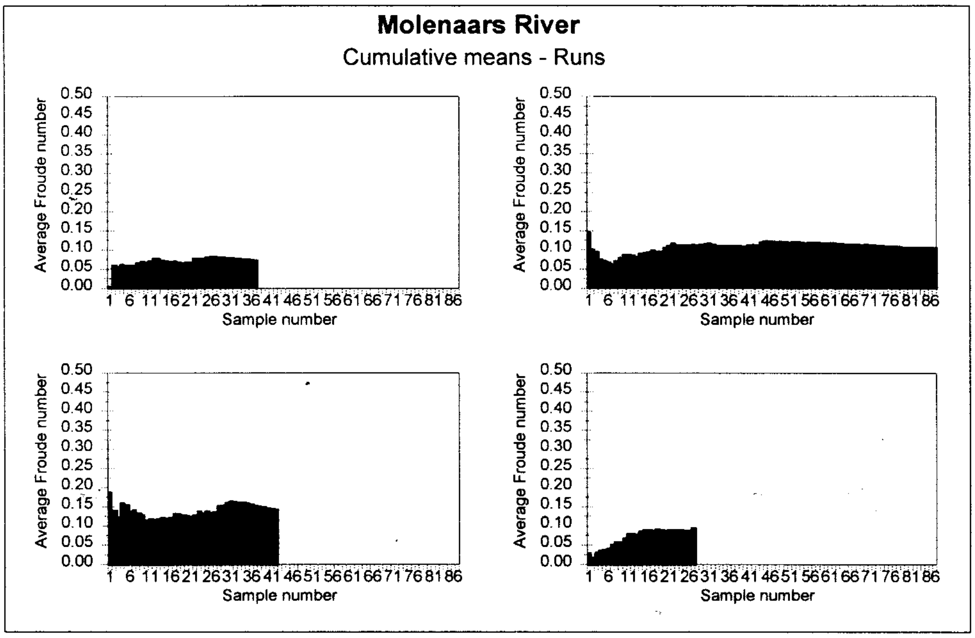


Figure 4.26 Cumulative means of the Froude number for runs at four different sites

Figure 4.26 shows cumulative means for runs. These results indicate that all sites require approximately 15 to 20 sampling points before any consistency is reached.

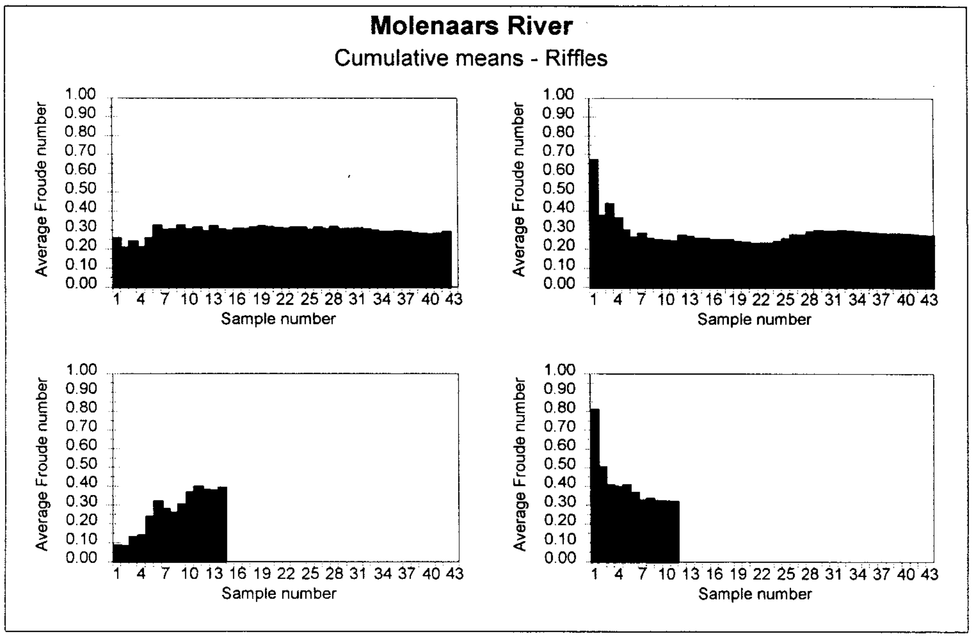


Figure 4.27 Cumulative means of the Froude number for riffles at four different sites

Figure 4.27 shows cumulative means for riffles. These results indicate that sites 1, 2 and 4 require about 7 sampling points to account for the full range of conditions. The results for site 3, which is within the complex morphological and hydraulic environment, indicate a requirement for at least 12 sampling points.

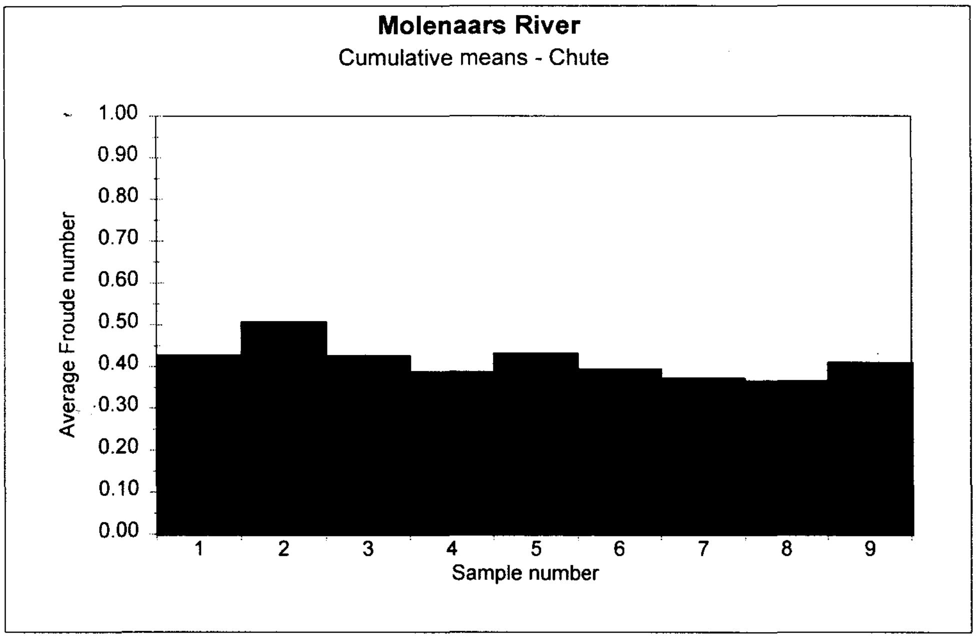


Figure 4.28 Cumulative means for the Froude number at chutes at one site

Figure 4.28 shows cumulative means for chutes at the only site they were present. These results indicate that approximately 6 sampling points are required to incorporate the full range of conditions.

In a study of this type, the most extensive sampling framework will provide the best results, unfortunately as always, there are serious time constraints. From the above results one can determine the minimum requirements for a reasonable hydraulic survey, 7 sampling points within pools, 4 sampling points in backwater pools, 15 sampling points in runs, 12 sampling points in riffles and 6 sampling points in chutes. With time permitting, between 10 and 15 sampling points will be taken within each hydraulic biotope in each selected reach of the Buffalo River.

4.4.7 Conclusion

Research carried out in the Molenaars River provided an opportunity to determine the influence of changes in channel morphology on the hydraulics of flow within different hydraulic biotopes. Unlike previous studies, a single discharge was considered but variability was introduced by looking at a number of different sites at that discharge. A detailed sampling programme allowed for the collection of enough data to carry out some statistical analysis and also provided a new component to the analysis of hydraulic biotopes; a consideration of substratum size allowed the calculation of a near-bed flow component.

Results from the study provided further evidence that the Froude number describing mean flow has potential as a useful, quick technique to characterise and quantify hydraulic biotopes. Despite vastly different geomorphological environments, there was a certain degree of consistency between the flow characteristics of hydraulic biotopes in the same reach and between hydraulic biotopes of different reaches.
Exploratory analysis of near bed flows indicated that the 'roughness' Reynolds number may be of equal significance as the Froude number of mean flows for the characterisation of hydraulic biotopes.

The detailed survey provided a useful data base for the determination of minimum requirements for a similar study. Data manipulation has provided valuable guidelines for the selection of sample sites and the formulation of a sampling strategy for a detailed hydraulic survey of the Buffalo River.

4.5 RECOMMENDATIONS FOR FURTHER RESEARCH

As a result of the findings of the three pilot studies presented in this chapter, the following recommendations are made for further research:

- The apparent associations between hydraulic biotope classes and the hydraulics of flow needs to be explored more rigorously, both in terms of mean and near bed flow characteristics. The importance of roughness height as a variable for the calculation of micro flow indices has been recognised and should be measured directly. The scale of the hydraulic biotope is smaller than that of the morphological unit. Observations indicate that transect sampling incorporates features at the scale of the morphological unit, this means that more than one hydraulic biotope is often encountered within a single transect. Point sampling along a transect is therefore recommended to overcome this problem.

- The hydraulic biotope is nested within the morphological unit, it is hypothesised that individual morphological units may have consistent associations of biotopes. This hypothesis needs to be explored further by analysing the distribution of hydraulic biotopes within channel morphology.

- Hydraulic biotopes appear to be spatially unstable. Spatial instability needs to be considered by looking at the variability of hydraulic indices characterising similarly recognised hydraulic biotopes within different morphological reaches. This research needs to be considered together with the potential associations with morphological units.

- Hydraulic biotopes appear to be temporaly unstable. Temporal instability is demonstrated by the change in hydraulic biotope classification as a response to changing discharge. The extent and direction of change needs to be explored further by carrying out fixed point sampling within a wide range of discharges.

CHAPTER FIVE
THE BUFFALO RIVER

5.1 INTRODUCTION

Results from pilot studies detailed in Chapter Four indicate that ecologically significant in-stream flow environments can be objectively categorised and described according to their hydraulic characteristics (the hydraulic biotope concept). Recommendations from these pilot studies point to the need for a detailed survey of both temporal and spatial variability of selected hydraulic indices within a single river network.

The Buffalo River in the Eastern Cape Province was considered as a good candidate for such a study for a number of reasons:

- The close proximity of the catchment to Rhodes University (120 km away) made for relative ease of access. Accessibilty was essential because of the research needs for a wide range of discharges and for diverse physical characteristics.

- The Buffalo River catchment has a good flow and rainfall gauging record. These records proved to be useful not only for the planning of research trips (from known rainfall events) but also for the assessment of flow conditions during sampling in relation to the longer term flow regime.

- The Buffalo River has been studied in depth with regards to the lotic ecology (Hill & O'Keeffe, 1992; Palmer, 1991; Palmer *et al.*, 1993a; Palmer *et al.*, 1993b; Palmer *et al.*, 1991; Palmer, 1991; Palmer & O'Keeffe, 1990a; Palmer & O'Keeffe, 1990b; Palmer & O'Keeffe, 1990c). An analysis of data from these studies enables linkages to be evaluated between the physical and biological characteristics of the river and provides some evidence for the ecological significance of hydraulic biotopes (Chapter Seven).

- Some of the catchment data for the Buffalo River had already been collected in a digital format for PC ArcInfo, this allowed for the relatively easy application of the hierarchical geomorphological model.

Some disadvantages of selecting the Buffalo River catchment include the large number of impoundments present within the drainage basin, unfortunately this is common to virtually every reasonably large river in South Africa. Flow is perennial in the upper reaches of the main Buffalo River channel above Maden Dam. This impoundment is the primary water source for the urban centre of King William's Town. Between Maden and Rooikrans Dams flow is often reduced to isolated pools, this situation is worsened by local abstractions for irrigation. Immediately below Rooikrans Dam there is always flowing water due to management releases to maintain the Pirie Trout Hatchery. By the time the river reaches King William's Town, flow is often reduced to nothing more than a trickle during the dry season. This is as a consequence of transmission losses, evaporation and irrigation abstraction. Return flows from industries and sewerage treatment works maintain the flow into Laing Dam, but there are no compensation releases downstream of the dam. Reaches of the Buffalo River between Laing and Bridle Drift Dams rely on seepage to maintain any base flow during the dry season. Water is released from Bridle Drift Dam to the Umzaniana weir, from which water is abstracted for East London and Mdantsane (O'Keeffe et al., in press).

Another problem is that the catchment experiences highly variable rainfall on both a seasonal and annual basis. At the time of commencement of this research, the Eastern Cape Province was experiencing a very serious drought, this drought has continued throughout the duration of this research and is only now (November 1995), showing signs of abating. All of these problems were considered in the initial research design. It was felt that by selecting research sites in the upper, high rainfall area of the catchment, the problems of drought, flow variability and impoundments would be minimised.

5.2 AIMS

The hydraulic biotope forms an integral component of the hierarchical geomorphological model, this model provides a suitable format for the presentation of catchment characteristics which either directly or indirectly influence the channel morphology and flow conditions within the fluvial environment. This chapter aims to apply the hierarchical geomorphological model to the Buffalo River catchment.

5.3 THE HIERARCHICAL GEOMORPHOLOGICAL MODEL

This section presents information on the general catchment characteristics of the Buffalo River. This information provides essential inputs for the hierarchical geomorphological model. The detailed procedure of a review of the geomorphological processes which are considered to be of special significance for the development of the model have been reviewed by Wadeson (1993a; 1993b) and constitute components of the final report to be presented in May 1996 to the WRC.

The South African model has six nested levels (Figure 5.1): the catchment, the zone, the stream segment, the reach, the morphological unit and the hydraulic biotope (Wadeson & Rowntree, 1994; Rowntree & Wadeson, 1994; Rowntree & Wadeson, 1995).

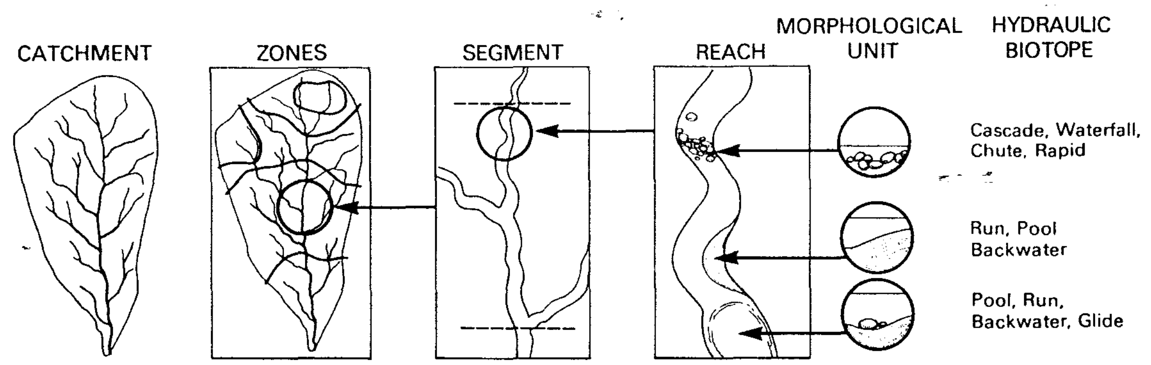


Figure 5.1 The structure of the hierarchical geomorphological model

The following discussion considers five of the nested levels of the hierarchy as they apply to the Buffalo River catchment: the catchment, zone, segment, reach and morphological unit. This information forms the basis for the selection of reaches, sampling sites and sampling frequency for the further testing of the hydraulic biotope concept.

5.3.1 The Catchment

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 5.2 shows the situation of the catchment.

The longitudinal profile of the Buffalo River and its tributaries are characteristically concave upwards with a relatively sharp break in slope between the mountain and piedmont zones (Figure 5.20). This can be demonstrated by comparing the gradients between the first 6 km of the main channel (0.19) as it falls steeply to the lowland Plateau or piedmont zone, and the gradient of the channel as it flows over the coastal plain (between 0.003 and 0.013). 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. Figure 5.3 shows a relief map of the Buffalo River catchment.

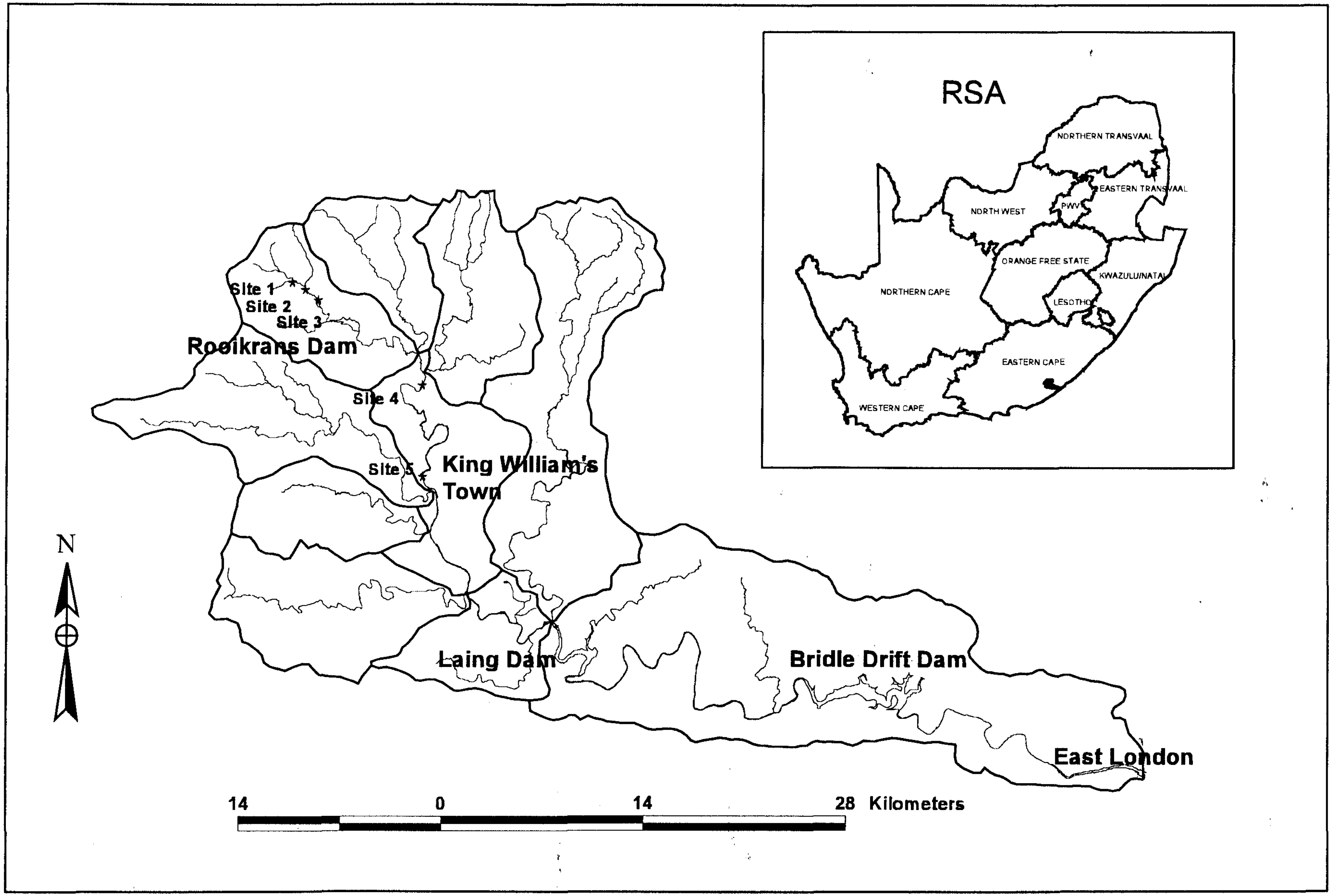


Figure 5.2 The Buffalo River Catchment

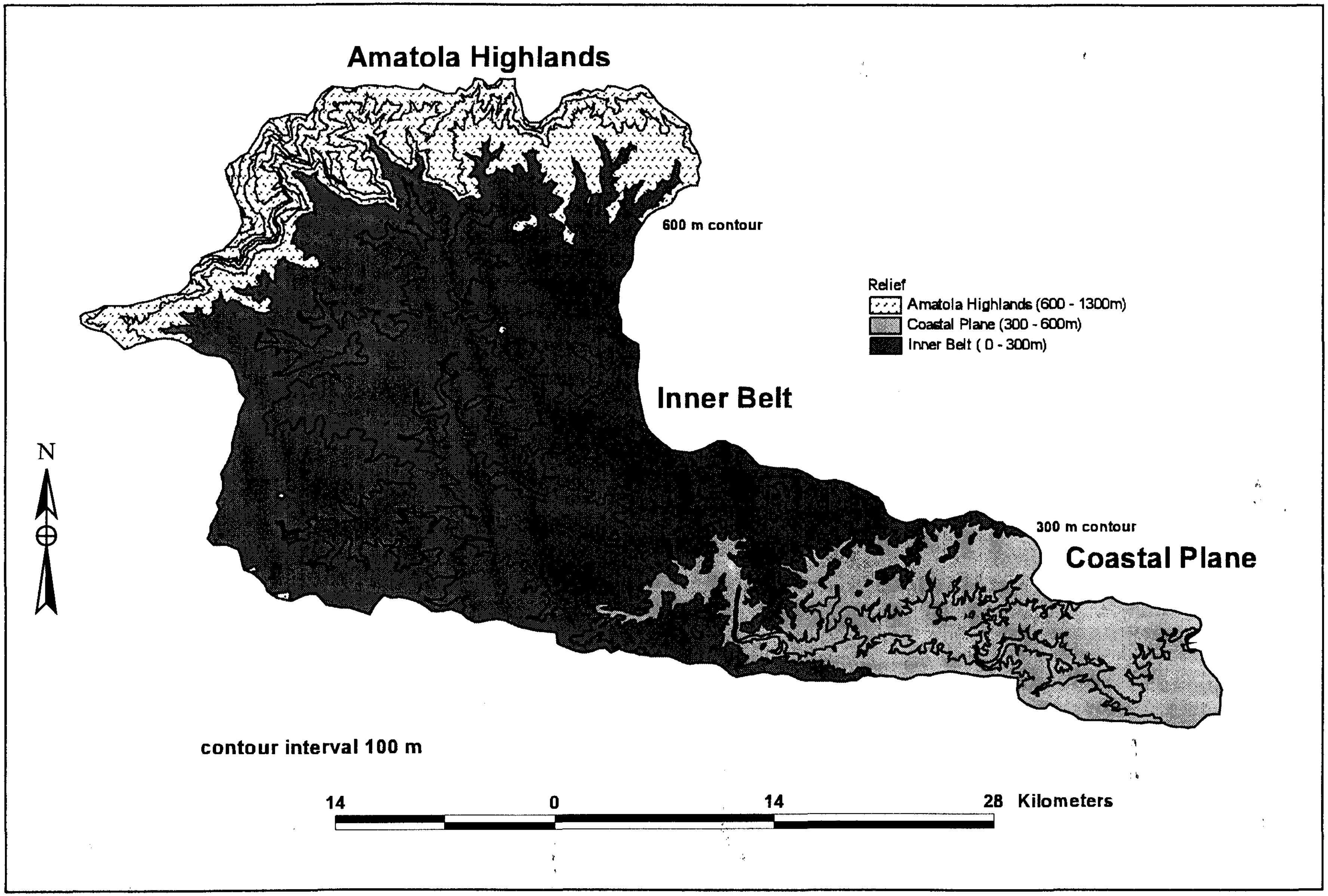


Figure 5.3 Relief map of the Buffalo River catchment

Catchment Analysis

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 (Rowntree & Wadeson 1995b). A somewhat basic description of catchment characteristics is a useful basis from which one can analyse geomorphic processes. The data requirements for classifying the catchment are based on nationally available map sheets. This data is transformed into a computerised format by capturng the required map elements utilising Geographical Information Systems (GIS) software.

Simple classification indices include topographic descriptors such as the *hypsometric integral* or *area-elevation curve* (Figure 5.4). This curve represents the distribution of catchment area with elevation and provides a useful first step for the description of variables that vary with altitude: for example rainfall and natural vegetation. If areas are expressed as percentages of the total catchment, the method provides a useful dimensionless technique to make comparisons between different catchments.

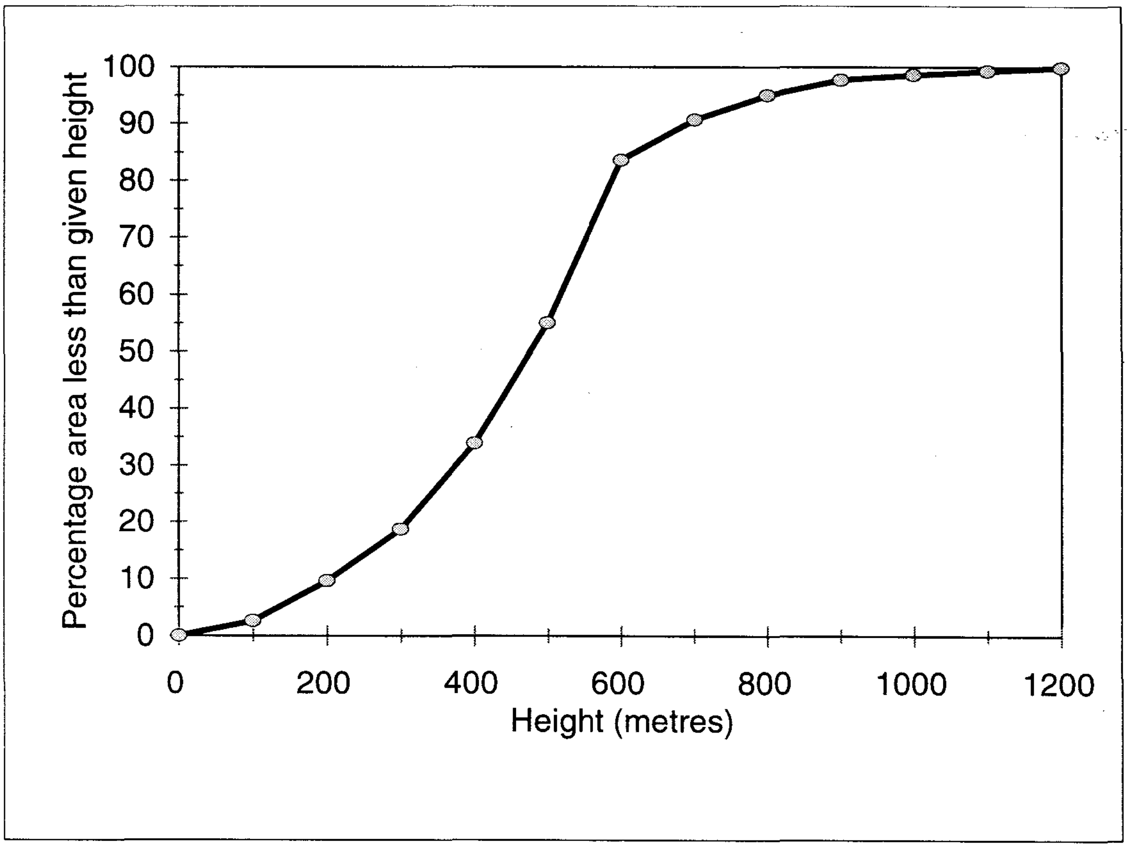


Figure 5.4 Area-elevation curve for the Buffalo River catchment

Stream ordering was carried out in the Buffalo River catchment using Strahlers (1952) method. The length of streams were obtained from the data base of the projected GIS covers. As suggested by Gordon et al. (1992), relationships were displayed between stream order and stream length by plotting values as semi-log plots as shown in Figure 5.5a and b. These simple relationships provide quantitative descriptions of the development of the drainage system in the Buffalo River catchment and display expected semi-logarithmic trends for both number and length of different stream-order.

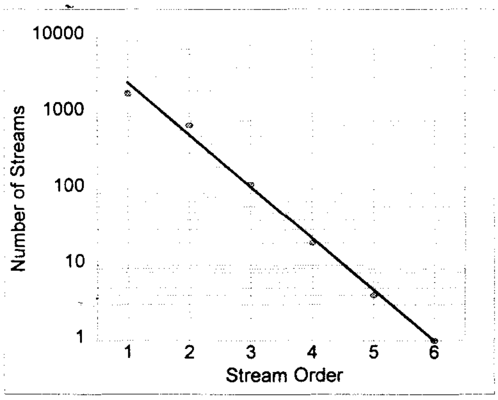


Figure 5.5a Semi-log plot of stream order versus number of streams for the Buffalo River catchment

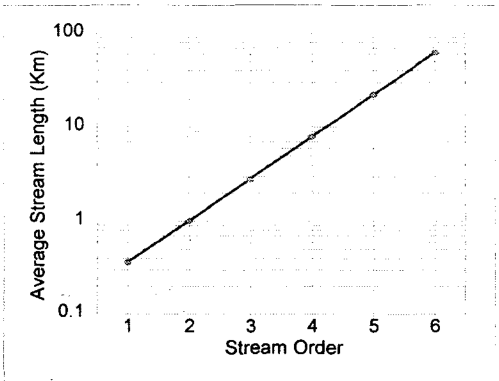


Figure 5.5b Semi-log plot of stream order versus average stream length in the Buffalo River catchment

Table 5.1 provides a summary of a number of indices which may be used to quantify catchment characteristics. These morphometric measurements can be used in the prediction of the catchments hydrological response to rainfall and for comparative or classification purposes.

Table 5.1 Indices describing morphometry of the Buffalo River catchment

Catchment Index	Formula	Reference	Value
Relief Ratio	$R_r = h / L$	Schumm (1956)	**0.017**
Elongation Ratio	$R_e = D_c / L$	Schumm (1956)	**0.51**
Average catchment slope	$S_c = \frac{\text{Elevation at source - Elevation at mouth}}{\text{Length of stream}}$	Gordon et al. (1992)	**0.54**
Bifurcation Ratio	$R_b = \frac{\text{number of streams of one order}}{\text{number of streams of next highest order}}$	Horton (1932)	**4.66**
Drainage density	$R_D = \sum L / A$	Horton (1932)	**1.72km.km^{-2}**

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.

Although none of the indices described above have any obvious relevance to the hydraulic biotope concept described in this thesis, they do provide important information about the general characteristics of the catchment in which the hydraulic biotopes are nested. It is important to remember that the hydraulic biotope is a hydraulic environment ultimately determined by catchment and stream network characteristics. This information may become particularly useful for the classification of hydraulic biotopes from different catchments or sub-catchments.

5.3.2 The Zone

Within higher order catchments there is much heterogeneity with respect to topography, climate, geology, vegetation cover, soils and landuse. 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 & Stephenson, 1970; Rudeforth & Thomasson, 1970). The variables making up these 'zones' are termed first-order independent elements by Morisawa (1985) and are recognised as the variables which determine the second-order factors of discharge and sediment load. All of these first and second-order variables interact in a complicated feedback mechanism which determines the third-order channel morphology of the catchment.

For the application of the hierarchical model to the larger catchments commonly considered for water resource development purposes, it was realised that it was necessary that data inputs into the model at this level be readily accessible from published sources. Further requirements were that these inputs should also allow a uniform application throughout the country and should not require detailed field mapping. A GIS such as PC ARC/INFO is well suited to meet these requirements as data inputs take the form of maps (covers) depicting rainfall and/or runoff, slope gradient, geology, soils, natural vegetation and landuse. The GIS then allows the manipulation of these covers to produce homogenous zones. The availability of data varies from catchment to catchment in South Africa. Most data is available in hard copy map form with only limited data available from GIS data bases held in various private and public archives. Limited data was available in the form of GIS covers for the Buffalo River; covers which were digitised for this project include: drainage network, geology, landuse, soils and slope. Sediment zones and hydrological zones maps were produced separately. These were overlayed to determine the next level of the hierarchy - the segment.

Sediment Zones

To create a map depicting areas of homogeneous sediment production various input variables as outlined in Figure 1.1 (geology, soils, vegetation, landuse, gradient) needed to be considered.

Geology

The Buffalo River catchment lies within the shallow structural basin of the Karroo and is just beyond the eastern limits of the Cape Fold Belt (Stone, 1982). Figure 5.6 shows the dominant geology of the Buffalo River catchment. The principle rock outcrops within the catchment consist of sedimentary rocks of the Lower Beaufort Series (Adelaide Subgroup) of the Karroo System (Mountain, 1945, 1974; Thornton et al., 1967; Hiller & Stavrakis, 1981; Hart, 1982; Stone, 1982; Weaver, 1982). These rocks produce erodible soils and consist of mudstones, shales and sandstones of Permian to Triassic age. Also of importance are intrusions of igneous rock, mostly dolerite. Both dolerite dikes and sandstones, locally metamorphosed due to contact with dolerite intrusions, outcrop down the length of the channel and provide local inputs of coarse sediment.

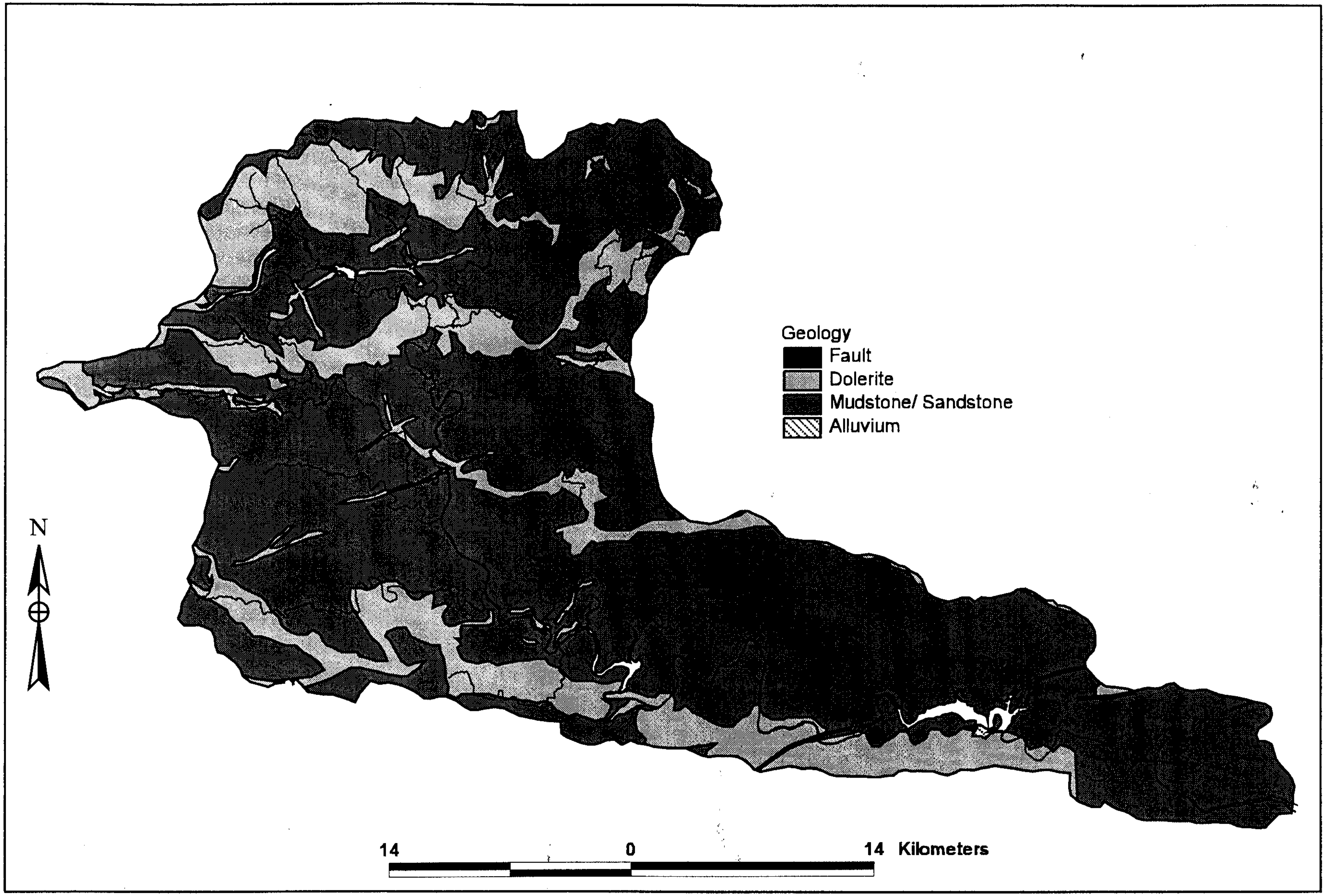


Figure 5.6 Dominant geology of the Buffalo River catchment

Soils

Mountain (1945, 1962, 1974), Bader (1962), Stone (1982), Weaver (1982) and Copeland (1985) discuss the soils and sediment production within the catchment. Owing to the roughly horizontal bedding of the Beaufort sandstones, soils which are produced tend to be moderate to very shallow and form a grey sandy loam with an average clay content of 23 %. The high clay content renders the soils impermeable, reducing the potential for infiltration and soil moisture storage. The majority of the soils formed on the Beaufort sediments comprise medium textured orthic A horizons with a significant fine sand content overlying weathering rock in various stages of decomposition (Copeland, 1985). Owing to the chemical and physical composition of the parent material, the topsoils are liable to crust or set hard on drying and are susceptible to erosion. A low iron content together with a relatively high sodium content in certain of the sedimentary strata produces soils with unstable clays. These soils overlie decomposing rock at relatively shallow depth with restricted permeability. This leads to the build up of a perched water-table within the profile causing saturation of the topsoils after heavy rains. The instability of the clay combined with saturation causes a serious erosion hazard on all but the flattest slopes. A result is the extensive formation of gullies and rills in the Buffalo catchment.

Soils derived from dolerite tend to be deeper than those formed on the sedimentary rocks due to the greater susceptibility of dolerite to weathering. These are heavier textured soils and may generally occur as two separate forms: red dolerite clays with a clay content of 55 % and high porosity and black clays with a clay content of 38 % and a lower porosity than the red clays. Mountain (1952) and Bader (1962) suggest that the dolerite soils of this region are less prone to erosion than the soils of associated with the sedimentary rocks of the Beaufort group. Generally these soils are highly productive in terms of agriculture potential and tend to be stable.

Some soils in the Buffalo catchment are also derived from mixed parent material but are very variable depending on the influence of one or other of the parent rocks. In the bottom lands where the terrain is flatter, pockets of soil derived from alluvial and colluvial material are found; these are deep and well drained and well suited for irrigation (Copeland, 1985). A reconnaissance soil survey commissioned by the consultant firm Hill Kaplan Scott and carried out by Copeland (1985) recognised 18 potential cataena associations (Figure 5.7). These cataena associations were grouped on the basis of erodibility and, together with slope, were used to create 7 broad potential soil erosion groups (Figure 5.13).

An extensive area of the catchment (78 %) is comprised of easily erodible Beaufort Series sandstones. This together with the excessive pressure placed on the land by subsistence agriculture and grazing causes extensive erosion and land degradation.

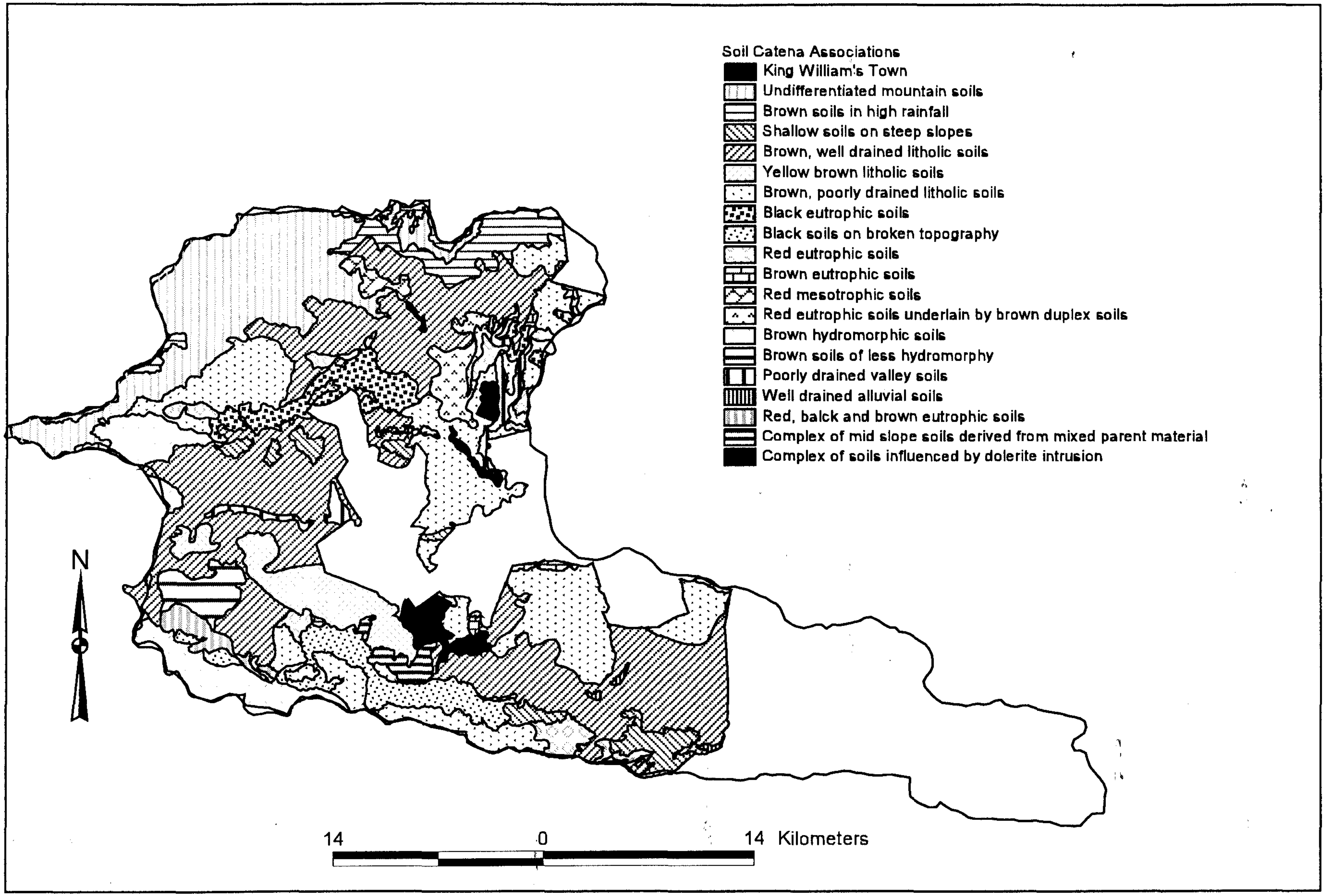


Figure 5.7 Soil catenae associations of the Buffalo River catchment (Copeland, 1985)

Vegetation

Following the designations of Acocks (1975) and as illustrated in Figure 5.8, the natural vegetation of the Buffalo catchment consists of four main biomes:

Grassland / Forest

This biome is dominated by the *Highland Dohne Sourveld and Dohne Sourveld* which occur in the higher rainfall belts in the upper catchment area of the Buffalo River. The vegetation consists of forest, grassland, False Macchia (Fynbos) and scrub. Forest are distinguishable by the dominance of Yellowwoods *(Podocarpus latifolius)* and climbers. Over exploitation has reduced much of the dense natural forest to scrub interspersed with invasive Black Wattle. The only true temperate forest still occurring is in the Amatola forest reserve in the Buffalo headwaters. Encroachment of grassland by False Macchia has reduced the agricultural potential in some areas (Weaver, 1988).

Savanna

The savanna biome of the area comprises the *Eastern Province Thornveld* which occupies the coastal Plateau. The climax vegetation of this area should be short forest and scrub forest but is today dominated by thornveld (*Acacia karroo*). In many areas there are no trees and the vegetation can be considered as grassveld. Dense sour mixed grasses typify the region with patches of sweetveld on dolerite soils (Weaver, 1988).

This biome also comprises the *False Thornveld of the Eastern Province* which is found on the undulating foothills of the escarpment. This area should consist of the Eastern Province Grassveld or marginal scrub forest; however the invasion of thornveld together with overgrazing has promoted erosion by reducing grass cover. According to Trollope and Coetzee (1978) these areas are dominated by inferior vegetation, have unreliable rainfall and poor quality soils and are badly eroded as a result.

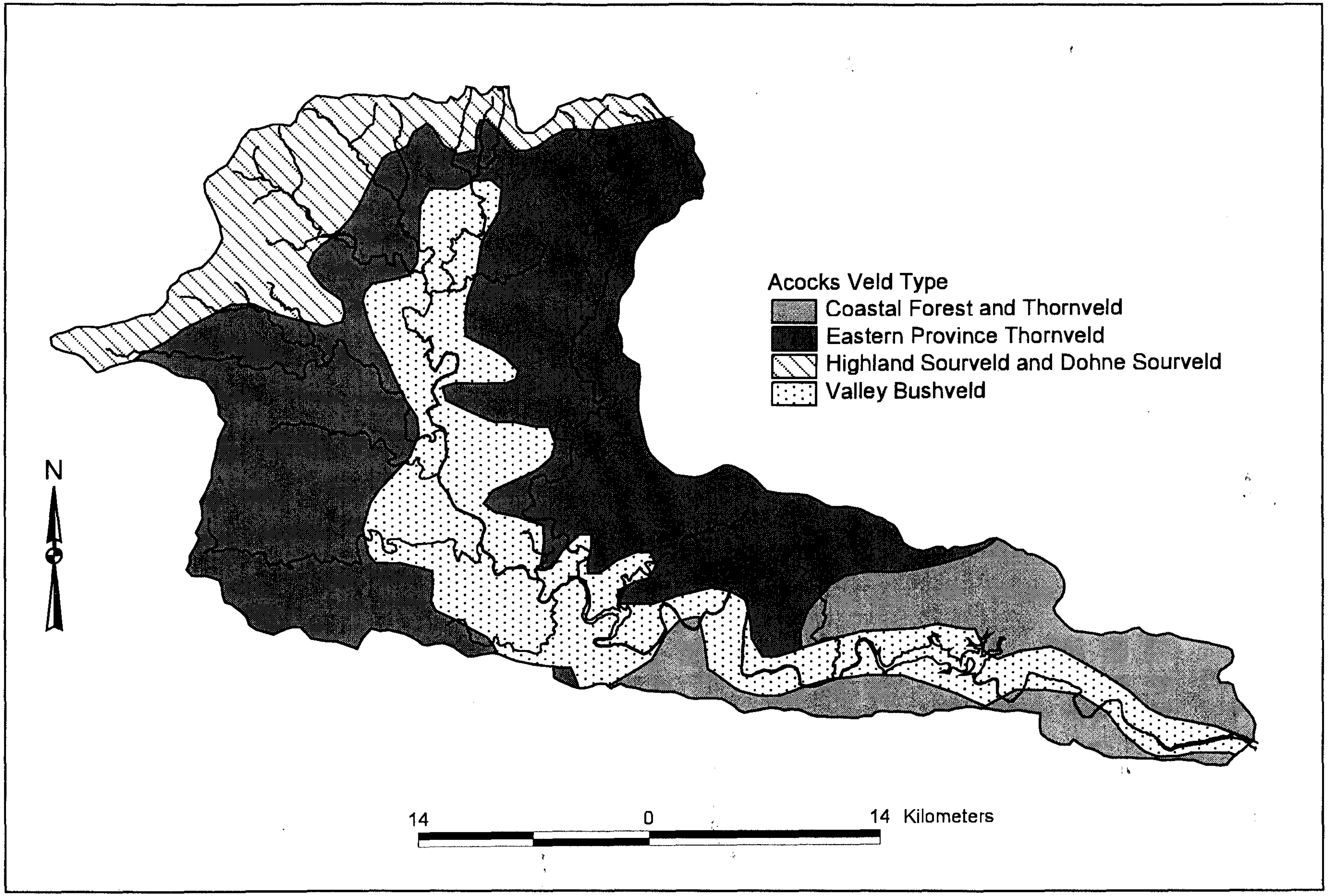


Figure 5.8 Vegetation map of the Buffalo River catchment (Acocks, 1975)

Thicket

This biome consists of the Valley Bushveld which is confined to the dry valleys dissecting the coastal Plateau. The vegetation consists of scrub forest dominated by trees (*Euphorbia*) According to Acocks (1975, p54) "...the bush tends to be scrubbier and reaches a higher altitude on the hotter and drier northern and western aspects, than it does on southern and eastern aspects. On the latter it is regularly tall *Euphorbia* forest, often with *Aloe bainesii*, merging on the upper slopes directly into forest, or where the forest has been destroyed, into grassveld or thornveld." *Acacia karroo* with mixed grass is generally found on the northern and western aspects (Weaver, 1988).

Forest

This biome comprises the *Coastal Forest and Thornveld* which is transitional between the typical coastal forests in the north and the drier *Alexandria Forest* in the south, this vegetation type has also been referred to as *Acacia Savanna* (Lubke et al., 1986). This area generally consists of open thornveld and patches of relic forest. The grassveld is scrubby with tall herbs and tall coarse grasses, evergreen vegetation predominates. Rainfall is insufficient to support a true forest (Weaver, 1988).

Land Use

The Buffalo River rises as a small, steep mountain stream in an area of open heathland and commercial forestry in the Amatola Mountains between King William's Town and Stutterheim. The steep upper reaches of the river flow through indigenous temperate forest dominated by Yellowwood trees before reaching the impoundments of Maden Dam and Rooikrans Dam. The high rainfall of the upper catchment ensures a permanent, high quality flow of water. The river in this part of the catchment supports breeding populations of introduced rainbow and brown trout.

Downstream of Rooikrans Dam the catchment is generally utilised for subsistence agriculture and range land for grazing. Between Rooikrans Dam and King William's Town there are local areas of intensive irrigation and cultivation alongside the river, these areas provide fresh produce for the local markets. These areas are insignificant when considering land use within the entire catchment, but may have an important influence on the riparian zone (Figure 5.9).

Within the land use mosaic of indigenous forest, subsistence agriculture, grassveld for grazing and limited irrigation are the densely populated urban and industrial areas of King William's Town, Berlin, East London, Zwelitsha, Bisho, Breidbach, Illitha and Mdantsane. Water requirements for these areas are met by four major impoundments on the main Buffalo River channel: Maden Dam and Rooikrans Dam in the higher rainfall upper reaches, and Laing Dam and Bridle Drift Dam in the drier middle reaches.

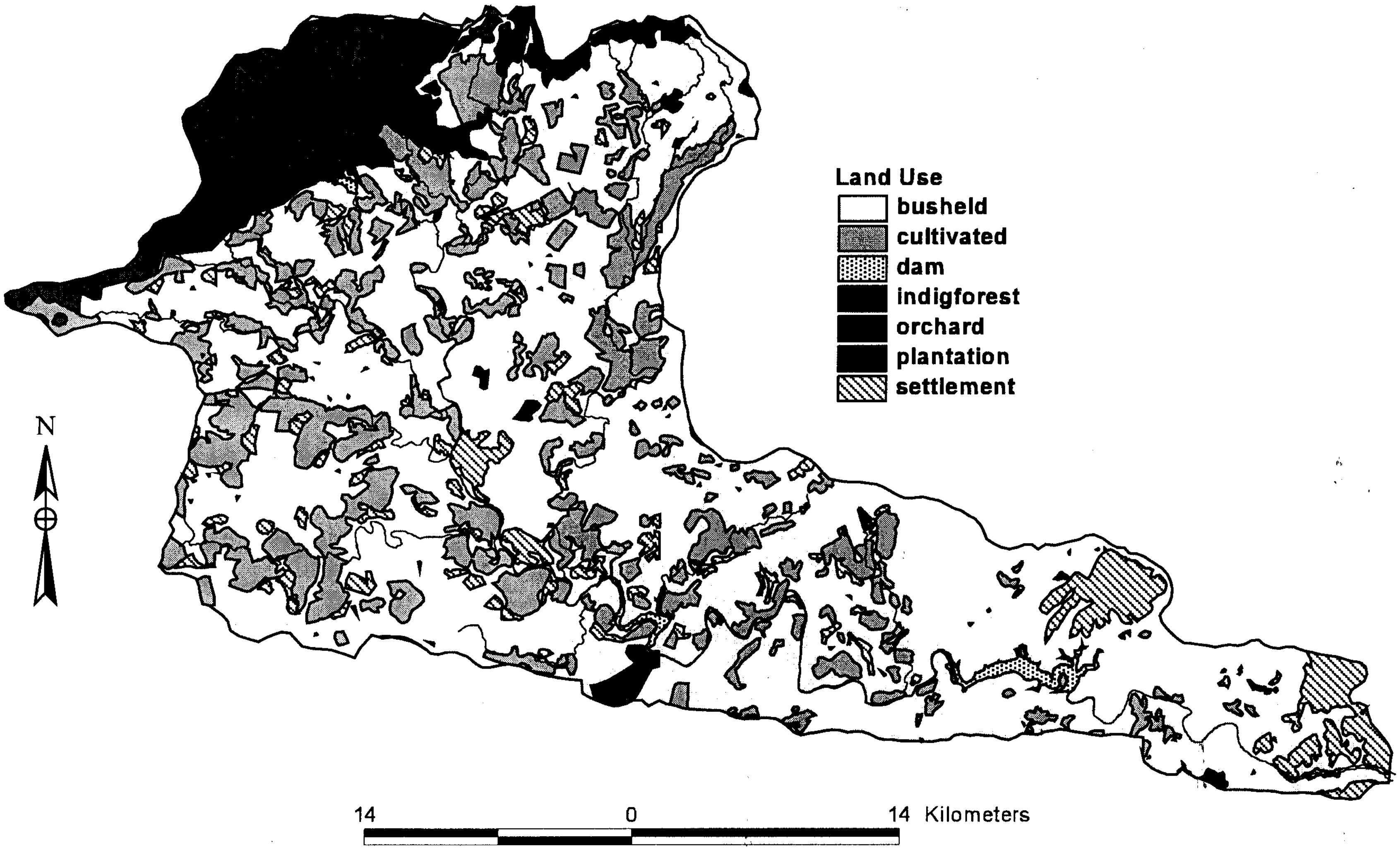


Figure 5.9 Land Use map of the Buffalo River catchment

Population Figures for the Buffalo catchment are unreliable because of a failed census in 1991. Data from O'Keeffe et al. (In press) estimate the total population of the Buffalo catchment as 311 000, with a very uneven distribution (Figure 5.10). Population densities are estimated in excess of 1000 people per km^2 in the larger urban and peri-urban areas. These are areas of high sediment production. In contrast to these Figures are estimates of less than 10 people per km^2 in many area of the upper catchment. Consistent with many other parts of rural South Africa, there is likely to be a high correlation between soil erosion and population density in the Buffalo River catchment.

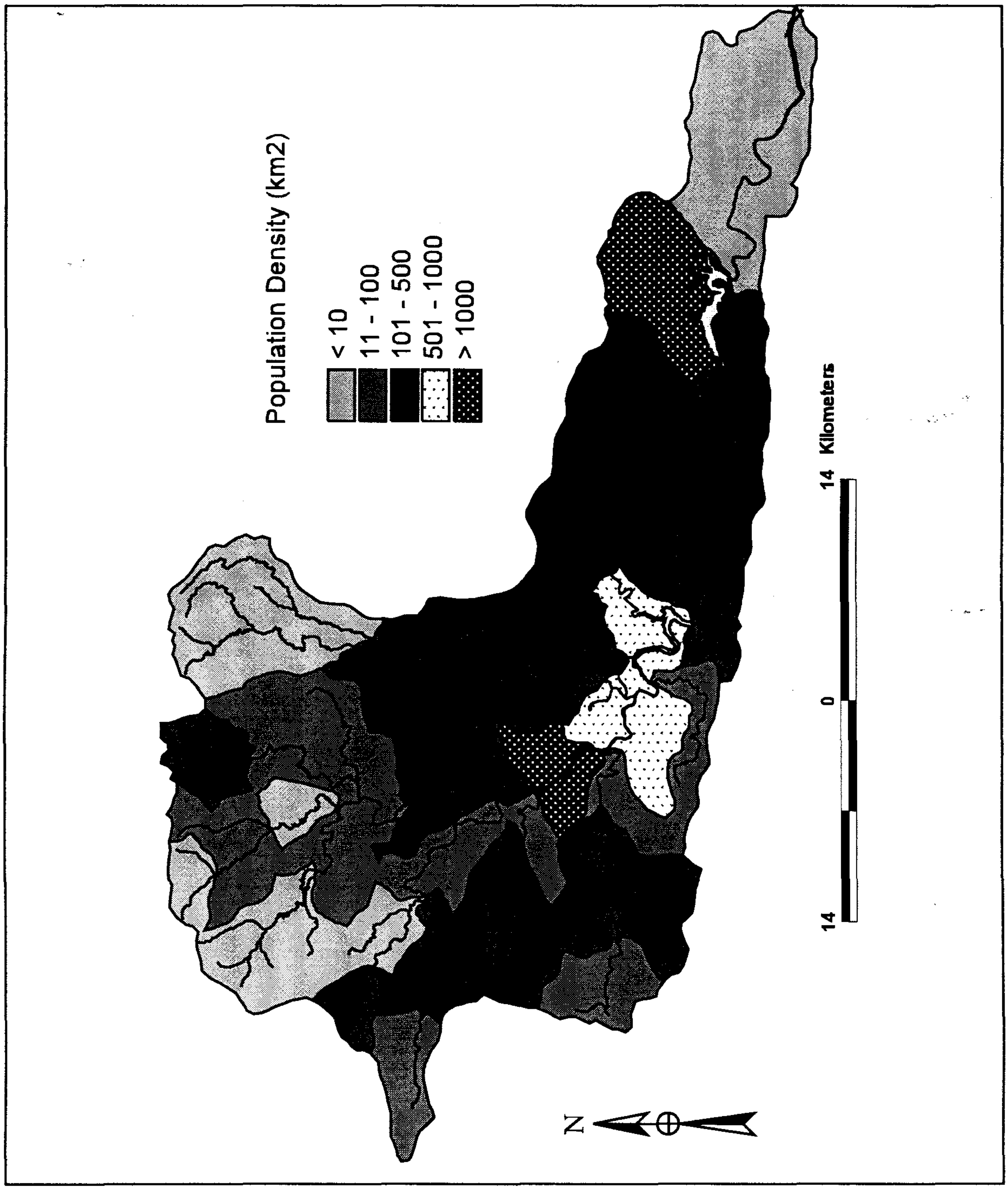


Figure 5.10 Population distribution within the Buffalo River catchment

Data analysis

The production of sediment production zones is a complex procedure which requires each contributing variable to be subdivided into classes based on aspects such as weathering potential, carrying capacity, population density etc. A series of logical matrices are then used to combine various contributing variables to produce a potential sediment production map. Maps of slope gradient class (Figure 5.11) and soil erodibility class (Figure 5.12) were combined to produce an erosion potential map for natural conditions (Figure 5.13). A map depicting present landuse within the Buffalo catchment (Figure 5.9) was superimposed onto the map of natural erosion potential to produce a map of potential sediment source areas (Figure 5.14). Although this is a qualitative rather than quantitative representation of general catchment condition, it can be related to work carried out by Rooseboom (1992). This researcher calculated the average annual sediment yield for the Buffalo River catchment utilising resevoir surveys. For the catchment above Maden Dam (30 km^2) a value of 42 $t/km^2.a$ is given, the catchment above Laing Dam (913 km^2) is estiamted to yield 75 $t/km^2.a$ and the catchment above Bridle Drift Dam (1176 km^2) approximately 751 $t/km^2.a$..

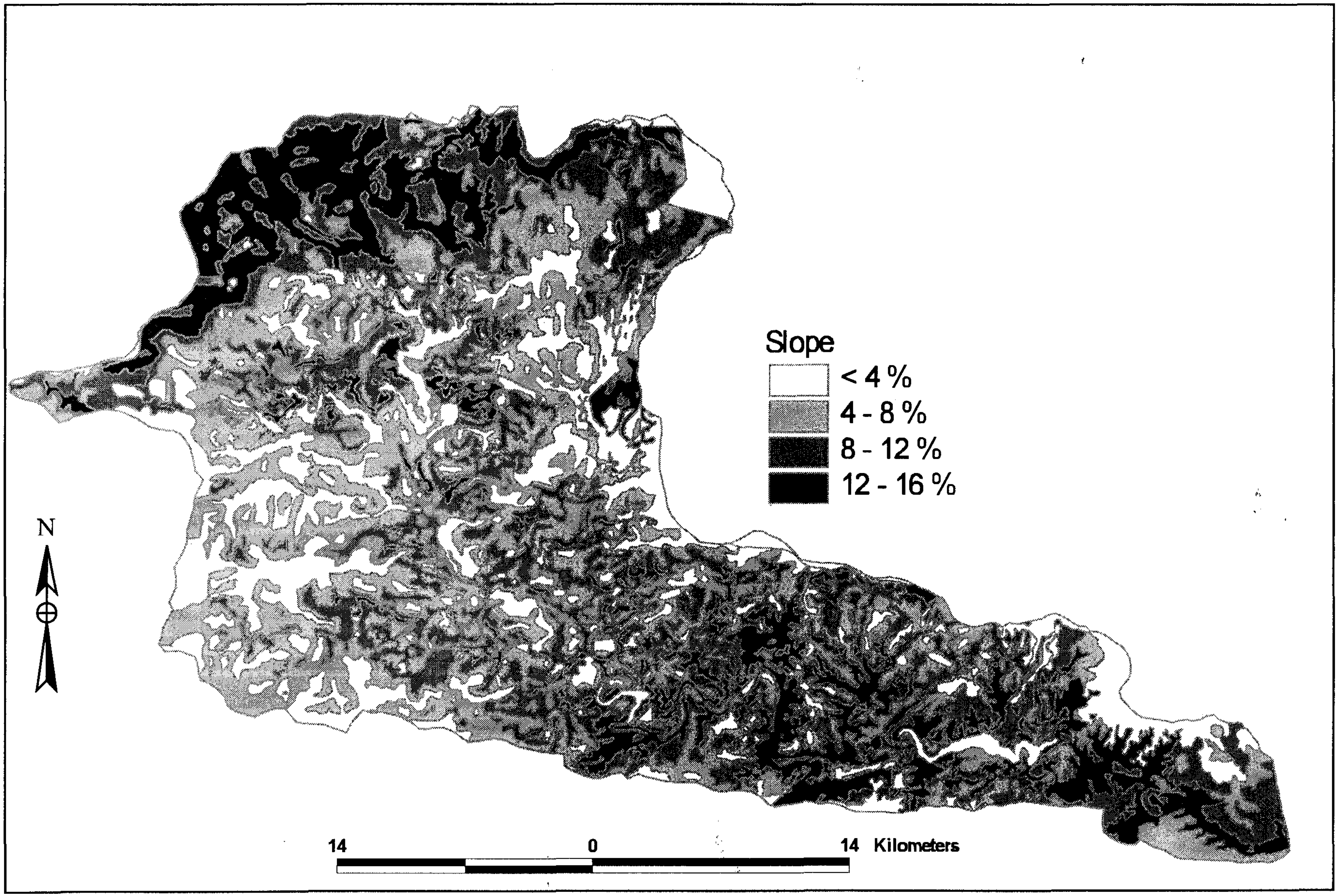


Figure 5.11 Slope class map of the Buffalo River catchment

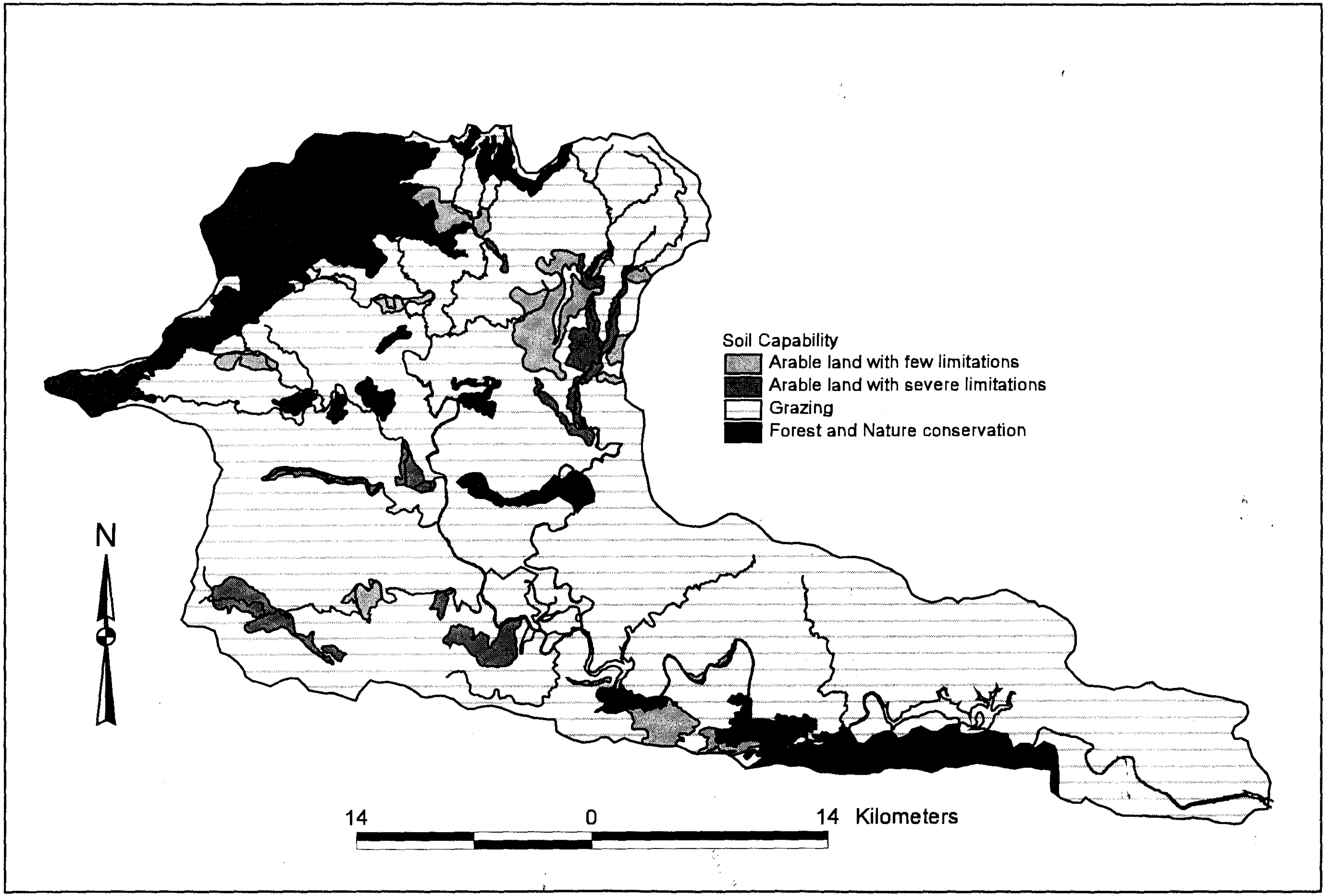


Figure 5.12 Soil class map of erodibility in the Buffalo River catchment

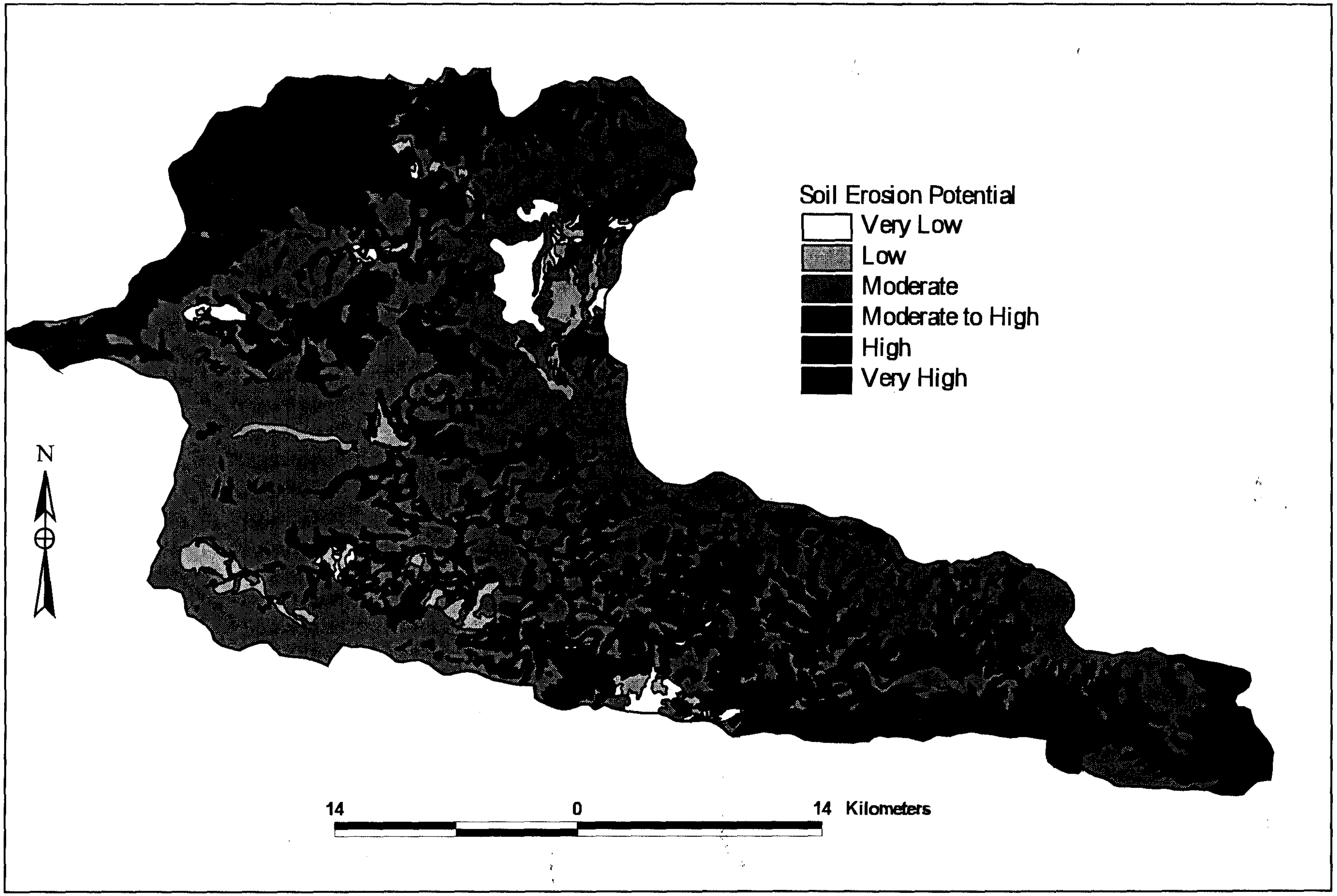


Figure 5.13 Erosion potential map of the Buffalo River catchment under 'natural' conditions

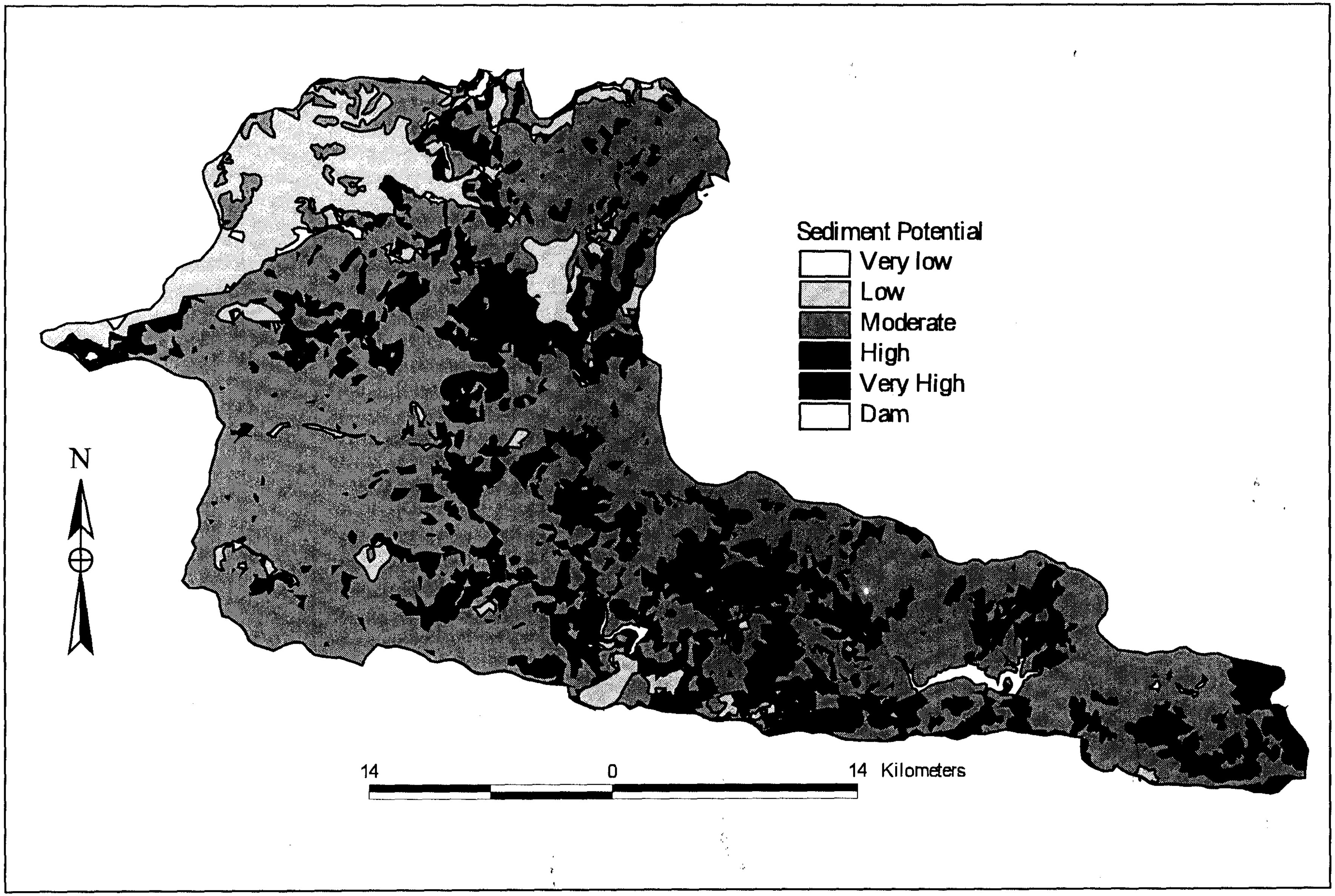


Figure 5.14 Potential sediment source map of the Buffalo River catchment

Runoff Zones

The Bufffalo River catchment can be divided into two major climatic zones, a high rainfall upland area with a humid, cooler temperate climate and a lower rainfall lowland area with a sub-humid, warmer temperate climate (Poynton, 1971).

Rainfall and evaporation
Mean annual precipitation over the whole catchment is 736 mm of which only 8.5 % reaches the river as streamflow, due to an average evaporation rate of 1360 mm per year (Hughes & Gorgens, 1982). Most of the rain falls at the top of the catchment, with between 1500 and 2000 mm at the watershed above Maden Dam. Figure 5.15 shows the rainfall distribution for each sub-area in the Buffalo River catchment. The Buffalo River systems can therefore be termed allogenic (Kale, 1990); that is the headwaters receive the highest rainfall and are the main area of runoff generation, whilst there is a much reduced contribution from downstream reaches.

From Rooikrans Dam to Bridle Drift Dam the mean annual precipitation is between 500 - 625 mm, generating local runoff only when there are episodes of heavy rain. As one gets closer to the coast, the influence of maritime weather conditions prevail. At Bridle Drift and Mdantsane mean annual precipitation increases to 700 mm and to more than 800mm in East London (O'Keeffe *et al.,* in press). Variations in rainfall between years is less extreme than for many catchments in southern Africa, with coefficients of variation for most of the rainfall stations of less than 0.25 (Hughes & Gorgens, 1982). There is a distinct seasonal variation in rainfall, with summer rains (October to March) producing double the volume of winter rains (May to August). Evaporation rates peak in December and January at 160 - 170 mm per month, reducing to 70 mm per month during June and July. As a result of the inverse correlation between rainfall and evaporation, seasonal streamflow variability is not as marked as that for rainfall (O'Keeffe *et al.,* in press)

Runoff
There are seven DWAF gauging weirs on the Buffalo River system (Figure 5.16), unfortunately only three of these weirs are situated on the main channel (R2H001, R2H005 and R2H010). There is however a relatively good duration of flow record for these stations; 48 years for site R2H001 above Maden Dam, 23 years for site R2H005 at King William's Town and 39 years for R2H010 above Laing Dam. A major shortfall of this gauging network is the absence of information on flows between Laing Dam and Bridle Drift Dam.

A map depicting homogenous runoff zones was obtained from Hughes *et al.* (in press) who carried out hydrological modelling of 38 sub-catchment of the Buffalo River. The initial simulation exercise involved a progressive calibration of Pitman's rainfall-runoff model (Pitman, 1973) starting in the upstream areas and working down to the river mouth. The starting point for parameter value estimation was always the regional values specified in Middleton *et al.* (1981). This provides a relatively standardised source of data for the mapping of runoff on a national level. A common 46 year period of rainfall record was used to simulate a typical flow regime that may be considered applicable to the present day situation. The resultant map (Figure 5.17) illustrates the contribution of total runoff of each sub-catchment area. Mean annual virgin runoff is expressed in mm.

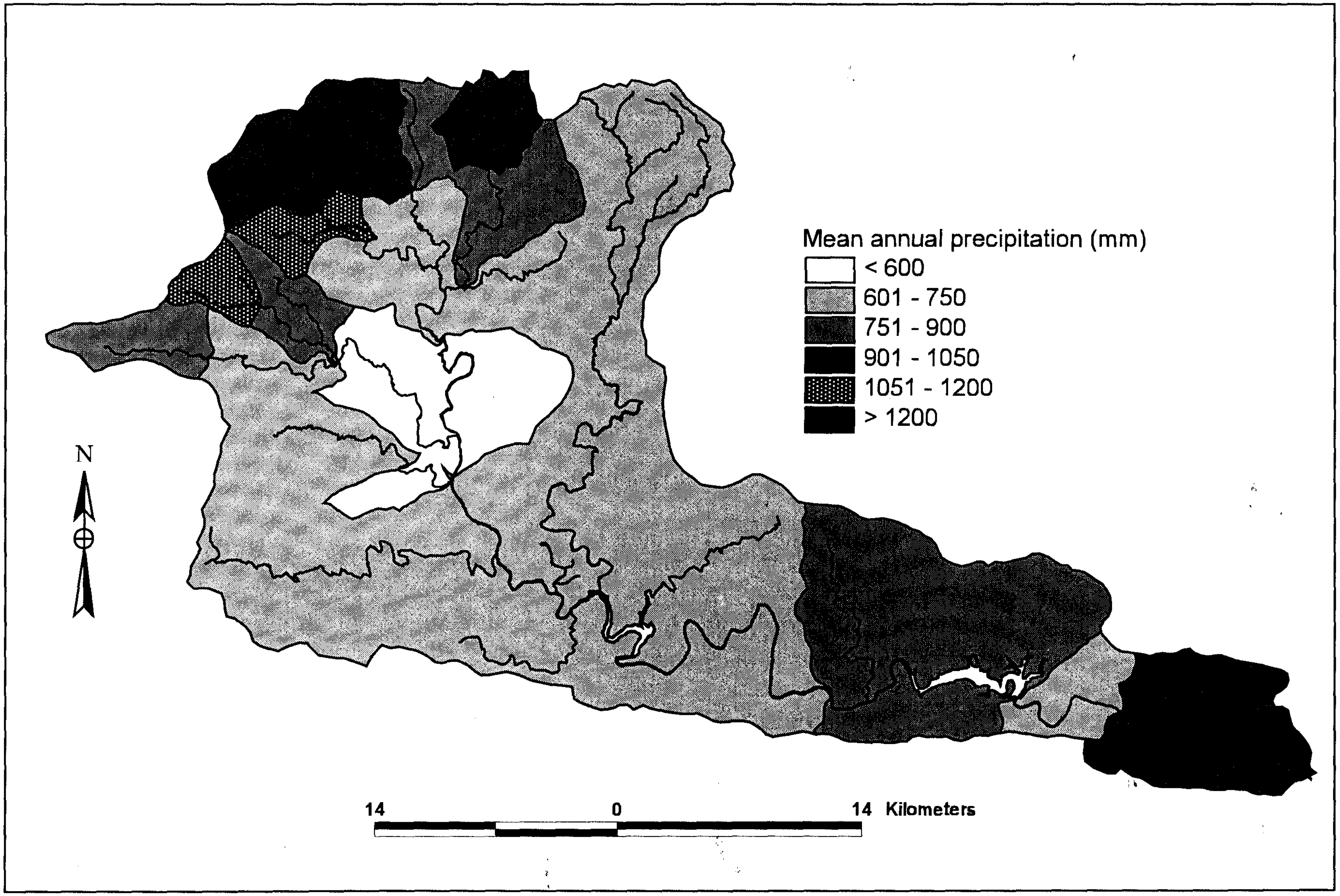


Figure 5.15 Rainfall distribution for sub areas of the Buffalo River catchment (Hughes et al., in press)

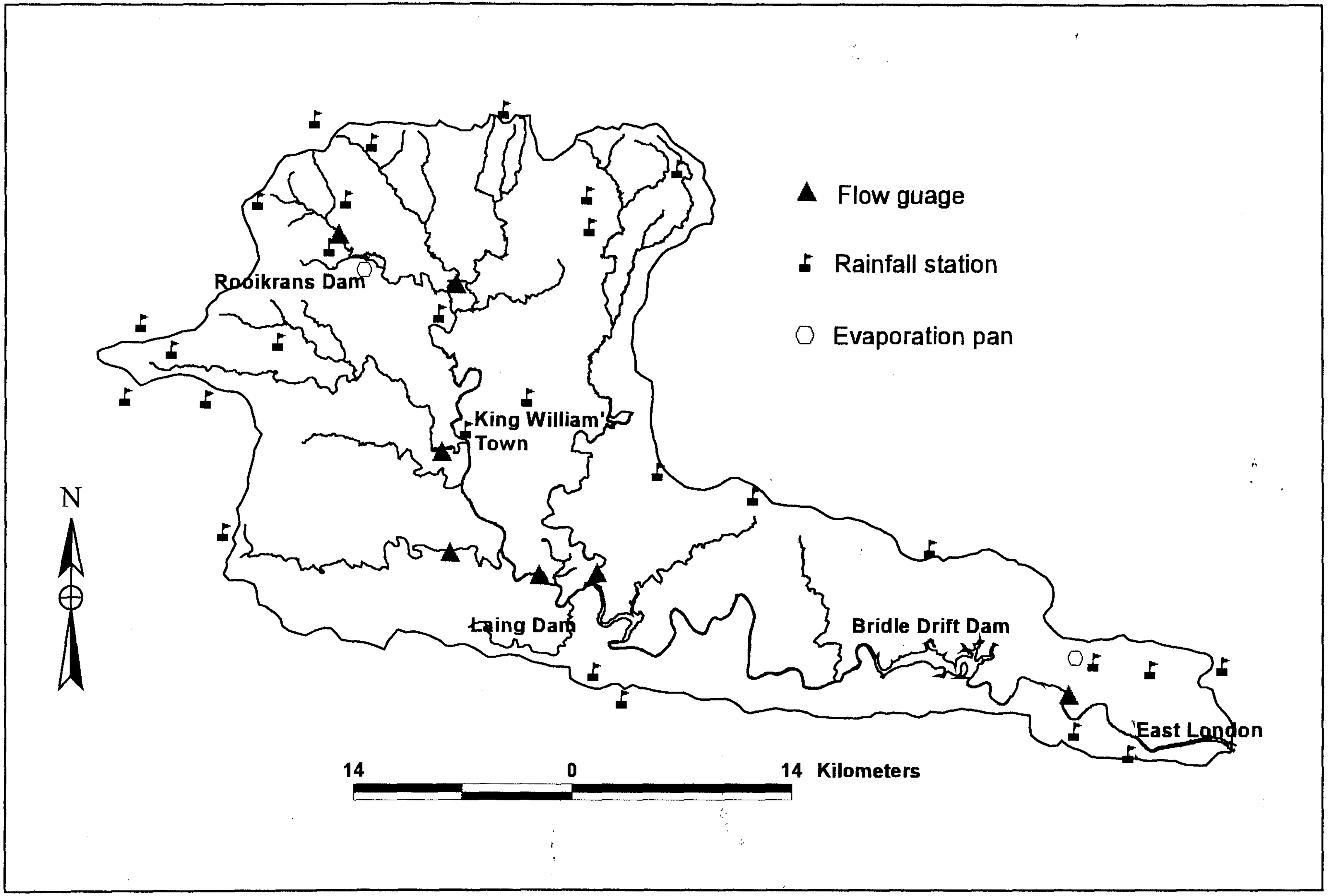


Figure 5.16 Hydrological monitoring network of the Buffalo River catchment

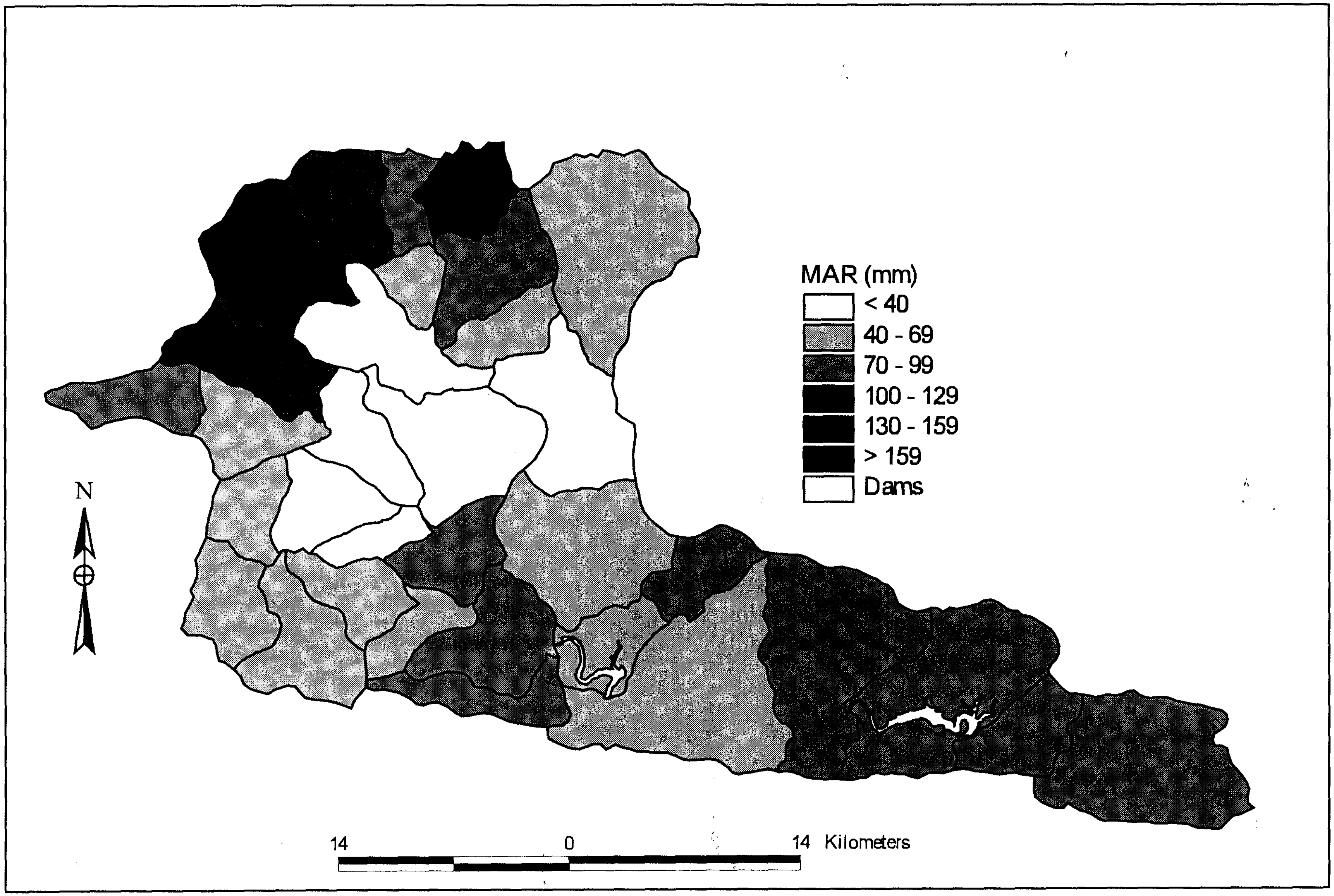


Figure 5.17 Map showing mean annual runoff for sub-catchments of the Buffalo River (after Hughes *et al.* In press)

As sediment and discharge are the two major variables influencing the morphology of the river channel, the homogeneous zones created in this level of the hierarchy provide the basic inputs for the third level of the hierarchy, the stream segments.

5.3.3 The segment

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, where a segment is a length of channel along which there is no significant change in the imposed flow discharge or sediment load.

Segments are delineated in terms of their position in the drainage network and their relationship to catchment zones, with major tributary junctions or impoundments defining points at which significant changes in the discharge of sediment and/or runoff entering the channel can be expected. Segments can theoretically 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.

Using the software programme Quattro Pro, a relatively simple technique was devised to route cumulative sediment and runoff through the catchment. This segment analysis is for 'natural' conditions and assumes no abstraction occurs and that no dams are present. A sediment-runoff ratio was plotted so as to indicate points along the channel at which major changes in inputs occurred (Figure 5.18). These points were considered as segment boundaries and plotted onto the drainage network as shown in Figure 5.19

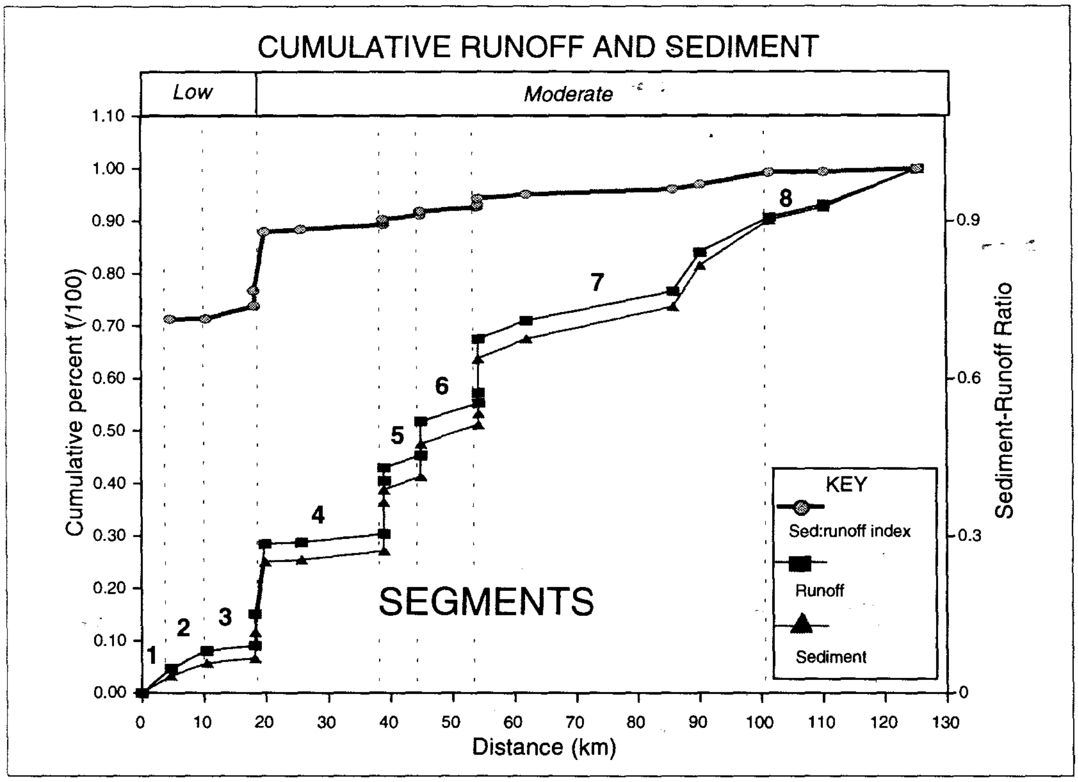


Figure 5.18 Cumulative runoff and sediment curves for the Buffalo River Catchment

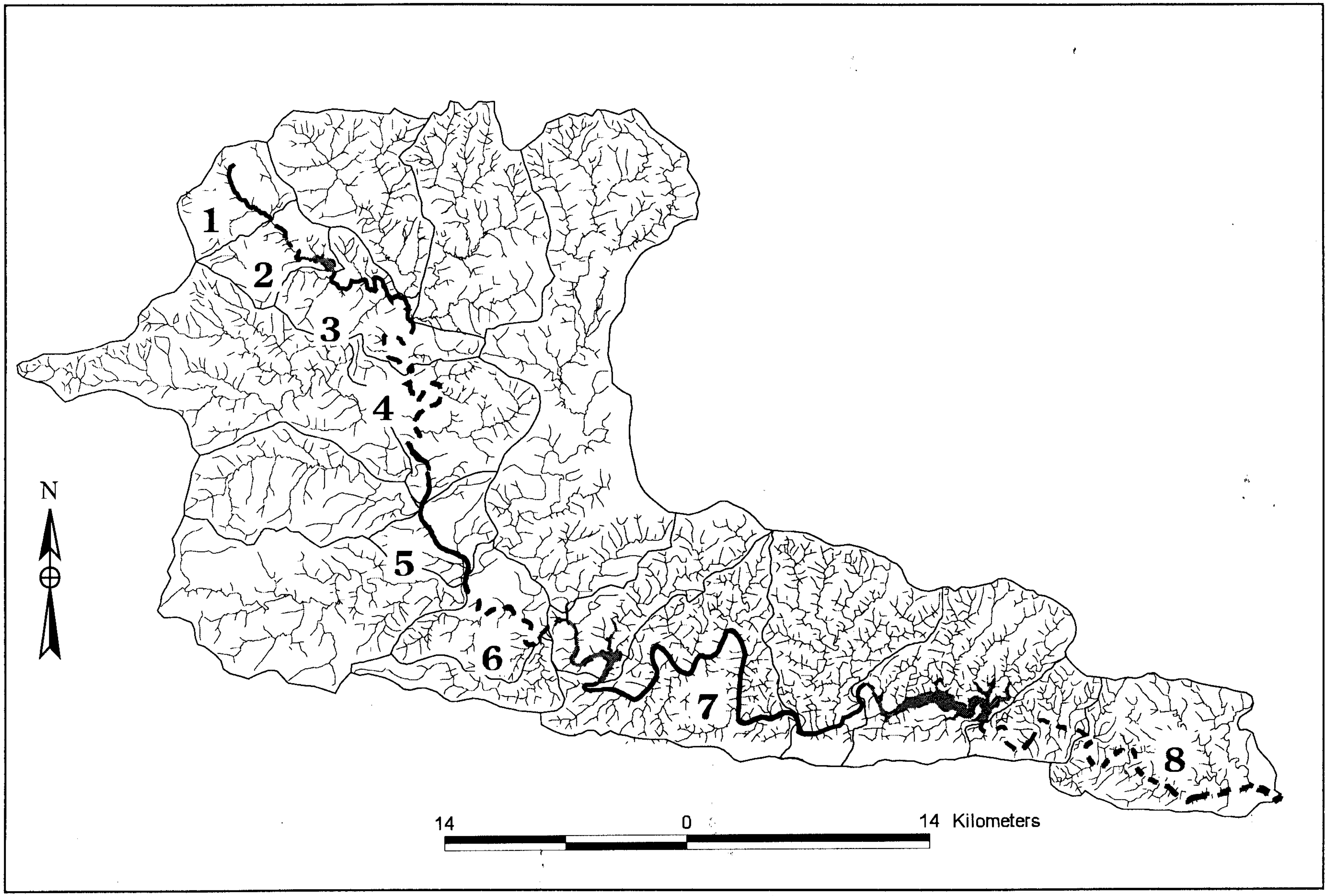


Figure 5.19 Segment map of the Buffalo River drainage network

5.3.4 The Reach

Variations in channel morphology may occur within a segment due to changes in the perimeter conditions of the drainage network. A reach is defined as a length of channel within which the local constraints on channel form are uniform. Reaches exhibit a consistent association of bedforms or channel units. Valley slope together with discharge and sediment load are the dominant controls of channel form adjustment. These three independent variables integrate the effects of climate, vegetation, soils, geology and basin physiography.

The long profile of a river channel is the least transient expression of fluvial processes, reflecting as it does geological influences such as the effect of tectonic history and base level change on available relief and the distribution of outcrops of different lithologies, or of climatic change on the processes of erosion and deposition. Long profile adjustments are emphasized as being necessary to maintain sediment transport with the available discharge and given channel characteristics (Mackin, 1948). However, mutual adjustment of gradient, plan form and cross section properties characterize the true response of alluvial streams to the multivariate environment controls of runoff, flood magnitude and frequency, sediment yield and sediment calibre. The interaction of these controls determines the gradient at the reach scale, and their downstream variation determines the spatial adjustments of gradient which create the complete long profile.

Utilising the technique outlined in Appendix Three, the longitudinal profile of the Buffalo River provided the initial basis for sub-dividing the stream segments into stream reaches (Figure 5.20). Field verification was carried out for the Buffalo River by completing a reach analysis form (Appendix Two) for each reach. Previous experience of this technique in the Sabie and Olifants River had shown stream reaches to 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). As a result of these associations reaches can be classified as "Reach Types". Table 5.2 provides a summary of the different types of reaches found within the Buffalo River.

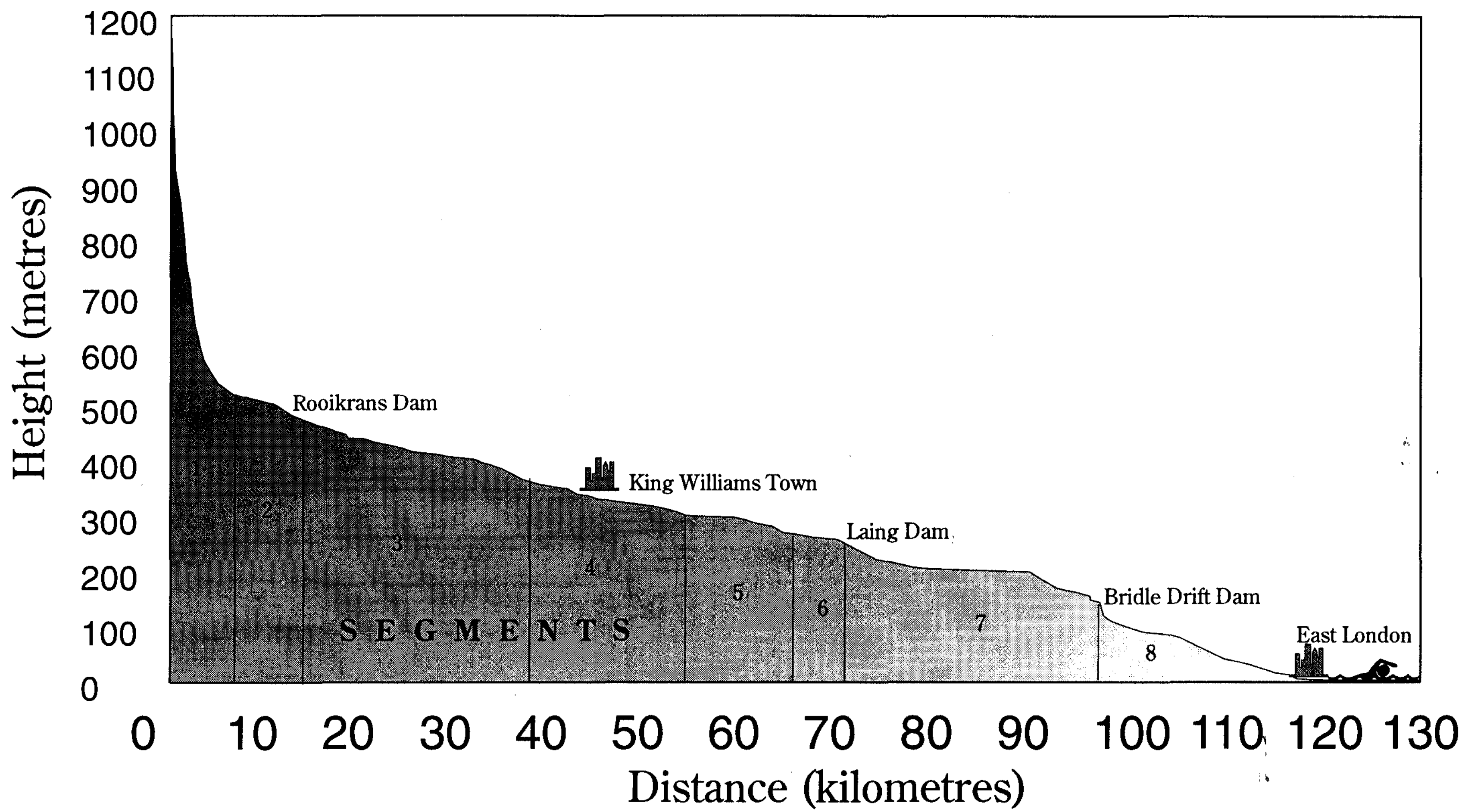


Figure 5.20 Longitudinal profile of the Buffalo River

Table 5.2 Summary of the reach types found in the Buffalo River. (Adapted from Grant *et.al.*, 1990; Montgomery & Buffington, 1993 and Van Niekerk *et al.*, 1994).

Reach Type	**Description**
Cascade	High gradient stream within a confined valley. Energy dissipation is dominated by jet and wake flow, hydraulic jumps and turbulence around individual large clasts.
Step-Pool	Occur within confined valleys and are characterised by large clasts which are organised into discrete channel spanning accumulations that form a series of steps separating pools containing finer material. Pool spacing tends to be 1- 4 channel widths.
Plane-Bed	Often associated with unconfined valleys and lack well defined bedforms. They are characterised by flow around particles that are large relative to the flow depth and are occasionally punctuated by channel spanning rapids or shallow pools. Occur at gradients and relative roughness intermediate between pool-riffle and step-pool reaches.
Pool-Riffle	Often associated with unconfined valleys and have an undulating bed that defines a sequence of bars (riffles) and pools.
Regime	Often associated with unconfined valleys in either sand or gravel. The channel exhibits a succession of bedforms with increasing flow velocity. The channel is characterised by low relative roughness.
Planar Bedrock	A contiguous alluvial bed is absent but some alluvial material may be temporarily stored in scour holes and behind flow obstructions. Significant falls or rapids are absent.
Bedrock Fall	Occur within confined valleys. A steep channel where water flows directly on bedrock with falls and pools which lead to free surface instability.
Pool-Rapid	Often associated with unconfined valleys. Channels are characterised by long pools backed up behind channel spanning bedrock intrusions. Sediments are deposited upstream of the local control in the form of braid and lateral bars (Van Niekerk et.al., 1994).

Reach analysis

A desk study was carried out to determine the approximate natural boundaries of physical reaches throughout the length of the main Buffalo River channel. Using orthophotos at a scale of 1 : 10 000 and contour intervals of 5 metres, 34 reaches were identified. Table 5.3 provides a summary of the reach charateristics observed in the Buffalo River.

Table 5.3 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	.46	5	Straight	L.Cobble, c.gravel	waterfall, bedrock pool, plunge pool, cascade
	2	1060-1000	Cascade	Confined	Indigenous forest	.40	7	Straight	Boulder, bedrock	waterfall, bedrock pool, plunge pool, cascade
	3	1000-980	Cascade	Confined	Indigenous forest	.19	6	Straight	Bedrock, boulder	waterfall, bedrock pool, plunge pool, cascade
	4	980-660	Cascade	Confined	Indigenous forest	.17	5	Sinuous	Bedrock, boulder	waterfall, bedrock pool, plunge pool, step
2	**1**	**660-640**	**Step-pool**	**Mod Confined**	**Indigenous forest**	**.17**	**8**	**Sinuous**	**Boulder, cobble**	**waterfall, bedrock pool, plunge pool, step**
	2	**640-600**	**Plane bed**	**Unconfined**	**Indigenous forest**	**.11**	**7**	**Sinuous**	**Cobble, boulder**	**plane bed, bedrock pool**
	3	600-540	Plane bed	Unconfined	Indigenous forest	.02	8	Sinuous	Cobble, boulder	plane bed
	4	**540-520**	**Pool-riffle**	**Unconfined**	**Indigenous forest**	**.008**	**12**	**Sinuous**	**Cobble, gravel**	**alluvial pool, riffle**
	5	520-500	Planar brock	Unconfined	Mixed Woody	.004	9	Irreg meander	Bedrock, boulder	rapid, bedrock pool
3	1	500-455	Pool-rapid	Unconfined	Mixed Woody	.004	13	Straight	Bedrock	rapid, bedrock pool
	2	455-450	Planar brock	Unconfined	Mixed Woody	.011	16	Irregular	Bedrock	rapid, bedrock pool, bedrock pavement
	3	450-445	Pool-riffle	Unconfined	Mixed Woody	.004	15	Reg meander	Gravel, cobble	alluvial pool, riffle
	4	445-440	Bedrock fall	Unconfined	Indigenous forest	.05	15	Straight	Bedrock	waterfall, bedrock pool, rapid
	5	**440-435**	**Pool-rapid**	**Confined**	**Mixed Woody**	**.002**	**30**	**Irreg meander**	**Cobble, gravel**	**alluvial pool, rapid**
4	1	435-410	Pool-riffle	Unconfined	Mixed Woody	.0041	15	Reg meander	Bedrock, cobble	alluvial pool, riffle, brock pool, brock pvmt
	2	410-400	Pool-rapid	Unconfined	Mixed Woody	.002	18	Irreg meander	Bedrock, gravel	rapid, bedrock pool
	3	400-380	Planar brock	Unconfined	Mixed Woody	.0075	20	Straight	Bedrock	rapid, bedrock pool, brock pavement

Table 5.3(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**	**380-330**	**Pool-rapid**	**Mod Confined**	**Shrubs & grasses**	**.0056**	**20**	**Anastomosing**	**Bedrock**	**rapid, bedrock pool, brock pavement**
6	1	330-315	Plane bed	Confined	Reeds & grasses	.0024	15	Sinuous	Cobble, gravel	plane bed, bedrock pool
	2	315-280	Planar brock	Confined	Reeds & grasses	.0041	15	Forced meander	Bedrock, boulder	waterfall, bedrock pool, rapid
7	1	280-275	Plane bed	Unconfined	Mixed Woody	.007	12	Anastomosing	Boulder, cobble	plane bed, bedrock pool, rapid
	2	275-270	Bedrock fall	Part Confined	Mixed Woody	.007	25	Forced meander	Bedrock	waterfall, bedrock pool, rapid
	3	270-250	Planar brock	Confined	Mixed Woody	.005	15	Anastomosing	Bedrock, boulder	rapid, bedrock pool, brock pavement
	4	250-240	Riffle-pool	Part Confined	Mixed Woody	.010	65	Straight	Boulder, bedrock	waterfall, bedrock pool, rapid, riffle
	5	240-195	Bedrock fall	Part Confined	Reeds & grasses	.006	10	Forced meander	Bedrock	waterfall, bedrock pool, rapid, riffle
	6	195-180	Riffle-pool	Confined	Mixed Woody	.007	25	Forced meander	Bedrock, boulder	bedrock pool, rapid, riffle
	7	180-160	Pool-rapid	Part Confined	Reeds & grasses	.006	45	Straight	Cobble, gravel	rapid, bedrock pool, brock pavement
	8	160-155	Pool	Confined	Reeds & grasses	.003	30	Straight	Cobble, gravel	alluvial pool
	9	140-115	Bedrock fall	Confined	None	.05	30	Forced meander	Bedrock, boulder	waterfall, bedrock pool, rapid, plunge pool
8	1	115-100	Riffle-pool	Part Confined	Mixed Woody	.006	50	Reg meander	Boulder, bedrock	alluvial pool, riffle
	2	100-85	Bedrock fall	Part Confined	Mixed Woody	.004	50	Straight	Bedrock	waterfall, bedrock pool, rapid, plunge pool
	3	85-40	Bedrock fall	Part Confined	Mixed Woody	.008	80	Straight	Bedrock	waterfall, bedrock pool, rapid, plunge pool
	4	40-10	Plane bed	Confined	Mixed Woody	.003	70	Forced meander	Cobble, boulder	plane bed, bedrock pool, rapid
	5	10-0	Estuary	Confined		.005	70			

The reach characteristics of the Buffalo River are largely a result of post-Mesozoic tectonism (King, 1972). The drainage network is degradational with considerable downcutting and limited sediment storage. The summary of reach characteristics of the Buffalo River clearly illustrates this pattern with the predominance of bedrock. The lack of significant quantities of alluvial material in the channel can be attributed to the high transport capacity associated with relatively short, steep channels. Some of the reaches within the Buffalo River have local pockets of alluvial material which makes up more than 60% of the channel perimeter, Kale (1990) classifies such channels as semi-controlled. These reaches have more freedom to adjust their form than the bedrock controlled reaches and hence show a channel morphology more commonly associated with alluvial channels (riffle-pool).

5.3.5 The Morphological Unit

The morphological units are the basic structures or building blocks recognised by fluvial geomorphologists as comprising the channel morphology and may be either erosional or depositional features. A summary of the morphological units recognised in the Buffalo River is given in Table 5.4.

Table 5.4 Morphological units within the Buffalo River adapted from Wadeson (1994) and Van Niekerk *et al.* (in press).

Morphological Unit	Description
Alluvial Pool	Topographic low points with sandy beds at low flows.
Alluvial Backwater	Stationary or near stationary bodies of water adjacent to the active channel.
Riffle	Topographic high points in an undulating bed long profile composed of coarser sediments.
Step	Occur within headwater streams, characterised by large clasts organised into discrete channel spanning accumulations.
Plane Bed	Consist of large clasts relative to flow depth and lack well defined bedforms
Cascade	Occur within steep headwater streams, characterised by very large clasts approximating bankfull size randomly distributed.
Plunge Pool	Erosional feature below a resistant strata (waterfall).
Bedrock Pool	Form behind resistant strata lying across the channel.
Rapid	Local steepening of the channel long profile over bedrock.
Bedrock Pavement	Horizontal or near horizontal area of exposed bedrock.
Cataract	Step like succession of small waterfalls which are seldom drowned out at high flows.
Waterfall	Abrupt discontinuity in channel slope.
Braid Bar	Accumulation of sediment in mid channel
Lateral Bar	Accumulation of sediment atatched to the side of the channel
Point Bar	Accumulation of sediment on the inside of a meander bend
Lee Bar	Accumulation of sediment in the lee of a flow obstruction

The channel form features listed above have special ecological significance within the hierarchical model because of their influence on flow hydraulics and hence hydraulic biotope distribution. Reach analysis places special emphasis on the occurrence of morphological units within a stretch of river.

5.3.6 The Hydraulic Biotope

The hydraulic biotope is the lowest level of the hierarchical model and provides the essential scale based link between the physical characteristics of the river and the aquatic biota which respond to changes in substratum and flow conditions. It is the development of this level of the hierarchical model that forms the focus of the remaining research carried out in this thesis.

Before presenting the methods used for the Buffalo River study, a reminder of the specific aims of this detailed study are given.

***Specific Aims*:**

The specific aims of the detailed study carried out in the Buffalo River arise from the development of the hydraulic biotope concept presented in the pilot studies of Chapter Four and the recommendations as a result of those studies.

① To apply the hierarchical geomorphological model to the Buffalo River catchment - ***addressed in this chapter.***

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

③ To test the use of hydraulic indices representing micro flow conditions as quantitative variables to characterise hydraulic biotopes.

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

⑤ To determine the influence of substratum, scale and discharge on the near bed flow characteristics of hydraulic biotopes.

⑥ To assess the validity of using a hydraulic biotope matrix to classify ecologically significant hydraulic environments.

⑦ To determine the relationship between hydraulic biotope distribution and channel morphology within selected reaches of the Buffalo River.

⑧ To determine the pattern and direction of change of hydraulic biotope classification in response to changing discharge.

⑨ To link the hydraulic biotope concept to the hierarchical geomorphological model.

5.4 METHODS

5.4.1 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. An observation from the reach analysis summary is that the more diverse hydraulic environments within the Buffalo River were to be found within the upper reaches where large substratum dominated the bed material and discharge was more consistent.

Within a diverse hydraulic environment there was a need for a relatively reliable and variable flow regime, a difficult requirement for the drought stricken Eastern Cape. This task was made even more difficult by the large number of dams in this catchment which alter the natural flow regime. Furthermore none of the dams in the Buffalo catchment are managed for downstream releases.

Site selection within the river needed to meet the requirements of different spatial scales of hydraulic biotopes and diverse channel morphology. This was a particularly difficult task due to the absence of flow in the lower reaches of the channel (below Laing Dam) for most of the year, therefore excluding that part of the river A further consideration here was the problem of access; many parts of the Buffalo River flow in deeply incised valleys making them inaccessible. Security is also a problem as large rural and peri-urban settlements rely on the Buffalo River as their only source of water; these inhabitants can be very suspicious of strangers working in their water source. Considering the criteria of this study, five distinct morphological reaches were selected, within these reaches appropriate study sites were chosen.

Site 1. Trestle Bridge

The uppermost site resides within segment 2, reach 1 of the hierarchical model (Table 5.3). This reach 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 (Table 5.2) can be classified as step-pool after Griffiths (1980), Ashida *et al.* (1981), Whittaker and Jaeggi (1982), Whittaker and Davies (1982), Whittaker (1987), Chin (1989) and Grant *et al.* (1990). 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 bed morphology 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 (Table 2.4), 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, backwater pools, 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 at a relatively high discharge to try and encompass the full range of observed flow conditions. Plate 5.1a 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 5.21 while cross sections of surveyed transects, together with sampling points, are given in Figures 5.22a, b, c, d, e, f, g, h and i.

Plate 5.1a Photograph of site 1 (Trestle Bridge), looking upstream.

Plate 5.1b Photograph of site 1 (Trestle Bridge), looking downstream.

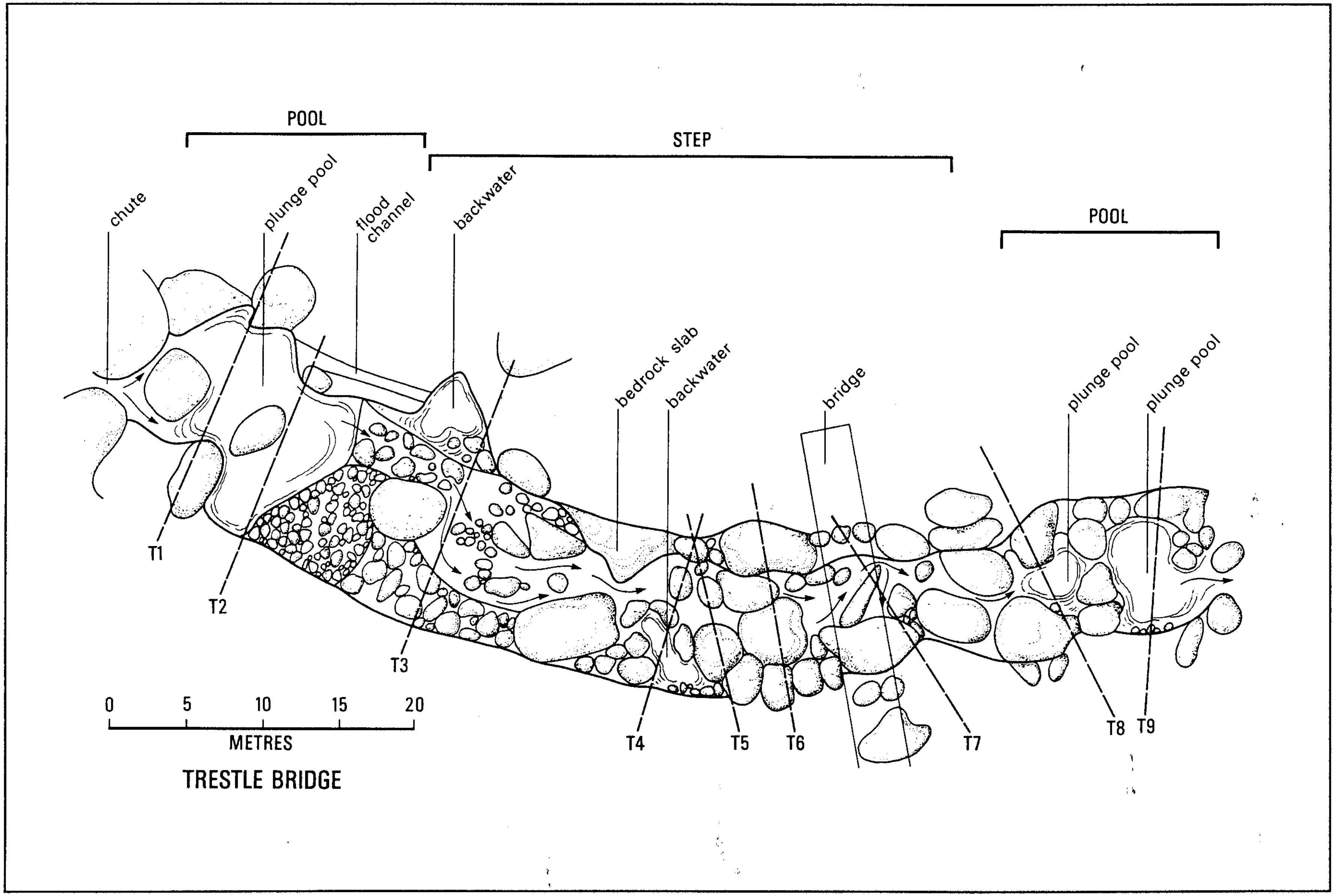


Figure 5.21 Plan view of site 1 (Trestle Bridge)

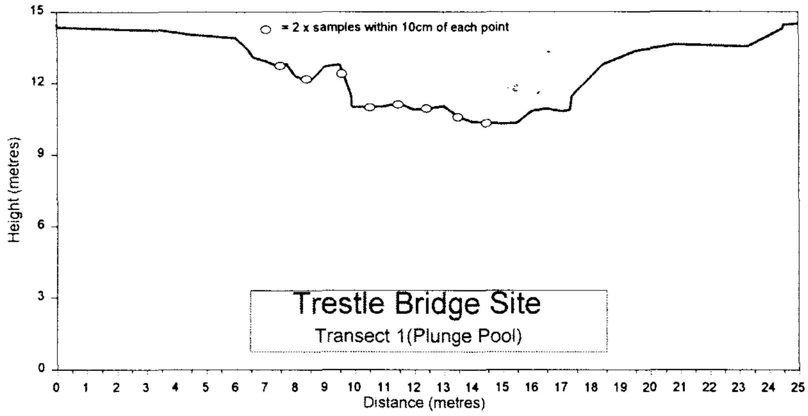


Figure 5.22a Transect 1 Cross Section

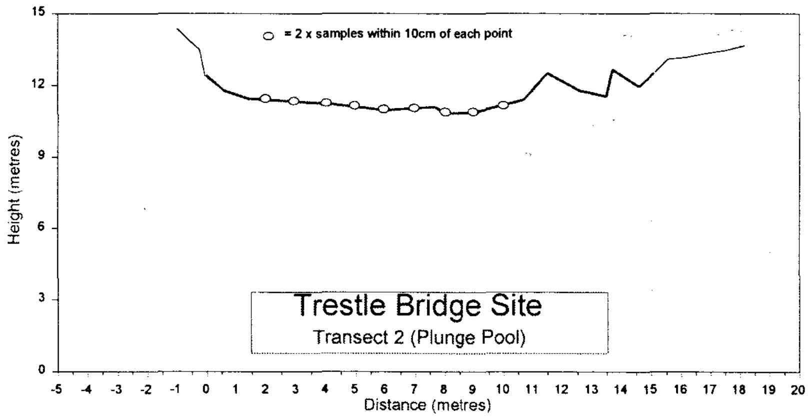


Figure 5.22b Transect 2 Cross Section

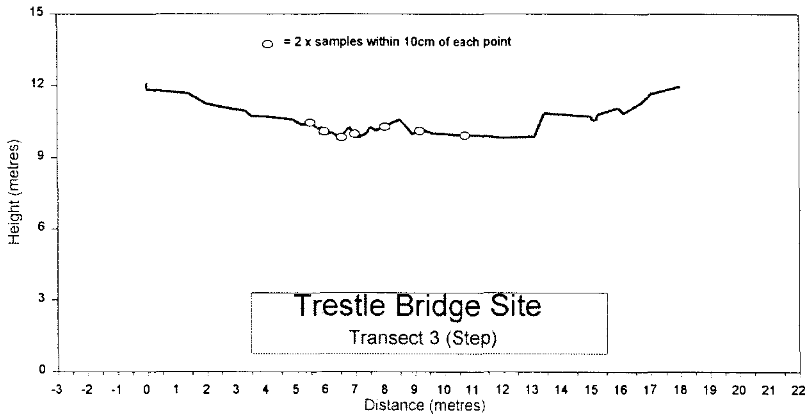


Figure 5.22c Transect 3 Cross Section

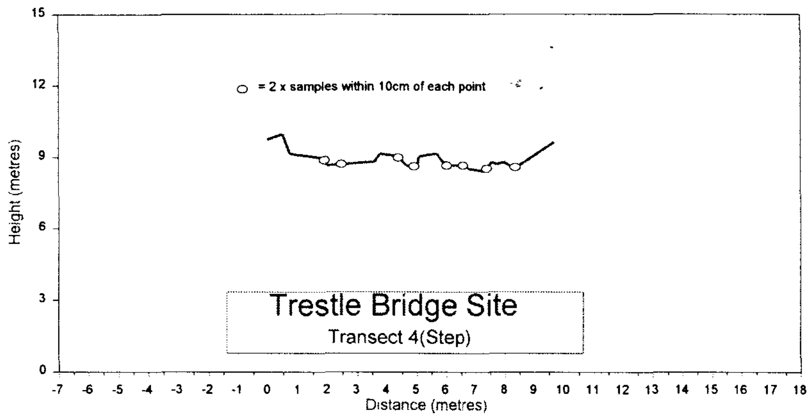


Figure 5.22d Transect 4 Cross Section

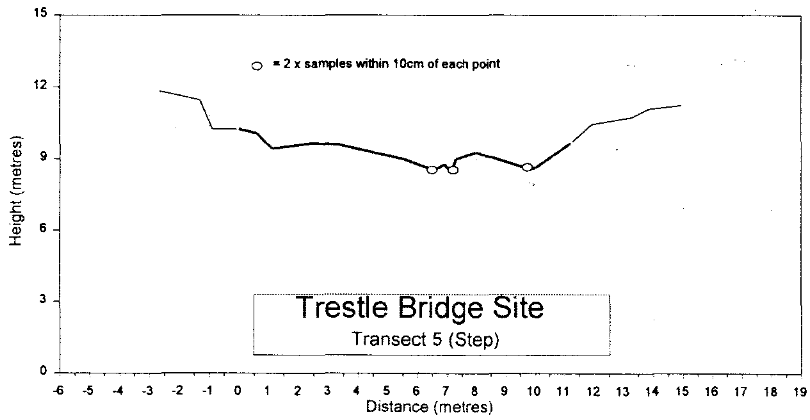


Figure 5.22e Transect 5 Cross Section

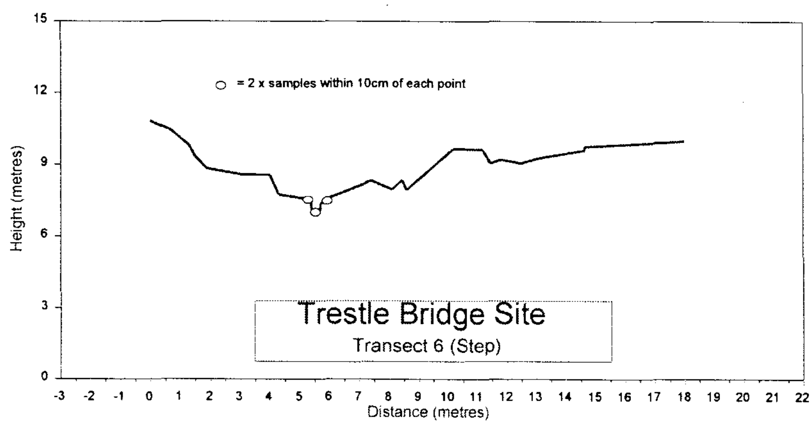


Figure 5.22f Transect 6 Cross Section

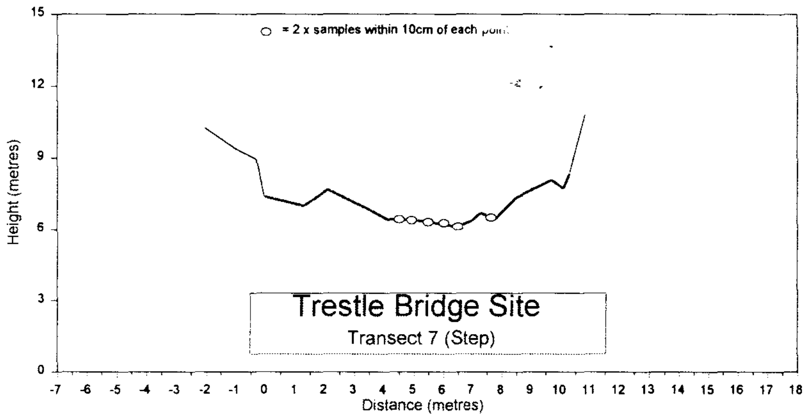


Figure 5.22g Transect 7 Cross Section

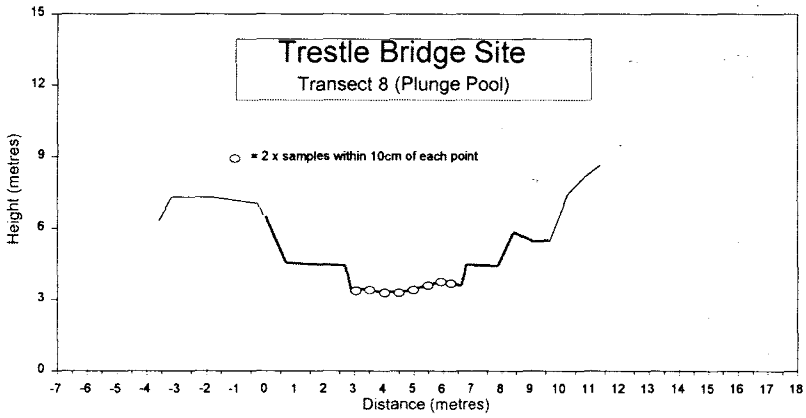


Figure 5.22h Transect 8 Cross Section

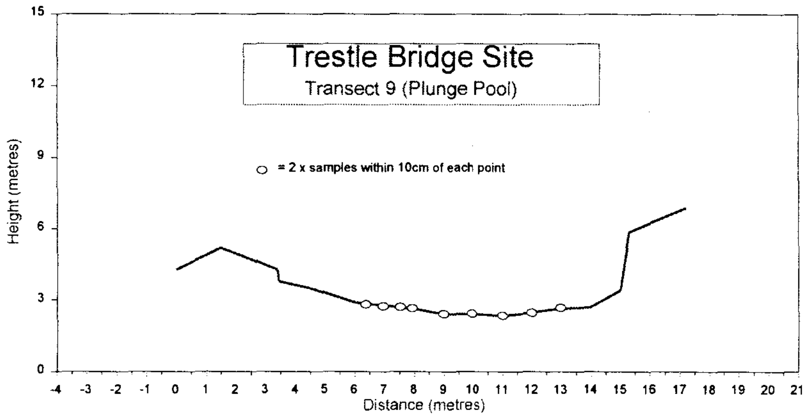


Figure 5.22i Transect 9 Cross Section

Site 2. Causeway

This reach is also situated in the Amatola forest reserve but occurs on the flatter foothills. The site is relatively close to site 1, but is within a different reach (segment 2, reach 2 of Table 5.3). The average channel gradient for this reach is (0.11) and it flows within the Beaufort group geology of 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 a plane-bed morphology (Table 5.3). 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. According to Montgomery and Buffington (1993), these reaches may occur at gradients and relative roughness intermediate between pool-riffle and step-pool reaches. Specific bed morphology found within this reach include series of low waterfalls over large clasts, termed 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 5.2a and b illustrate the channel morphology at this site. A plan view of the research site is given in Figure 5.23 while cross sections of surveyed transects, together with sampling points, are given in Figures 5.24a, b, c, d, e, f, g, h and I.

Plate 5.2a Photographic overview of site 2 (Causeway), looking upstream.

Plate 5.2b Photographic overview of site 2 (Causeway), looking downstream.

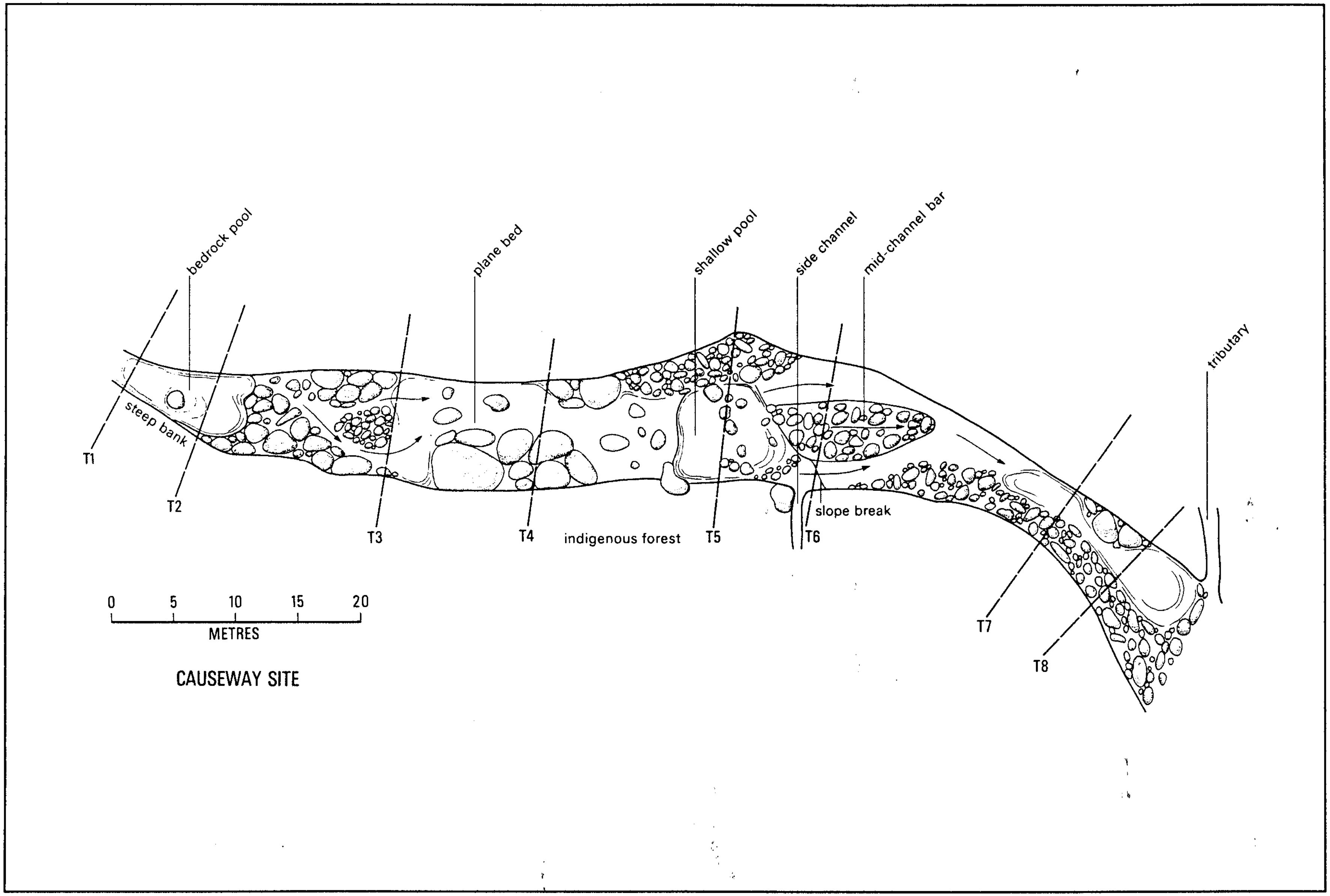


Figure 5.23 Plan view of site 2 (Causeway)

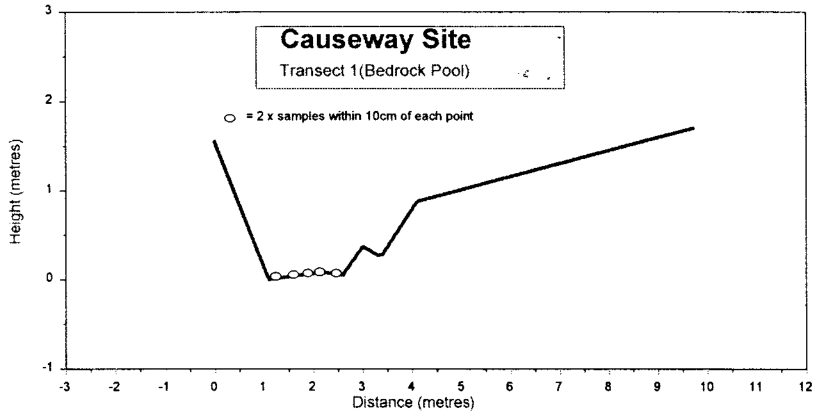


Figure 5.24a Transect 1 Cross Section

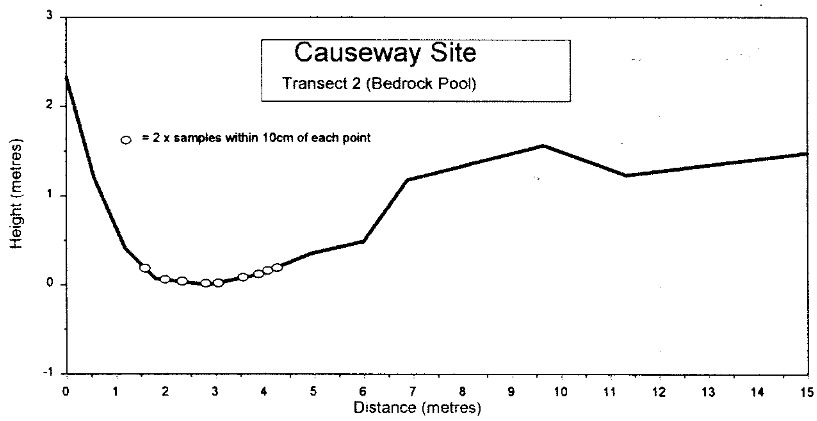


Figure 5.24b Transect 2 Cross Section

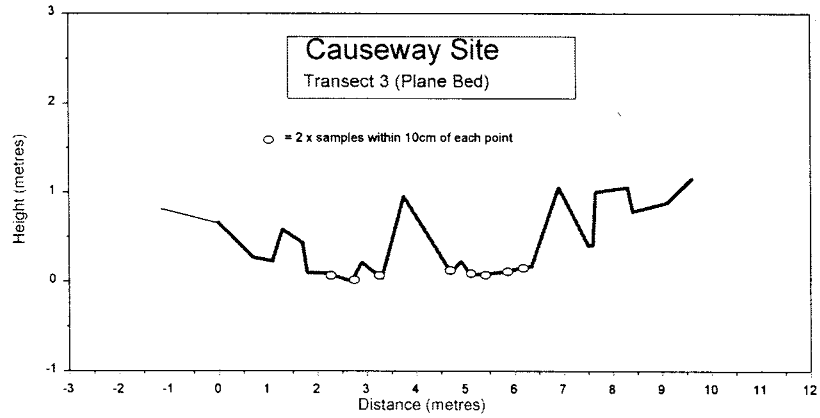


Figure 5.24c Transect 3 Cross Section

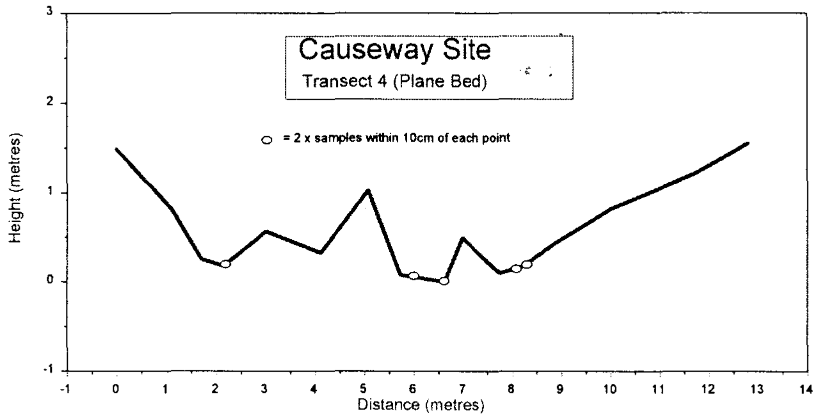


Figure 5.24d Transect 4 Cross Section

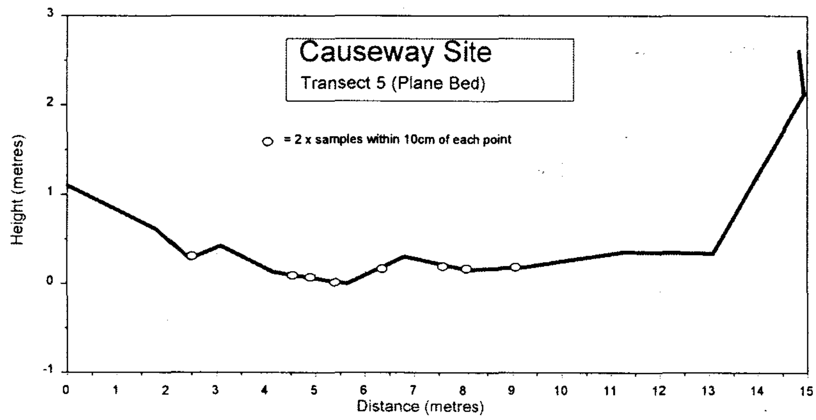


Figure 5.24e Transect 5 Cross Section

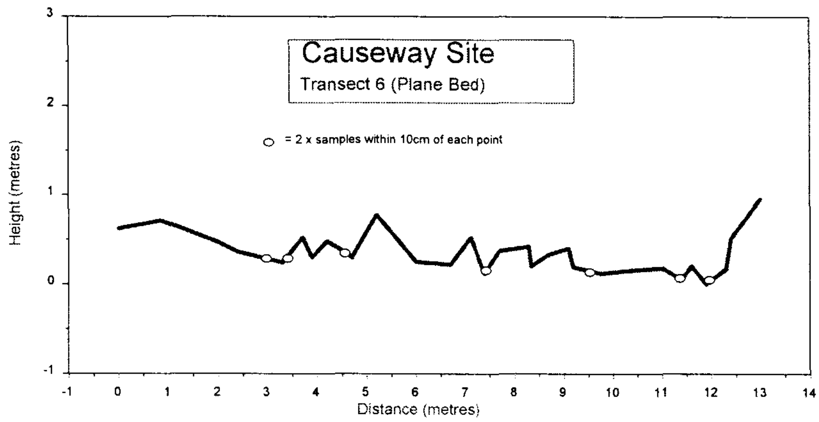


Figure 5.24f Transect 6 Cross Section

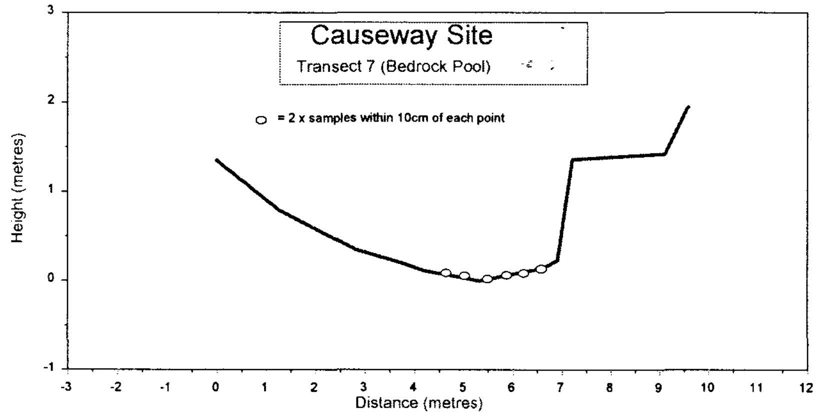


Figure 5.24g Transect 7 Cross Section

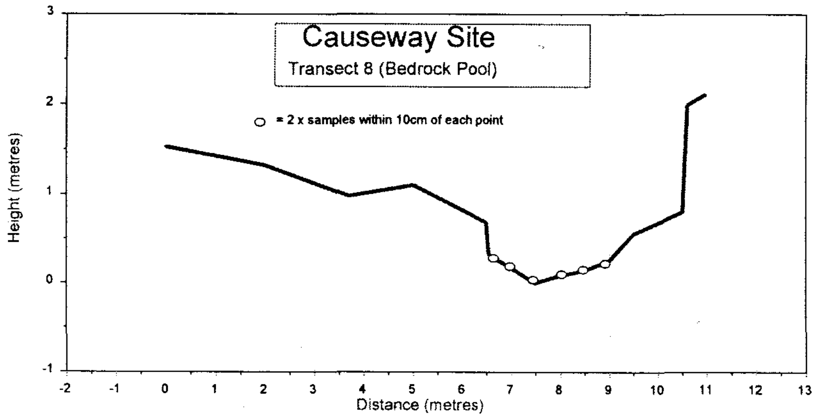


Figure 5.24h Transect 8 Cross Section

Site 3. Trout pools

This reach is situated on the margins of the Amatola state forest approximately 1 km upstream of Maden Dam (segment 2, reach 4 of Table 5.3). 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 (1990) 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 (Table 5.2). These features represent topographic low (pool) and topographic high (riffle) points within an undulating bed. The formation of pool and riffle sequences is not well understood but is believed to be as a result of local flow convergence and divergence which is either freely formed by cross stream flow or may be forced around obstructions. Cross channel oscillating flow causes flow convergence and scour on alternating banks of the channel. Downstream flow divergence results in local sediment accumulation in discrete bars. Specific morphological units associated with this reach type are lee bars, lateral bars, alluvial pools and riffles.

This 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 usage of the pool features for trout habitation. 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 succesion 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 5.3a and b. A plan view of the research site is given in Figure 5.25 while cross sections of surveyed transects, together with sampling points, are given in Figures 5.26a, b, c, d, e, f, g, h and i.

Plate 5.3a Photograph of site 3 (Trout Pools), looking upstream

Plate 5.3b Photograph of site 3 (Trout Pools), looking downstream

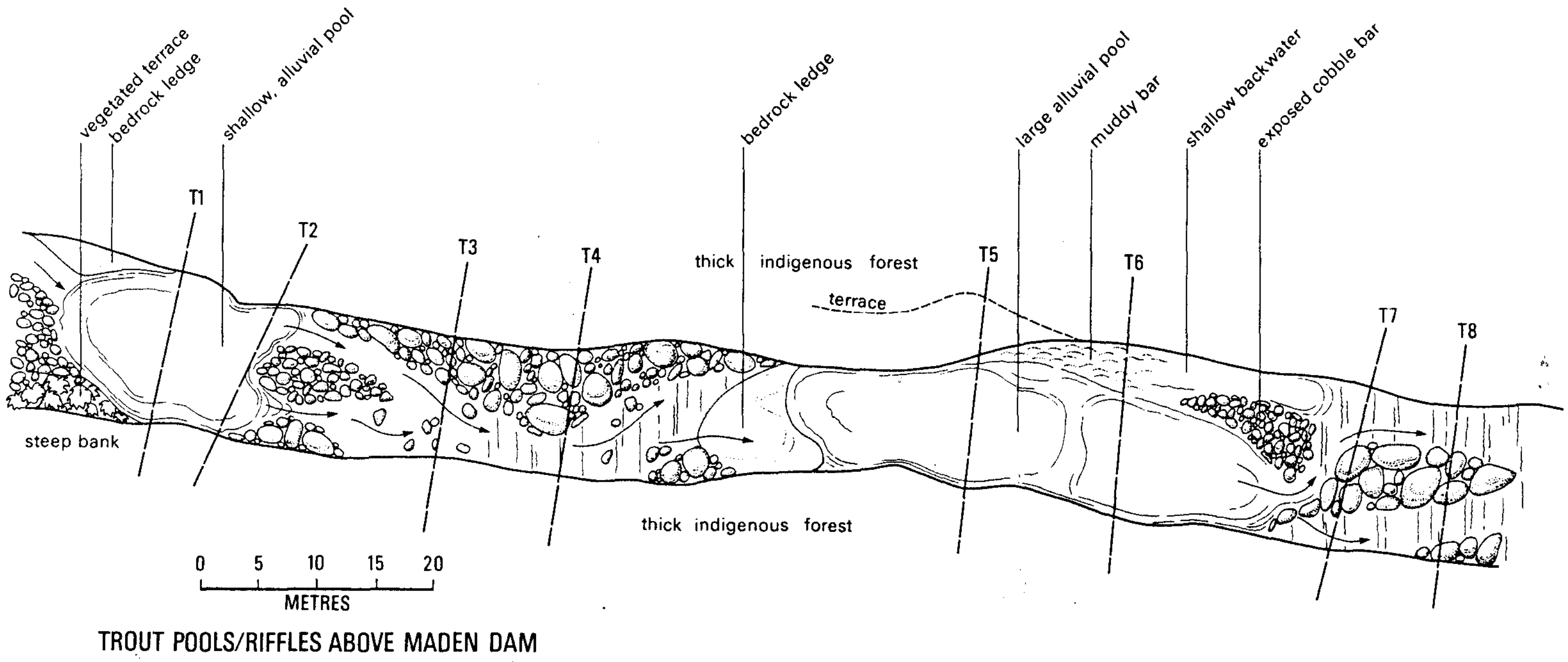


Figure 5.25 Plan view of site 3 (Trout pools)

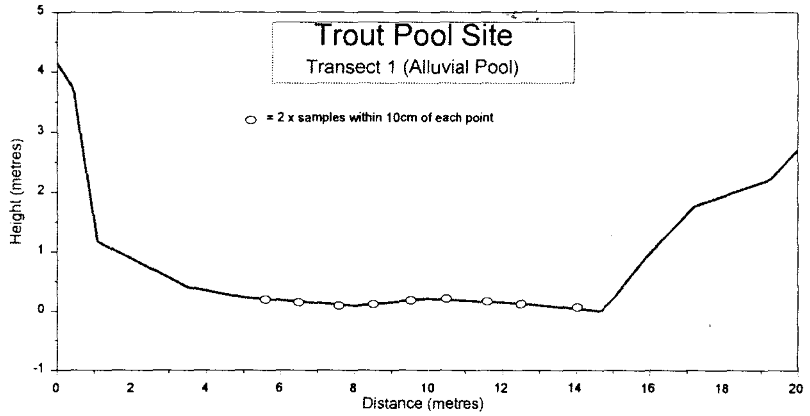


Figure 5.26a Transect 1 Cross Section

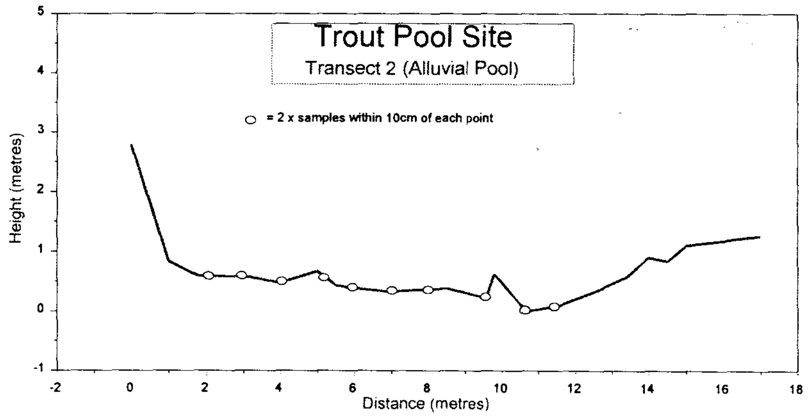


Figure 5.26b Transect 2 Cross Section

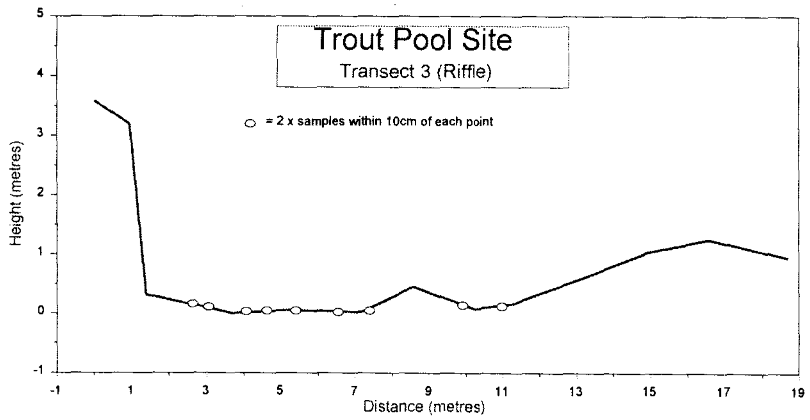


Figure 5.26c Transect 3 Cross Section

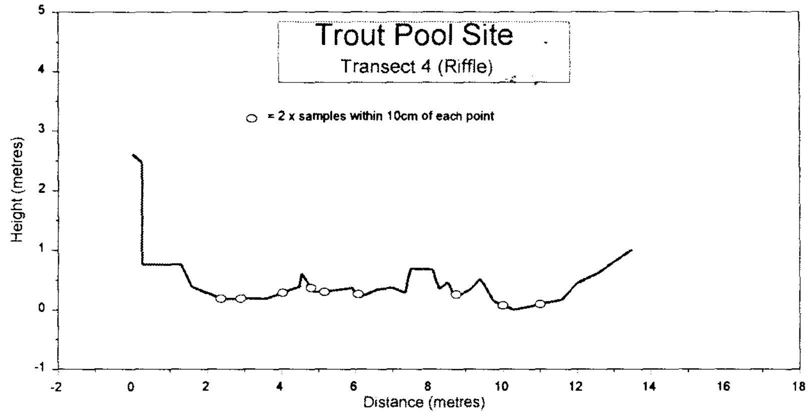


Figure 5.26d Transect 4 Cross Section

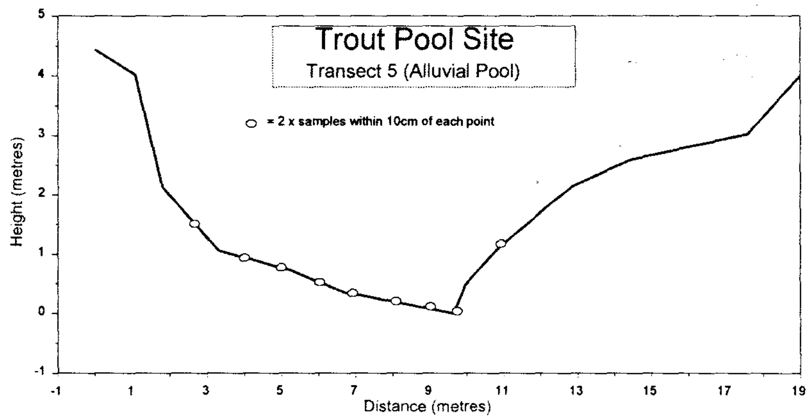


Figure 5.26e Transect 5 Cross Section

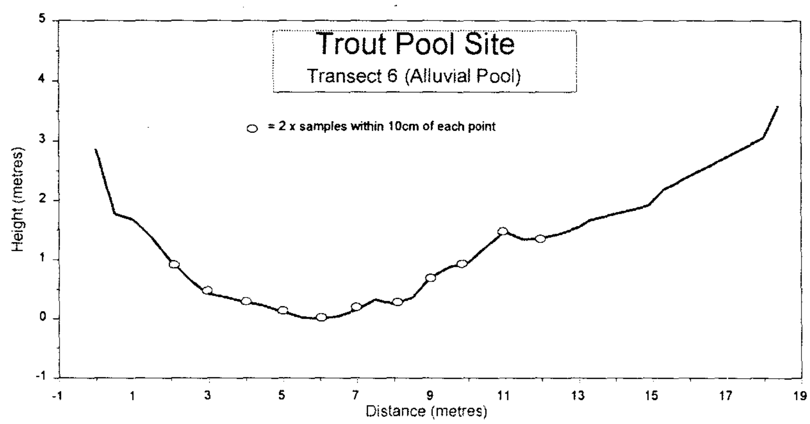


Figure 5.26f Transect 6 Cross Section

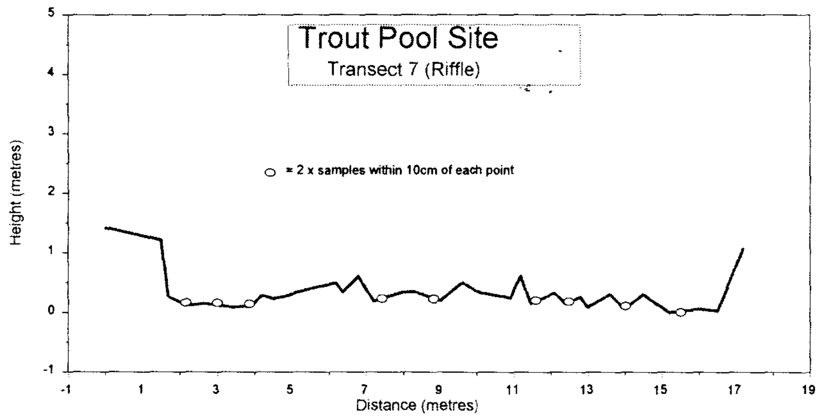


Figure 5.26g Transect 7 Cross Section

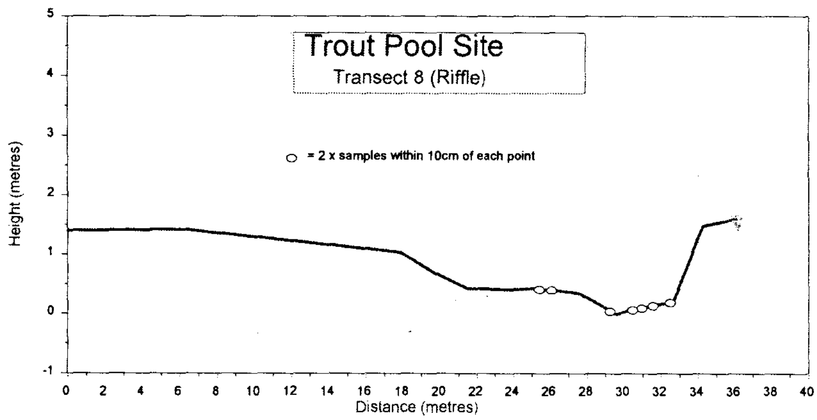


Figure 5.26h Transect 8 Cross Section

Site 4. Braunschweig

This reach is situated in the drier lowland areas of the catchment approximately 10km downstream of Rooikrans Dam (segment 3, reach 5 of Table 5.3). 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 Rooikraans 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 Rooikraans 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, 1990).

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 bedrock. These small vegetated islands have been termed bedrock core bars by van Niekerk *et al.* (in press), and are formed by the deposition of sediments on topographical high points as floods recede. The development of these features within this reach of the Buffalo River has been encouraged by river impoundment. 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 5.2). 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 backwater pools, 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 5.4. A plan view of the research site is given in Figure 5.27 while cross sections of surveyed transects, together with sampling points, are given in Figures 5.28a, b, and c.

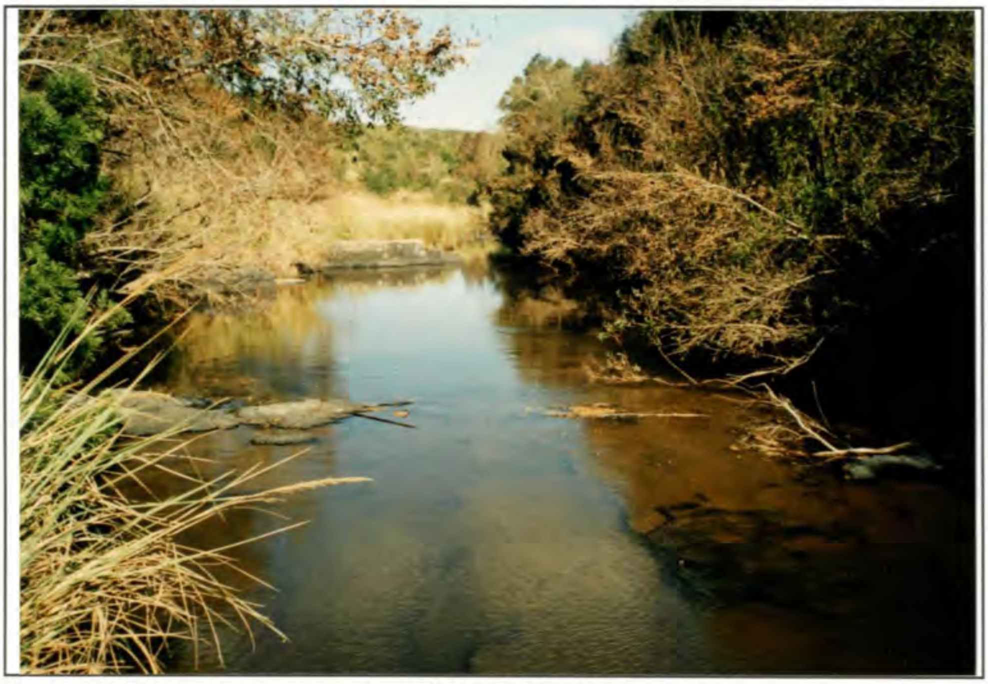


Plate 5.4 Photographic overview of site 4 (Braunschweig)

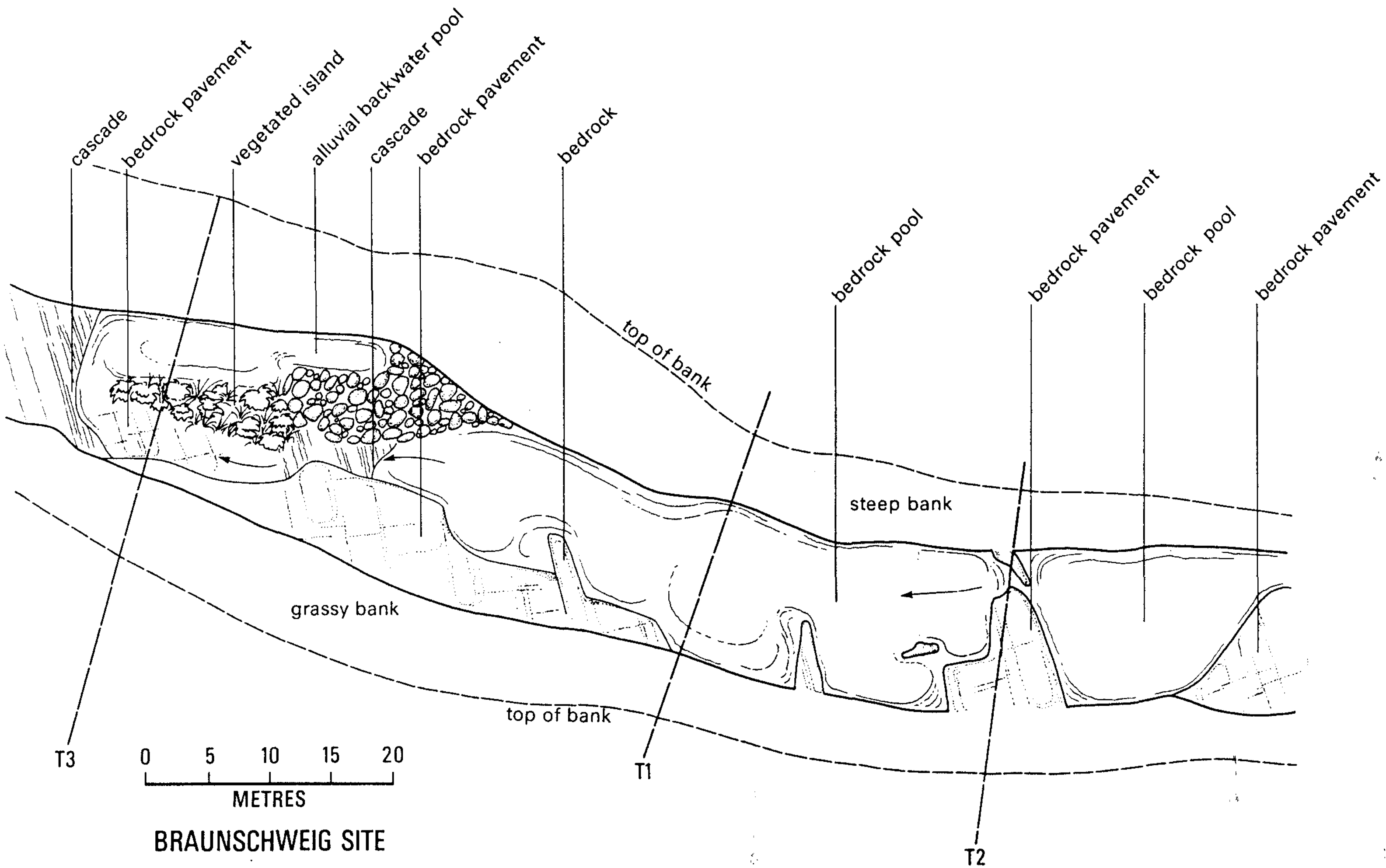


Figure 5.27 Plan view of site 4 (Braunschweig)

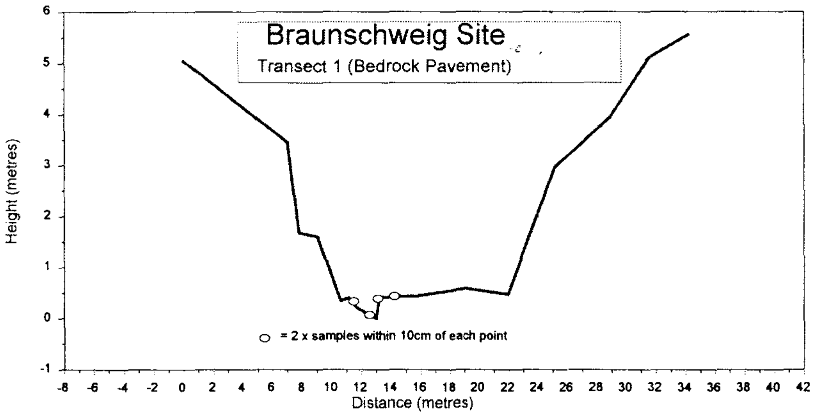


Figure 5.28a Transect 1 Cross Section

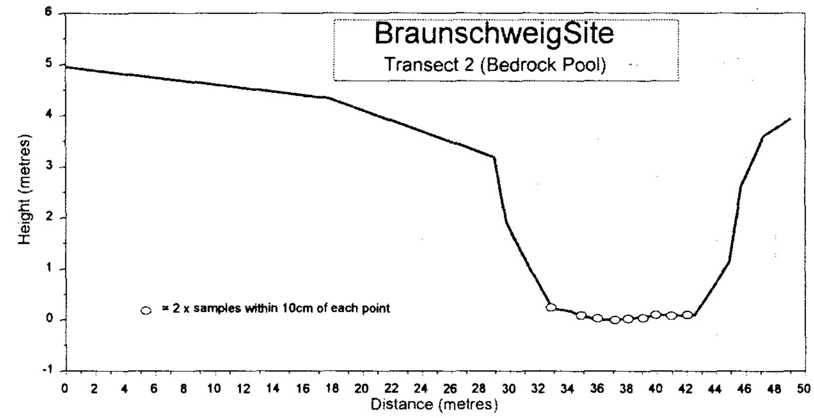


Figure 5.28b Transect 2 Cross Section

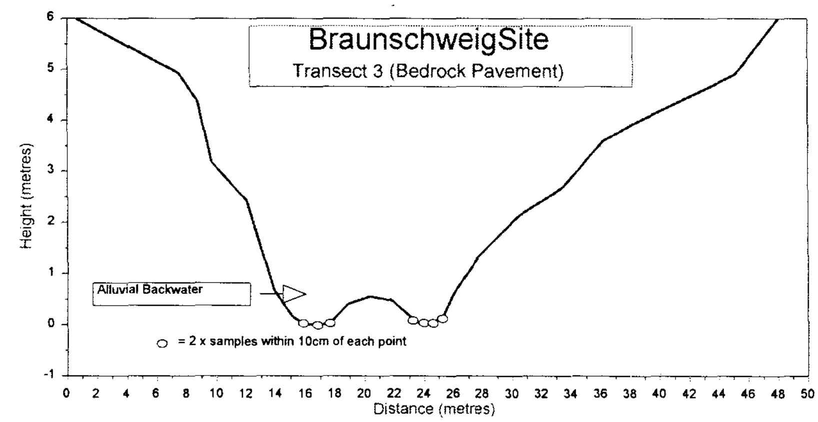


Figure 5.28c Transect 3 Cross Section

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 (segment 5, reach 1 of Table 5.3). 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, 1990) 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 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.

Channel pattern for the reach is anastomosing as evidenced by well vegetated islands within numerous channels. Reach morphology is very similar to the previous site, that is a dominance of planar bedrock. The most important difference in this reach is the lack of incision and the presence of numerous channels. 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 specific morphology of this reach include rapids, bedrock pools and riffles.

Channel stability is high in this reach with the river flowing within a bedrock boundary (Plate 5.5a and b). 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 usin the same criteria as the previous sites. A plan view of the research site is given in Figure 5.29 while cross sections of surveyed transects are given in Figures 5.30a, b, and c.

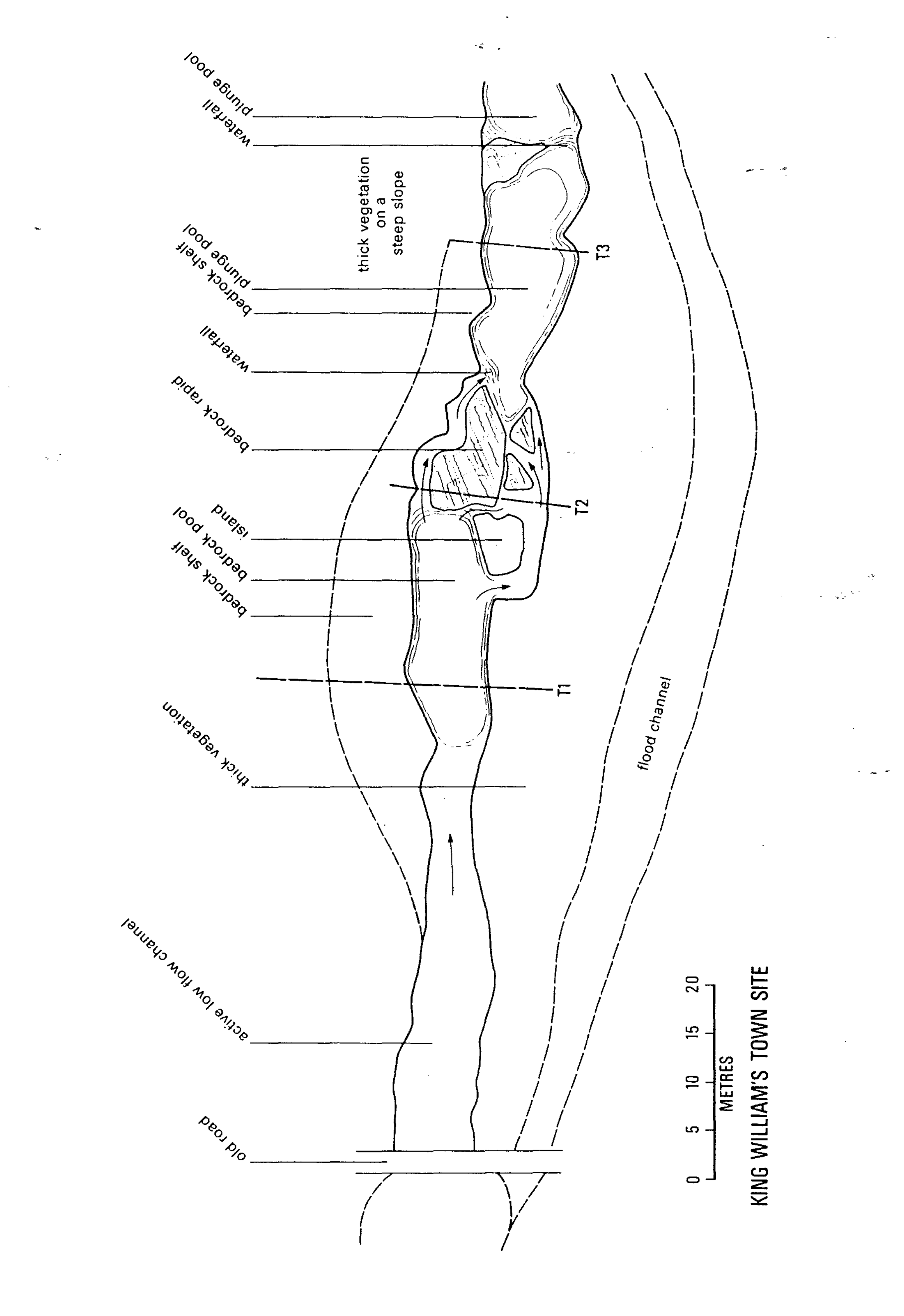


Figure 5.29 Plan view of site 5 (King William's Town)

Plate 5.5a Photograph of site 5 (King William's Town), looking upstream

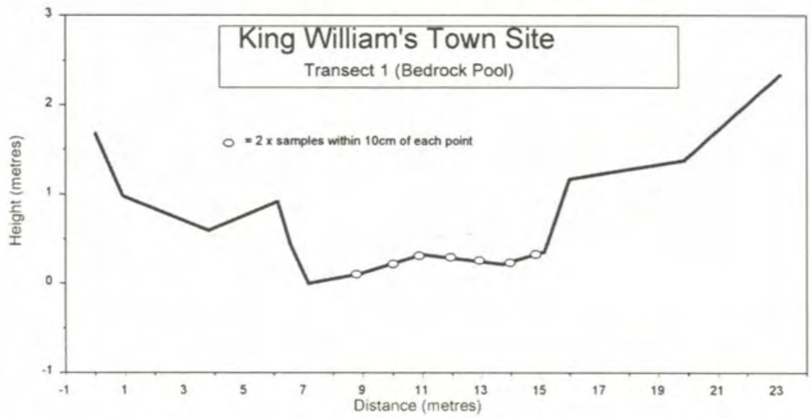


Figure 5.30a Transect 1 Cross Section

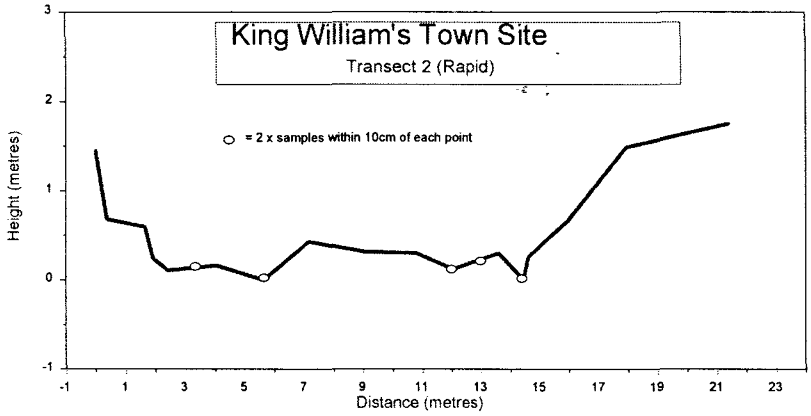


Figure 5.30b Transect 2 Cross Section

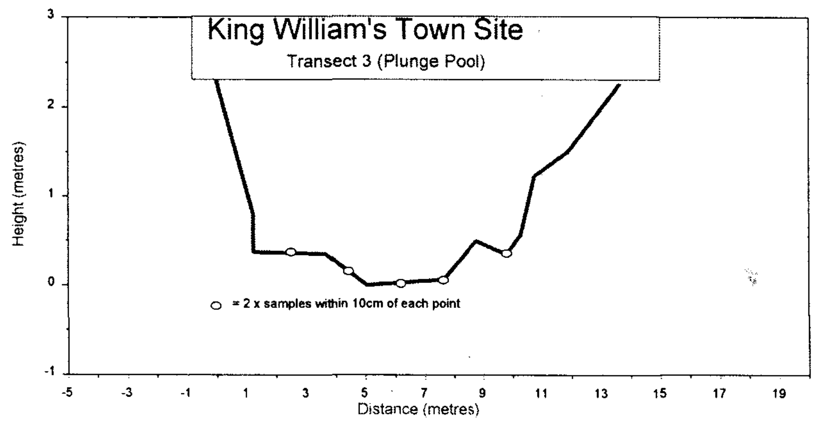


Figure 5.30c Transect 3 Cross Section

5.4.2 Sampling frequency

A visual assessments of the hydraulic variability of the five research sites showed that the upper reaches of the channel had a highly irregular bed dominated by shallow flows and the lower reaches had more regular beds but with restricted flows. These observations highlighted potential problems in the selection of sampling points. The requirements of the study for data collection at fixed points at different discharges meant that there was a possibility that some points were going to be lost or gained as the wetted perimeter of the channel increased with discharge. This problem was complicated further by the high degree of irregularity of the bed in certain reaches. To overcome the problem, sample points were subjectively selected to incorporate a full range of flow conditions observed during a relatively high discharge (second highest discharge observed). The motivation for this was that one was more likely to be sampling at lower discharges than the original baseline flow, was more likely to loose sampling points than gain them, and could therefore incorporate an adequate number of points to account for this loss.

A requirement of this study was to assess the hydraulic characteristics of different hydraulic biotopes in response to changing discharge. An obvious approach to this problem is to sample as often and regularly as possible and hope that a wide range of discharges are incorporated. This is unlikely to produce a good range of discharges, particularly in the Buffalo River which has been experiencing extreme drought conditions for the last few years (1992/1993). This problem was anticipated and influenced the decision to select a number of sample sites within higher rainfall mountainous reaches. Despite these problems, a random sampling was impossible in this study due to time constraints imposed by the detailed level of data collection required. Previous experience indicated that if possible at least four discharges should be sampled.

In an attempt to obtain a good discharge variation within the natural flow regime, flow duration curves were constructed using the available hydrological records. Flow duration curves display the relationship between discharge and the percentage time it is exceeded. These curves can assist in the selection of the range of discharges that should be sampled to incorporate the full range of flows that naturally occur. Curves were constructed from the mean daily flow records collected at gauging stations R2H001 and R2H005, as these fell within two of the selected reaches.

The first curve was constructed from 48 years of data which had been collected from gauging weir R2H001. Although this station is downstream of the top three selected reaches (immediately below site 3), it was felt that the flow duration curve would give a reasonable estimate of where the sampled discharges fell within the flow regime (Figure 5.31)

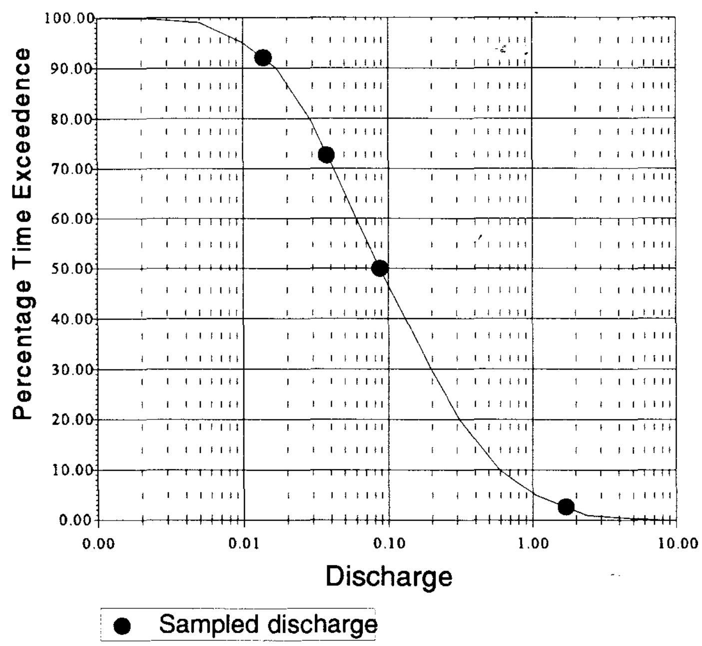


Figure 5.31 Daily flow duration curve - site R2HOO1

The second flow duration curve was constructed from a 23 year record of mean daily flows at gauging station R2H005 (Figure 5.32). This station is situated immediately below site 5 in King William's Town. It was felt that this curve would act as a good indicator as to how sampled discharges at sites 4 and 5 were distributed within the long term flow regime.

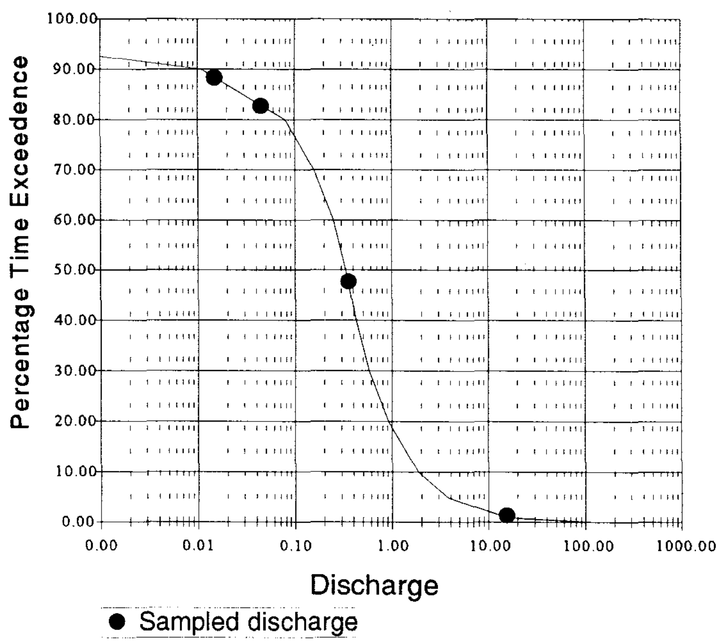


Figure 5.32 Daily flow duration curve - site R2H005

Once flow duration curves were constructed it was a relatively easy task to convert a discharge reading to a stage Plate height from stage discharge tables provided by the DWAF. This allowed a quick assessment in the field as to where an observed flow discharge was situated within the flow duration curve and whether it was a flow suitable for sampling.

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.

5.4.3 Data collection

Sampling points

The number of transects set out at each site was determined by hydraulic variability. A total of 31 transects were laid out and surveyed; 9 at the Trestle Bridge (site 1, Figure 5.21), 8 each at the Causeway (site 2, Figure 5.23) and the Trout Pools (site 3, Figure 5.25) and 3 each at Braunschweig (sites 4, Figure 5.27) and King William's Town (site 5, Figure 5.29). 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.

Hydraulic indices

Measurements of depth, velocity, bed profile and water temperature were collected at each point at four different discharges, an attempt was made each time to collect data for all sites during the same flow event. As discussed in Chapter Three these variables are the essential components of hydraulic equations to calculate Froude number (Equation 3.2), Reynolds number (Equation 3.1), shear velocity (Equation 3.6) and the 'roughness' Reynolds number (Equation 3.9). These indices are used to characterise conditions of flow both near the bed 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 Three, 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 Three (Figure 3.7). 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 3. These measurements are essential components for the calcualtion of shear velocity and 'roughness' Reynolds number. The data was also used for the classification of flow after Morris (1955) as discussed in Chapter Three. A further use of this data was to determine potential differences in substratum between sample sites, this data is presented in the form of cumulative frequency plots (Figures 6.3 a, b, c, d and e).

Discharge

Discharges were estimated using the velocity area method (Gordon *et al.,* 1992) and are given in Table 5.5, in all instances discharges were below bankfull. Stage was monitored in the channel at each site using a stage plate. A summary of the raw data is given in Appendix One.

Table 5.5 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 2.1. At each new discharge, the hydraulic biotopes along each transect were reclassified. The use of photographic evidence for the classification/re-classifcation 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. Subsequent experimentation has also shown that it is extremely difficult to clearly photograph hydraulic biotopes and it is suggested here that the use of video might be more appropriate.

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.

5.4.4 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, 1977).

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.

CHAPTER SIX
RESULTS AND DISCUSSION

6.1 INTRODUCTION

This chapter presents the results of descriptive and statistical analysis carried out on selected hydraulic indices collected in the Buffalo River. The chapter considers in more detail questions introduced and partially answered in the pilot studies of Chapter Four. Specific aims of this chapter include:

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.

⑧ To link the hydraulic biotope concept to the hierarchical geomorphological model.

To meet these aims the following questions will be addressed:

1. Is there evidence that selected hydraulic characteristics measured for hydraulic biotope classes in the Buffalo River coincide with findings from other studies?

2. What hydraulic indices best quantify hydraulic biotope characteristics?

3. How do five selected reaches in the Buffalo River differ with regards bed material characteristics?

4. How do hydraulic biotopes in the Buffalo River respond to changes in scale?

5. Is the classification or identification of hydraulic biotopes discharge dependent?

6. Is there a relationship between hydraulic biotope distribution and channel morphology within the Buffalo River?

7. How succesfull is the hydraulic biotope matrix as a tool for hydraulic biotope recognition

6.2 AGGREGATE ANALYSIS

A preliminary analysis was carried out on all data (aggregate analysis) in order to determine what hydraulic indices best quantify hydraulic biotope characteristics. 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 One. 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, energy slope, 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 6.1a, b, c, d and e). These variables were used for a more detailed analysis of hydraulic biotope characteristics. The variables shear stress, energy slope, relative roughness and roughness height showed no pattern of variability between hydraulic biotopes and were therefore excluded from further analysis.

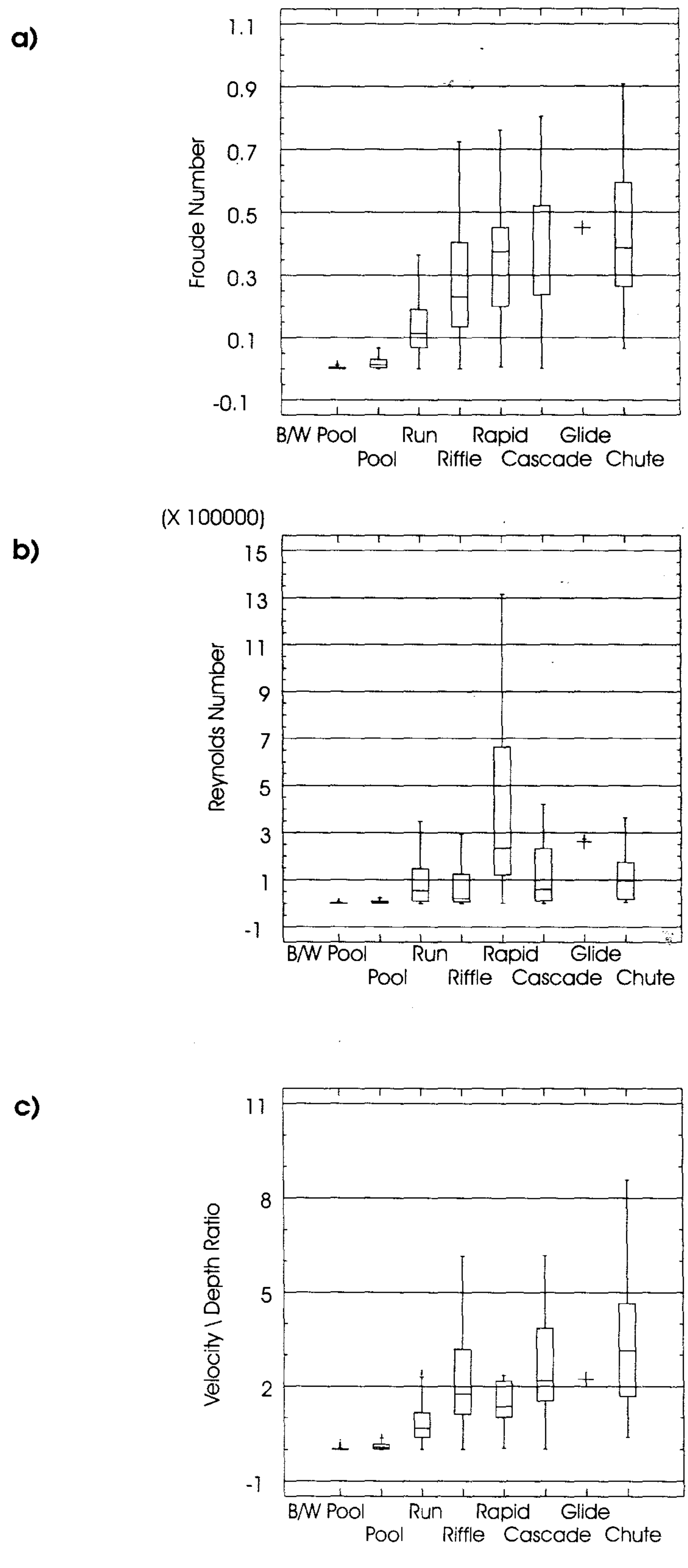
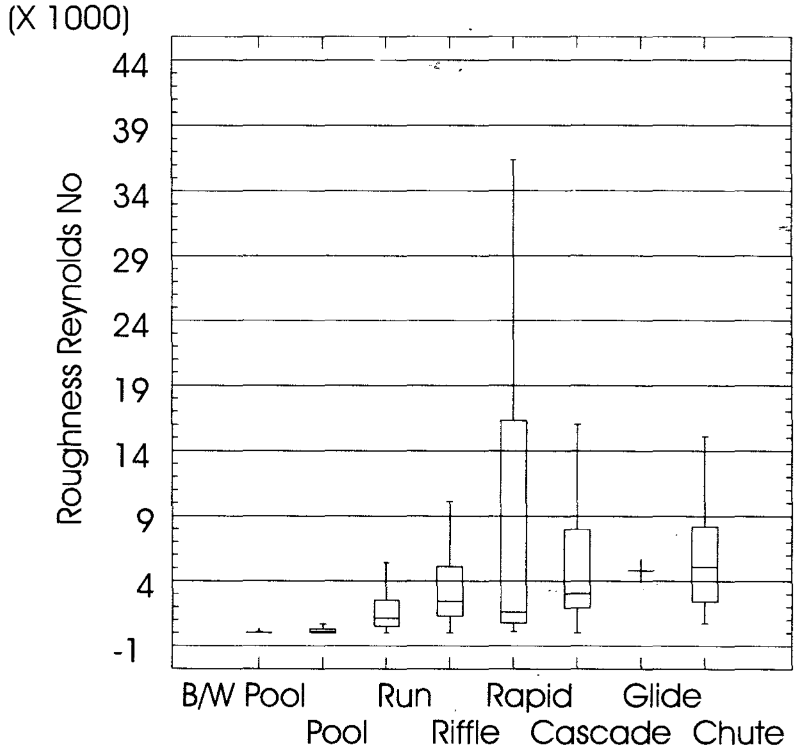


Figure 6.1 Box and whisker plots of selected hydraulic indices for hydraulic biotope classes observed in the Buffalo River

d)



e)

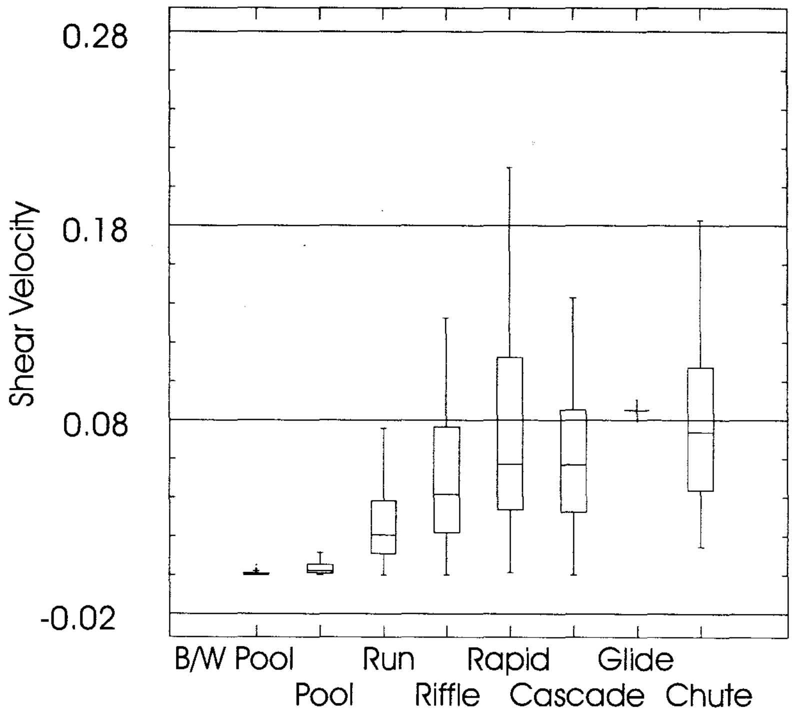


Figure 6.1(continued) Box and whisker plots of selected hydraulic indices for hydraulic biotope classes observed in the Buffalo River

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 6.1 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.

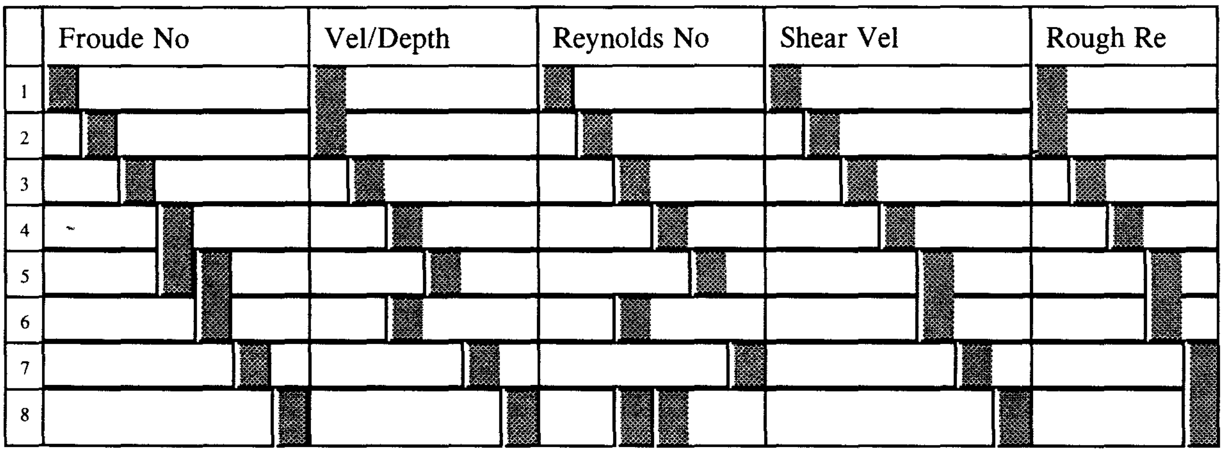
Table 6.1 Tests for normality of data distribution

	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**

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 6.2, 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 6.2 Homogeneous groups identified using multiple range analysis (n =1581, confidence level = 99.5, significance level = 0)



Hydraulic biotope codes: **1** -backwater pool **2** -pool **3** -run **4** -riffle **5** -rapid **6** -cascade **7** - glide **8** -chute

6.2.1 Froude number

A visual analysis of the box plots in Figure 6.1 a 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 6.3.

Table 6.3 Froude number : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater Pool	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

This table shows a clear progression in both mean and median values from one hydraulic biotope class to the next.

Results of the multiple range analysis in Table 6.2 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 and also that mean flow characteristics are likely to be quite similar between some classes (riffles, rapids and cascades). It is important to realise that even if mean flow conditions are similar within these "grouped" hydraulic biotope classes, they are likely to provide very different refuge conditions for organisms living on or near the bed. 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 $Fr=1$.

6.2.2 Velocity Depth Ratio

The velocity depth ratio is a very similar index to the Froude number, the only difference being that in this ratio the value of depth is not reduced to a square root multiplied by the constant of gravity. Visual analysis of the box plots in Figure 6.1b 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 6.4.

Table 6.4 Velocity/Depth Ratio : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater Pool	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

Results from the multiple range analysis given in Table 6.2 indicate that six homogenous groups can be recognised with only one grouping occurring, 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 riffles and cascades. Unfortunately this index does not distinguish between riffles and cascades. The aggregate results presented here are in direct conflict with Jowett (1993) who in a limited study in New Zealand, determined that the velocity-depth ratio was the best single descriptor of three habitat types.

6.2.3 Reynolds number

Pilot studies have indicated that, on its own, the Reynolds number is not a very good hydraulic biotope descriptor. A visual analysis of the box plots in Figure 6.1c indicates that this may not be necessarily so. 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 6.5.

Table 6.5 Reynolds number : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater Pool	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

Results from the multiple range analysis (Table 6.2) 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 the Reynolds number are not consistent with those from pilot studies, the variable on its own appears to be a much better descriptor than 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 6.5 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.

6.2.4 'roughness' Reynolds number

An analysis of the box and whisker plots in Figure 6.1d 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 6.6.

Table 6.6 '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

Results from the multiple range analysis (Table 6.2) 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.

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. These results compliment those presented for the Molenaars River pilot study where the pattern of hydraulic biotope progression and variability closely approximated that for the Froude number. Although there appear to be clear differences between data variability in many of the hydraulic biotopes, the use of range analysis (differences between the means) does not always demonstrate this.

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. It is still important to consider the role of discharge and scale on the variability of this index before any attempts are made to group or separate hydraulic biotope classes.

A traditional use of the 'roughness' Reynolds number is to differentiate between hydraulically smooth (<5), hydraulically rough (>70) and transitional (5 - 70) surfaces. Results from Table 6.6 indicate that only backwater pools can be considered as being dominated by a hydraulically smooth surface that is all surface irregularities are submerged in the laminar sub layer.

A very important component of the 'roughness' Reynolds number is roughness height which is largely a function of substrate size. The results presented here represent the grouping of data from five different reaches, each reach characterized by a different type and/or size of substratum. To assess the influence of roughness height on this hydraulic index it is necessary to disaggregate data by site.

6.2.5 Shear Velocity

The final hydraulic index to be considered is shear velocity, 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 6.1e show similar trends to those in Figure 6.1d ('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 6.7.

Table 6.7 Shear Velocity : Summary statistics for aggregate data

Hydraulic biotope	number	Mean	Median	Std Deviation
Backwater Pool	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 6.2) indicate that seven hydraulic biotope classes may be recognised with only two classes being combined; rapids and cascades.

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 6.1e) 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.

6.2.6 A comparison of aggregate results observed at different research sites

The developmental nature of this research has meant that data collection between sites has been inconsistant and therefore not always comparable. Examples of this include the use of transect data in the Great Fish River rather than point data (in all other studies). There has also been inconsistent identification of hydraulic biotopes throughout this research as a result of changing terminology and the late development of the hydraulic biotope matrix. In some instances (Molenaars River) data collection was inconsistent due to different levels of experience amongst field researchers. Despite all these difficulties it is important to consider the potential of the hydraulic biotope concept as a classificatory tool within diverse fluvial environments.

The box and whisker plots of Figure 6.2 attempt to show the relatively consistent hydraulic characteristics (Froude number) observed within the different hydraulic biotope classes at different sites. The Froude number has been selected because it is the one index that was measured at all sites and because initial results have indicated its its utility as a classificatory value. Unfortunately the same classes were not identified at all sites; only runs, riffles and pools being common to all. For the sake of comparison all hydraulic biotope classes are considered even if they were observed at only one site.

Despite the problems of inconsistent data collection different hydraulic biotope classes do appear to show similar flow characteristics from one river to another. Obvious inconsistencies that need to be discussed are the values for riffles in the Great Fish River which show higher variability than the other rivers. This can be explained by the classification of transects instead of points and the fact that many of the higher energy hydraulic biotope classes had not been described at that stage. The other obvious difference is between chutes in the Molenaars River and those in the Buffalo River. At the time of sampling in the Molenaars River, chutes had not been clearly defined. For this reason only six points were classified as chutes, these do not give an adequate representation of hydraulic characteristics.

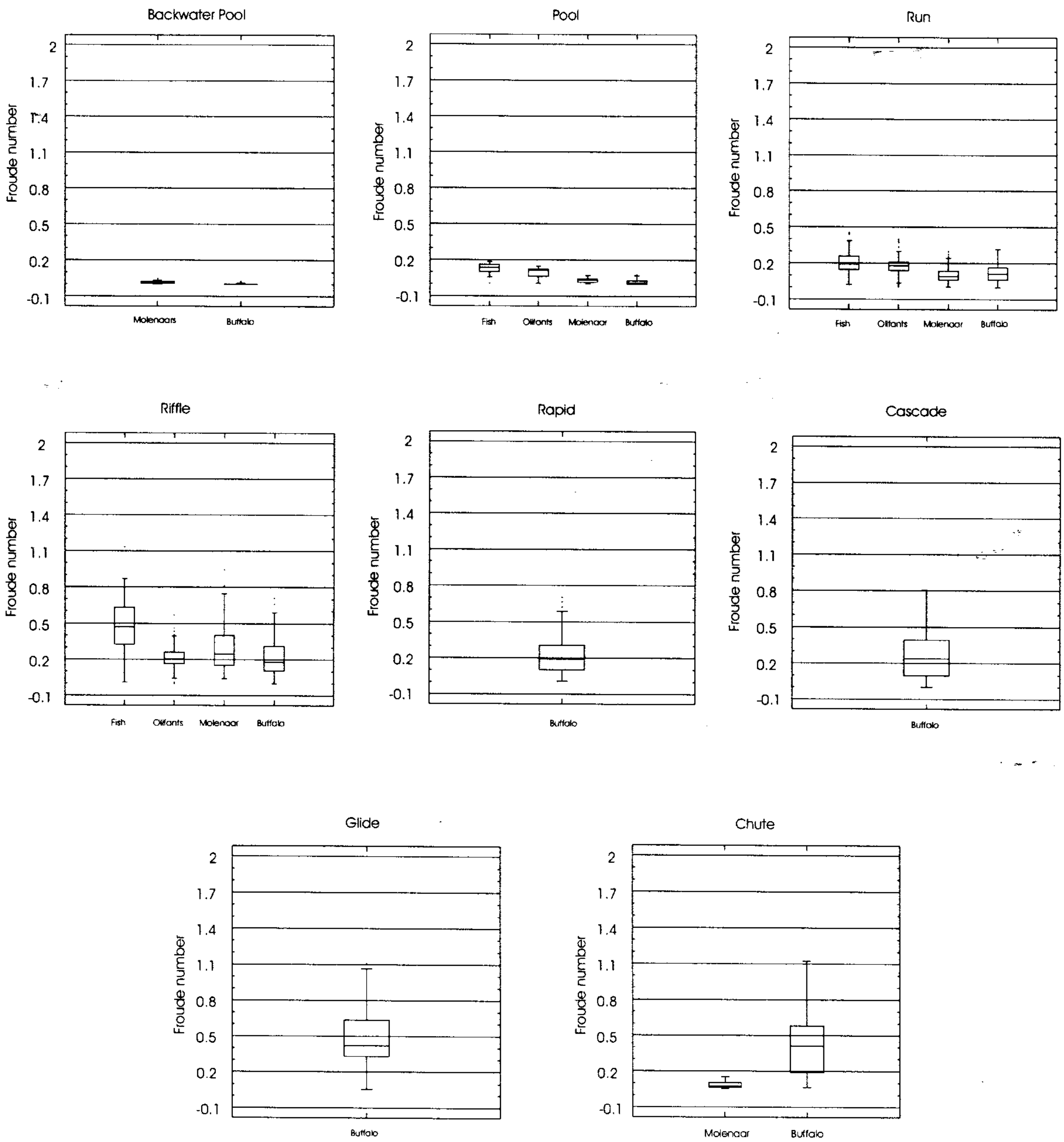


Figure 6.2 Box and whisker plots of Froude number for hydraulic biotope classes observed in different fluvial environments

Results from Figure 6.2 go some way towards answering the first question presented at the beginning of this chapter.

○ *Is there evidence that selected hydraulic characteristics measured for hydraulic biotope classes in the Buffalo River are consistent with findings from other studies?*

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 is predominantly a bedrock controlled system.

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 2.1).

6.2.7 Analysis of aggregate data - discussion

The analysis of grouped data for all sites and at all discharges serves as a useful means to determine the answer to question two introduced at the beginning of this chapter.

- *What hydraulic indices best quantify hydraulic biotope characteristics?*

Although a number of hydraulic indices appear to be very useful to quantify and classify hydraulic biotope classes, it is unrealistic and time consuming to attempt to use them all. The results from this aggregate data analysis agrees 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. These indices are extremely useful because they meet the requirements of both a near bed and a mean water column component of the flow. The remainder of the data analysis carried out in this thesis focuses on these indices.

6.3 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 substratum characteristics at each reach, determine differences between the hydraulic indices describing hydraulic biotope classes at different sites and finally to determine differences between hydraulic indices describing hydraulic biotope classes at different discharges.

6.3.1 Variations in substratum characteristics between sites

The nature of the channel bed (boulder and bedrock) together with the sampling framework carried out in this study did not allow disturbance of the bed characteristics at each point of data collection along transects. The study did however require the collection of a bed roughness component (roughness height) which it was felt could provide a useful surrogate for particle size distribution allowing comparison of substratum characteristics between reaches. Cumulative frequency curves were plotted for roughness height at each site and are given in Figures 6.3 a, b, c, d, and e.

Site 1: Trestle Bridge

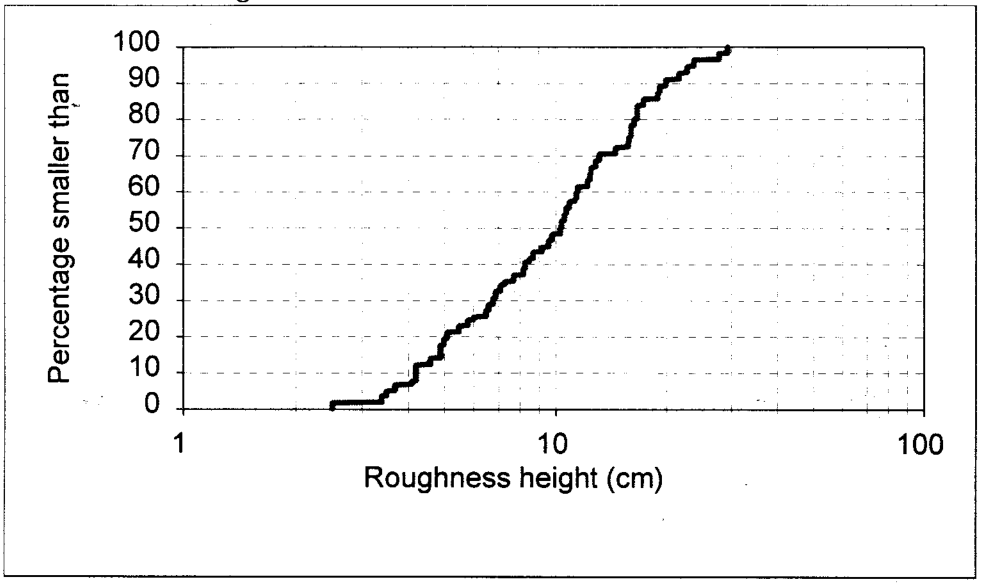


Figure 6.3a Roughness height cumulative frequency curve

This curve shows that 50 % of the bed material sampled was between 10 and 30 cm high. Of the larger material sampled, approximately 30 % was between 15 and 30 cm high and 10 % between 20 and 30 cm high. The smallest roughness hight measured was 2.5 cm.

Site 2: Causeway

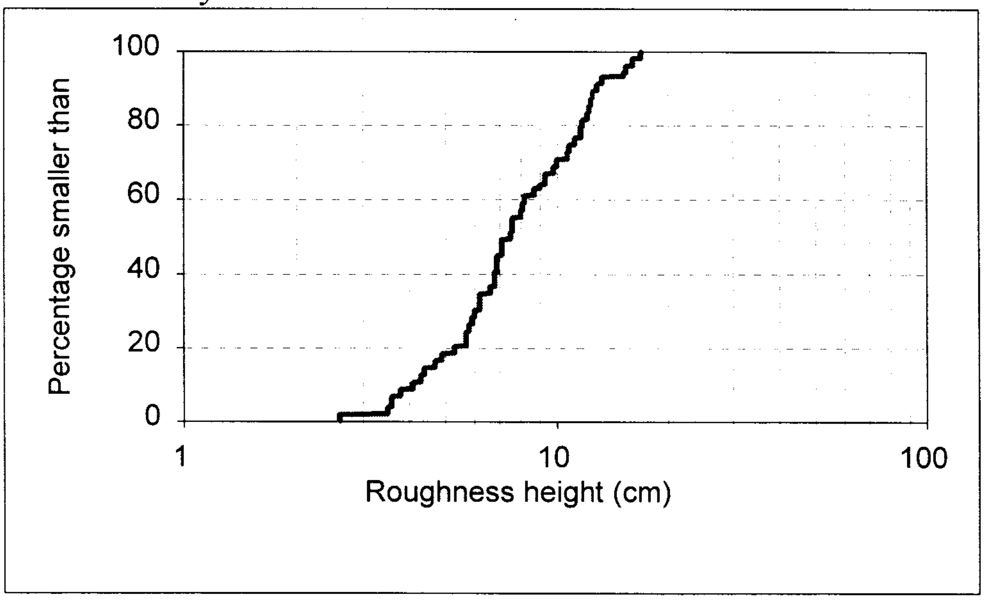


Figure 6.3b Roughness height cumulative frequency curve

The frequency curve for site 2 shows that approximately 50 % of the bed material sampled was between 6 and 10 cm high with about 30 % between 10 and 18 cm high. The roughness height of the bed material at this site is generally smaller than that for site 1.

Site 3: Trout Pools

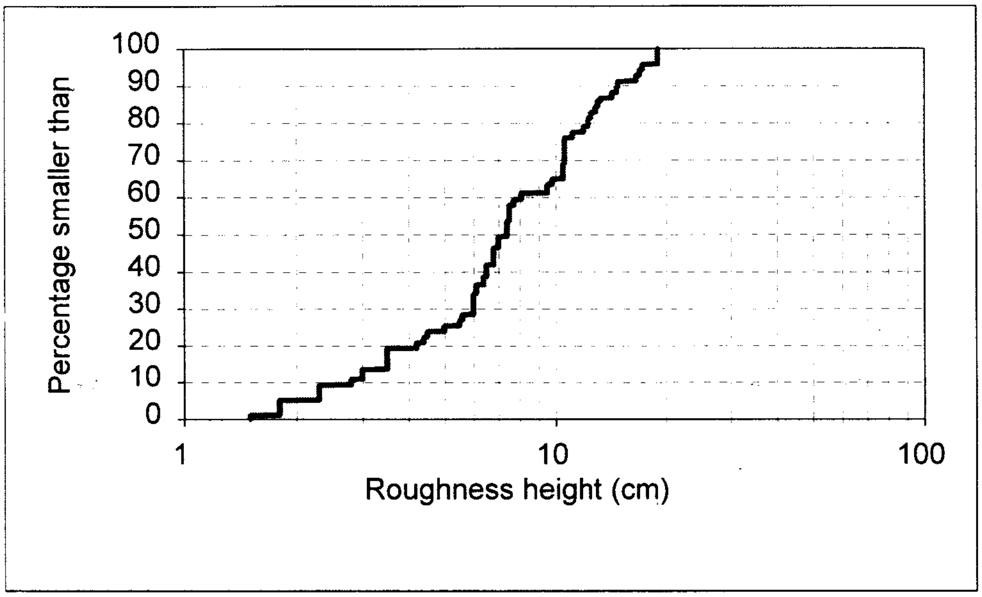


Figure 6.3c Roughness height cumulative frequency curve

The above plot indicates that approximately 60% of the material sampled at this site was smaller than 8 cm high with the other 40 % between 8 and 20 cm high. An important difference between the results shown here and those from the previous two sites is that this site shows a greater percentage of finer material with 30 % between 1.5 and 6 cm.

Site 4: Braunschweig

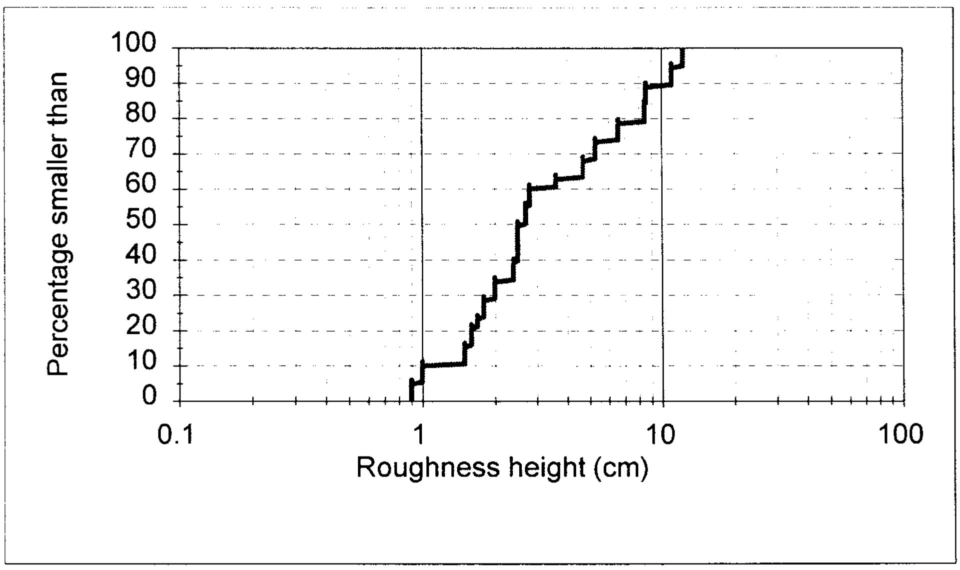


Figure 6.*d Roughness height cumulative frequency curve

The frequency distribution curve for the Braunschweig site shows that in terms of roughness height, this site is completely different from the previous three sites with 60 % of the bed material sampled smaller than 3 cm high. All material sampled was smaller than 13 cm in height. There was a significant presence of bedrock within this site.

*.Site 5 : **King William's Town***

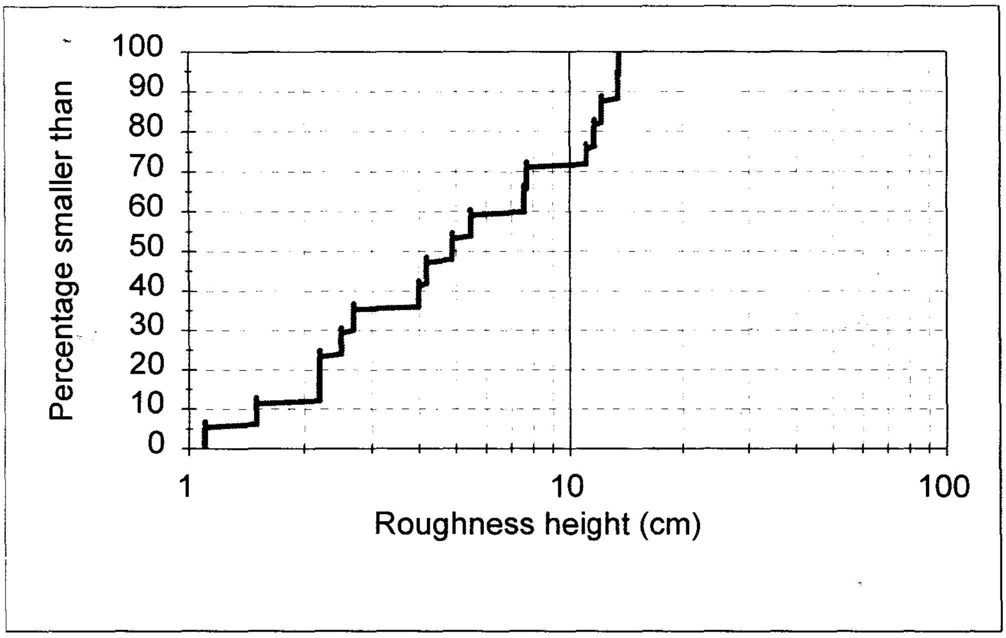


Figure 6.3e Roughness height frequency distribution curve.

The above diagram shows that approximately 50 % of the bed material sampled was less than 5 cm high with about 25 % of that being in the size range 2 to 3 cm. In the upper range of roughness height, 100 % of the material was smaller than 15 cm with about 30 % between 12 and 14 cm high. As with the Braunschweig site there was a signifacant component of bedrock.

Roughness height was used rather than bed material size in this analysis because it was felt that the height to which substrate elements project into the water column (and hence interact with flow) would provide adequate information to determine major physical differences between sites.

A number of difference can be recognised between the heights that substrate protrudes from the bed between the five different reaches and it would be difficult to group sites in terms of similar frequency distributions. These results were expected as substratum is a major determinant of reach analysis. These findings would suggest that a strong possibility exists for significant differences to occur between values of the hydraulic indices describing the same hydraulic biotope classes across the five different sites. This may be particularly prevalent in the use of the micro flow indices such as shear velocity and the 'roughness' Reynolds number which are dependent on the input of a roughness height (k) for their calculation.

The next section makes use of statistical analysis to determine if there are indeed significant differences between the hydraulic indices of Froude number, shear velocity and 'roughness' Reynolds number for each hydraulic biotope class between the five different reaches.

6.3.2 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 6.8 illustrates the results of a multiple range analysis carried out for all hydraulic biotope classes separately.

It is important to note that when trying to determine 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.

Table 6.8 Multiple range analysis by site for all hydraulic biotope classes (n = 1581, confidence level = 99.7, significance level = 0)

Hydraulic biotope class	Site	Froude number			Shear Velocity			Roughness ReNo		
		1	2	3	1	2	3	1	2	3
BACKWATER POOL	1	X			X			X		
	2	X			X			X		
	3	X			X			X		
	4	X			X			X		
	5	X			X			X		
POOL	1	X				X			X	
	2	X			X			X		
	3	X			X	X			X	
	4	X			X	X		X	X	
	5	X			X	X		X	X	
RUN	1	X			X			X		
	2	X			X			X		
	3	X			X			X		
	4	X			X			X		
	5	X			X			X		
RIFFLE	1	X	X		X	X		X	X	
	2	X	X		X	X		X		
	3	X		X	X		X		X	
	4	X			X			X	X	
	5	X			X			X	X	
RAPID	1	X			X			X		
	2	X			X			X		
	3	X			X			X		
	4	X			X			X		
	5	X			X			X		
CASCADE	1	X			X			X		
	2	X			X			X		
	3	X			X			X		
	4	X			X			X		
	5	X			X			X		
GLIDE	1	X			X			X		
	2	X			X			X		
	3	X			X			X		
	4	X			X			X		
	5	X			X			X		
CHUTE	1	X			X			X		X
	2	X			X			X	X	
	3	X			X			X	X	
	4	X			X			X		

General trends demonstrated in Table 6.8 are that each hydraulic biotope class, as characterised by selected hydraulic indices, can be considered as having consistent flow characteristics from one site to the next. In other words features such as runs, riffles and cascades show insignificant differences in their flow characteristics from one reach to another and can therefore be considered as being consistently recognised.

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.

Shear velocity

As with the Froude number, this index recognises no significant difference 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 worth noting that differences between sites may be as 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 considers all sites together, also considers sites 1 and 2 together as a group and site 3 on its own.

'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 6.8 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 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 2.1) 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 question seven from the introduction

- *How successful is the hydraulic biotope matrix as a tool for hydraulic biotope recognition*

To deal with this question more thoroughly we need to determine the influence of discharge on the hydraulic characteristics describing hydraulic biotope classes; this is the focus of section 6.3.3.

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 discussed earlier. One very important point which needs to be considered is the possibility of mis-classification of hydraulic biotopes in the field. It is sometimes very difficult to accurately determine the flow type and substrate for a specific point of measurement. One very often makes generalisations for a patch of flow. This may be very inaccurate in high energy environments which are dominated by large clasts creating highly variable flow conditions across the channel.

The analysis of hydraulic variability within classes from different sites allows the answering of question four presented in the introduction

- *How do hydraulic biotopes in the Buffalo River respond to changes in substratum characteristics or more generally, changes in scale?*

Changes in scale of channel morphology do not significantly influence both the near bed and micro flow conditions experienced within the hydraulic biotope classes. This conclusion leads to the next phase of data analysis, to determine the influence of discharge on hydraulic variability within each hydraulic biotope class.

6.3.3 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 6.9 and, as with the analysis of results for the influence of site (Table 6.8), homogenous groups cannot be considered across classes, only within a class across discharges.

Table 6.9 Multiple range analysis by discharge for all hydraulic biotope classes (n = 1581, confidence level = 99.7, significance level = 0).

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	2			
	3			
	4			
CASCADE	1			
	2			
	3			
	4			
GLIDE	2			
	3			
	4			
CHUTE	1			
	2			
	3			
	4			

An immediate observation that can be made from the results presented in Table 6.9 is that backwater pools were not observed at discharge 4 while rapids and glides 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, 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 pool

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 backwater pools at discharges 1 and 2.

An explanation for this could be that the very low velocities which characterise backwater pools and pools are difficult to detect and categorise using the flow conditions observed at the surface as defined by the hydraulic biotope matrix (Figure 2.1).

Another explanation which needs exploring is the possibility that although backwater pools may be sub-divided into different units statistically, they may all fall within a limited range of hydraulic conditions which have little or no influence on the distribution of stream biota. This would mean that it is unnecessary to differentiate between them.

Previous evidence from the pilot studies, and a visual analysis of the box and whisker plots (Figure 6.4 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 backwater pools 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 particularly prone to both user and mechanical error, particularly within the environment in which they were used i.e. high energy mountain stream dominated by large substratum. The very low velocities which characterise backwater pools are difficult to measure using this apparatus, particularly when only taking a single measurement in the water column.

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 pool class.

The explanations given for variation of flow hydraulics for different discharges in the backwater pool class are likely to hold true for this class and are demonstrated in Figures 6.4 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 (hydraulic) 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, Cascade and Chute

These hydraulic biotope classes show virtually the same pattern of discharge grouping. 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 of the riffle class which demonstrates a significant difference between discharges 3 and 4.

It would seem as though the hydraulic biotope matrix allows for consistent recognition of the classes common in higher energy environments. It would almost seem as though the matrix is biased towards the easy recognition of higher energy environments. It is worth mentioning that these environments are also less likely to be 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 barely noticeable ripple on the surface probably represents considerably different hydraulics from a clearly defined ripple which is almost but not quite a standing wave (run).

Rapid and Glide

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 to does the wetted perimeter, creating new hydraulic biotope classes.

Discussion

The data presented in this section attempts to answer question 5 presented in the introduction to this chapter:

- *Is the classification or identification of hydraulic biotopes discharge dependent?*

Results from the multiple range analysis in Table 6.9 indicate that generally the hydraulic indices of Froude number, shear velocity and 'roughness' Reynolds number are 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.

Interesting results from this analysis is the apparent increased accuracy of recognition of hydraulic biotope classes across discharge as one moves from a low energy environment (backwater pool and pool) towards a moderate energy environment (run) to the high energy environments of riffle, rapid, cascade, glide and chute. These results help answer question seven presented in the introduction

- *How successful is the hydraulic biotope matrix as a tool for hydraulic biotope recognition*

A suggestion is made that the hydraulic biotope matrix is a reasonably accurate method for the recognition of riffles, rapids, cascades, glides, and chutes at all discharges, but is less accurate for the recognition of backwater pools, pools and runs across the different discharges. A possible reason for this is the inability of the hydraulic biotope matrix to differentiate between small variations in flow in the lower energy environments. The question that now needs to be considered by lotic ecologists is whether these differences or similarities have any ecological significance?

Variability within hydraulic biotope classes across discharges suggests that a progression of hydraulic values exist from one hydraulic biotope class to the next. It is also suggested that a relatively high degree of hydraulic variability exists within each class with a certain amount of overlap to be expected between classes.

Box plots of variability with discharge (Figures 6.4 a, b and c) are presented to substantiate the theory of overlap and progression. Although there is some idiosyncratic data presented on these figures, a reasonably clear pattern of progression can be distinguished. A further generalisation that can be made from this data is that as higher energy environments are encountered, hydraulic variability and overlap between classes increases.

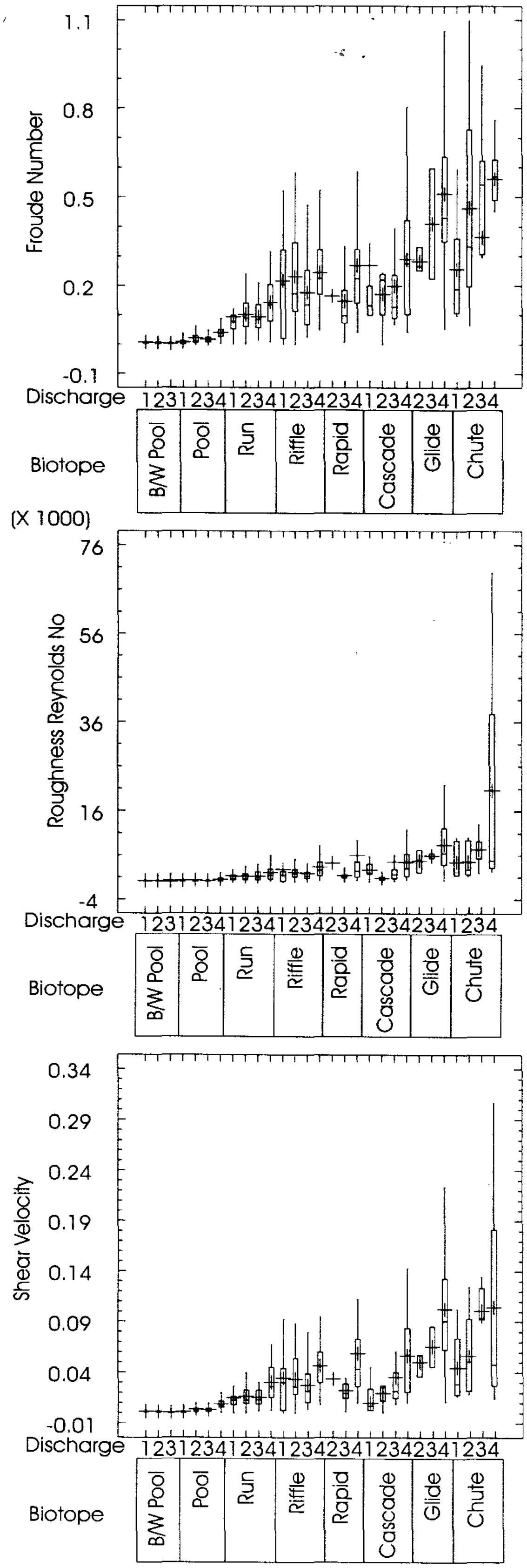


Figure 6.4 Box plots to show hydraulic variability as a response to increasing discharge.

6.3.4 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 6.9) which recognises differences between the hydraulics of the classes of backwater pool, 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 6.10 presents the results for the three different discharge groups.

Table 6.10 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**

Discharge 1 shows poor classification success for the hydraulic biotope classes of pool, riffle and chute. The riffle class improves when three or four classification functions are used. At this discharge, backwater pools, 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 reasons 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.

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 from these results 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 thesis, 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 traditionally used. It is felt that if this matrix had been available at the start of the research programme, results may have been more conclusive.

6.3.5 Hydraulic biotopes and their flow type associations (Morris, 1955).

As discussed in Chapter Three, Davis and Barmuta (1989), after Morris (1955), classify 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 3.8).

- Wake interference flow - when the roughness elements are closer together and the eddies from these elements interact causing intense turbulence (Figure 3.9).

- 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 3.10).

- 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 (Figure 3.11).

As discussed in Chapter Three, the classification of Morris (1955) describes conditions near the bed whereas the flow type classification used in this research (Table 2.3) describes conditions at the surface. The following results are presented to demonstrate associations between the two different classification techniques by considering the proportional make up of different flow types for each hydraulic biotope class. Following the research findings presented earlier in this chapter, indices characterising different hydraulic biotope classes were combined for all sites and all discharges.

Backwater Pools

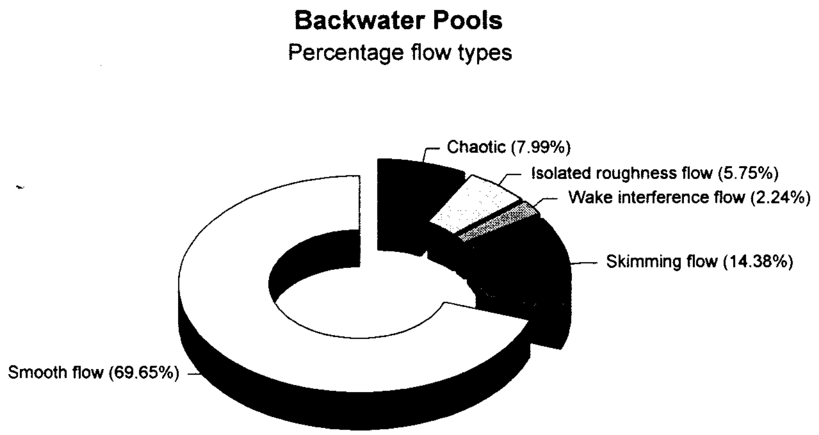


Figure 6.5 Proportional composition of different flow types within backwater pools

Figure 6.5 represents data from 317 points. The results demonstrates that backwater pools are dominated by smooth flow with relatively small proportions of the four flow classes found over rough surfaces. The fact that the four rough surface flow classes are present at all is a suprise because it means that 'roughness' Reynolds numbers greater than 70 were calculated. Their presence may point to the fact that measurement errors and mis-classification occured in this study.

Pools

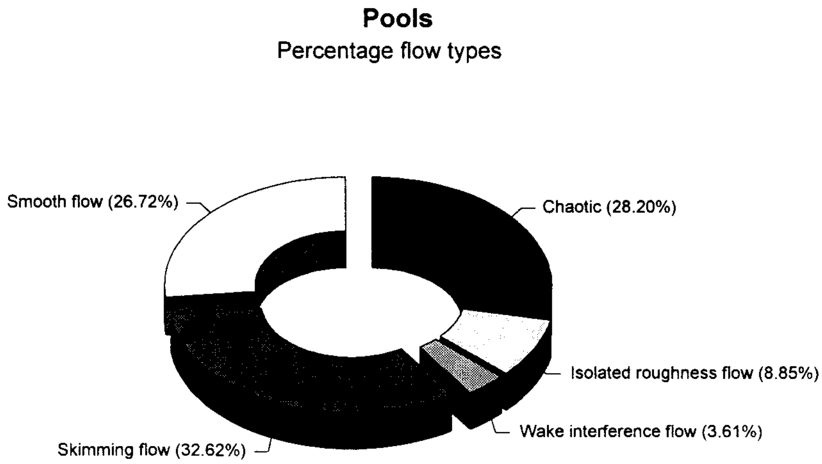


Figure 6.6 Proportional composition of different flow types within pools

Figure 6.6 represents data from 619 points. Results demonstrate considerable differences between this and the previous hydraulic biotope class. Flow is now dominated evenly by smooth, skimming and chaotic flow. Only small proportions of the other two flow types are observed. These results illustrate the high degree of hydraulic variability that occurs within instream flow environments, particularly within river channels dominated by large clasts such as the upper reaches of the Buffalo River.

Run

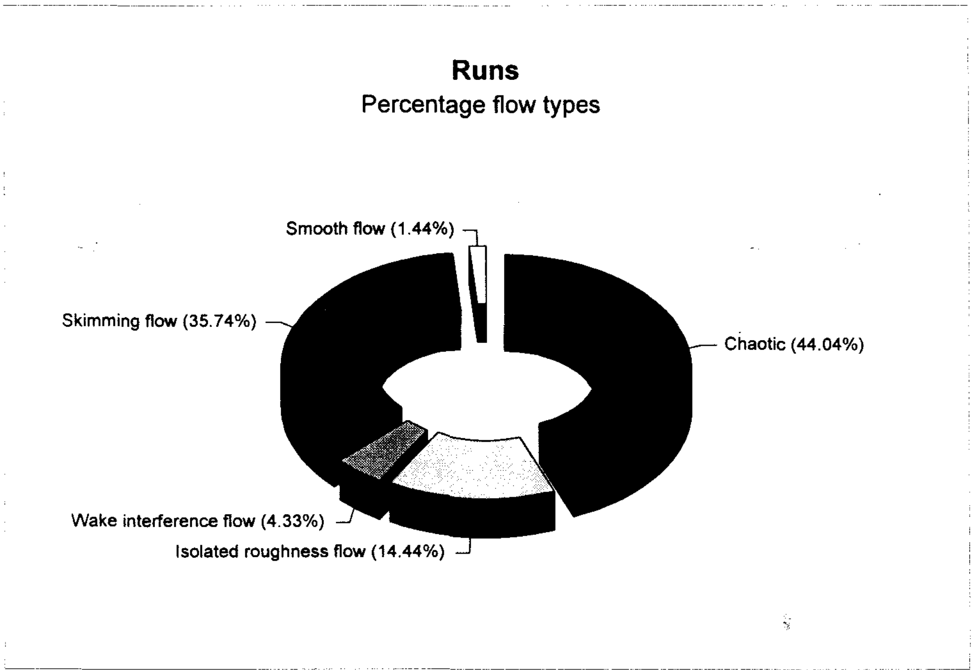


Figure 6.7 Proportional composition of different flow types within runs

Figure 6.7 represents data from 287 points. Results demonstrate significant differences between this hydrulic biotope class and the previous ones. Smooth flow is virtully redundant while chaotic flow and skimming flow dominate. This class also shows an increase in the proportion of isolated roughness flow.

Riffle

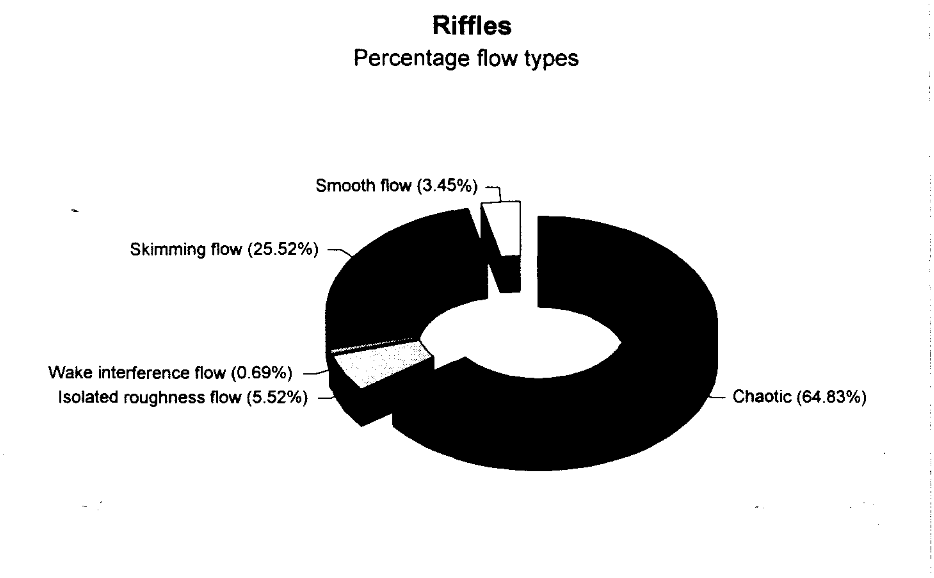


Figure 6.8 Proportional composition of different flow types within riffles

Figure 6.8 represents data from 146 points. Results demonstrate that chaotic flow is the dominant flow type within this hydraulic biotope class followed by skimming flow. An interesting observation is the presence of smooth flow in a feature which intuitively should not have any. The relatively small proportion of smooth flow is matched by a roughly equal proportion of isolated roughness flow. Very little wake interference flow occurs.

Rapid

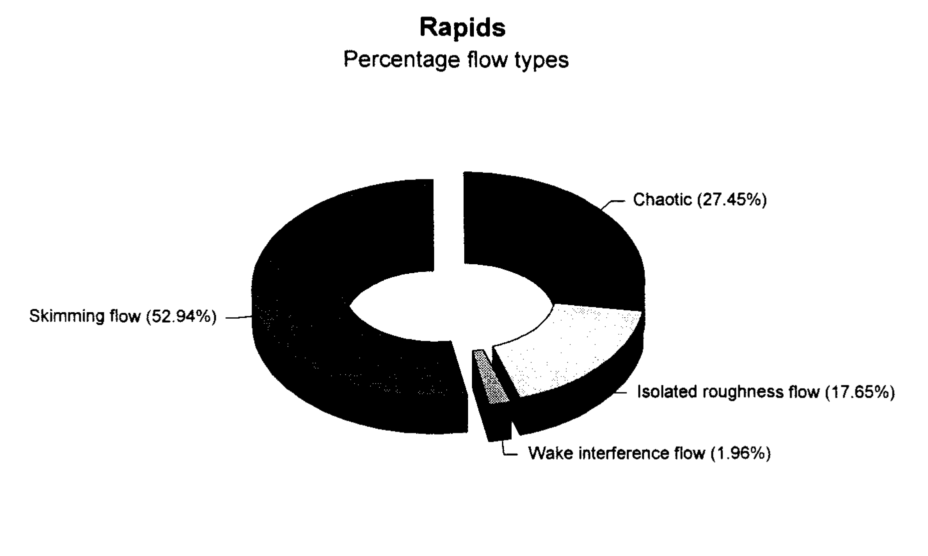


Figure 6.9 Proportional composition of different flow types within rapids

Figure 6.9 represents data from 51 points. Results demonstrate a dominance of skimming flow within this hydraulic biotope class with a sub-dominance by chaotic flow. Isolated roughness flow also makes up a relatively large proportion. Wake interference flow appears to be relatively insignificant.

Cascade

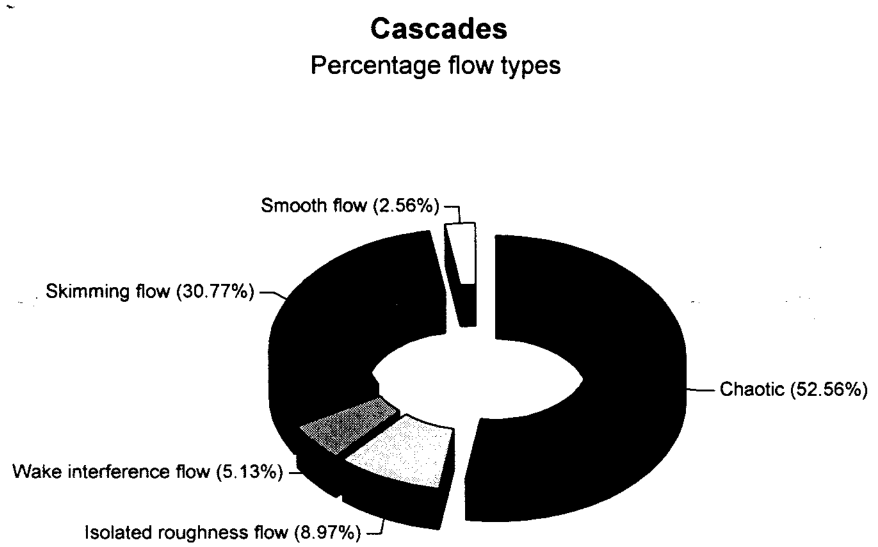


Figure 6.10 Proportional composition of diffferent flow types within cascades

Figure 6.10 represents data from 79 points. This hydraulic biotope class shows a very similar flow type composition to that observed in the run with a dominance by chaotic flow and skimming flow. An extremely suprising result is the presence of smooth flow in this feature.

Glide

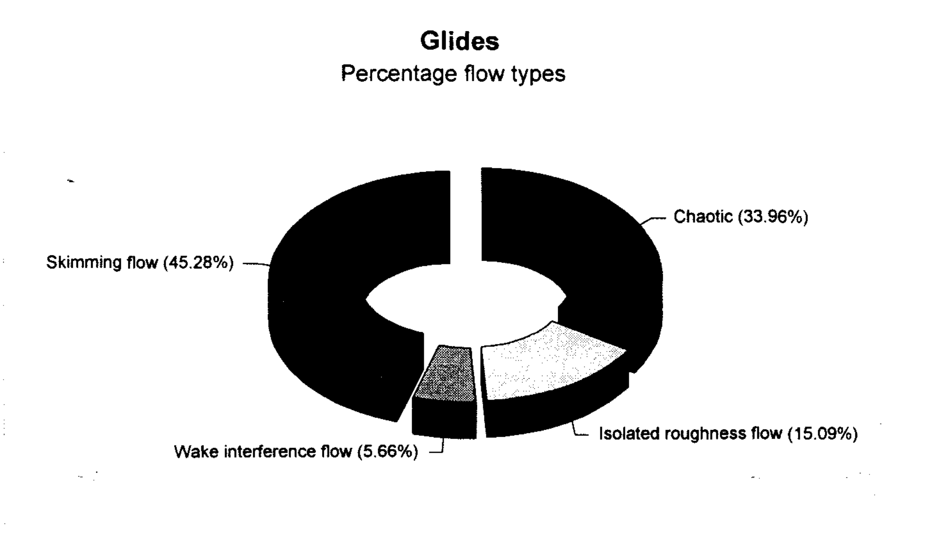


Figure 6.11 Proportional composition of different flow types within glides

Figure 6.11 represents data collected from 54 points. Results demonstrate a similar pattern of flow type composition as that observed in rapids with skimming flow showing dominance followed by chaotic flow, isolated roughness flow and wake interference flow.

Chute

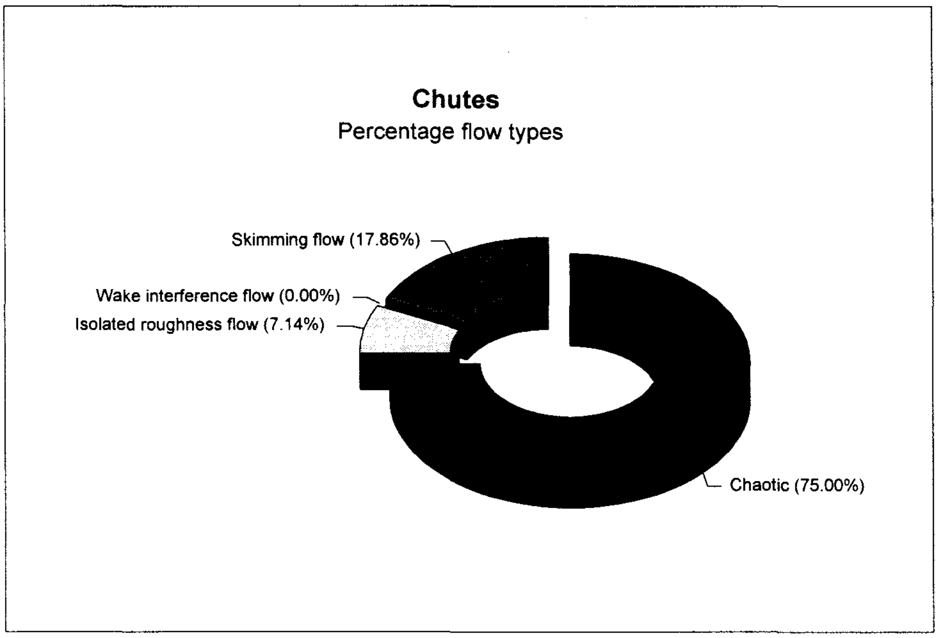


Figure 6.12 Proportional composition of different flow types within chutes

Figure 6.12 represents data collected from 28 points. Results demonstrate a domination of this hydraulic biotope class by chaotic flow followed by skimming flow and isolated roughness flow. Smooth flow and wake interference flow do not appear within this class.

Discussion

This section considers possible relationships between the classification of rough flow (Morris, 1955; Davis & Barmuta, 1989) and the hydraulic biotope classes identified in this research. Consistent with expectations, no clear associations are shown to exist. An interesting observation from the results presented here are the distinct differences in flow type composition between some of the hydraulic biotope classes.

The most obvious groups of hydraulic biotopes which show similarities in flow type composition are:

① Backwater pools
② Pools
③ Runs, Riffles and Cascades
④ Rapids and Glides
⑤ Chutes

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.

6.3.6 Summary data for the classification of hydraulic biotopes

From the results presented in this chapter it can be concluded that hydraulic biotope classes appear to be valid instream flow environments with tangible hydraulic characteristics. Table 6.11 provides values for the 25th, 50th and 75th percentiles of hydraulic indices used to characterise hydraulic biotopes in this study.

Table 6.11 Percentile values for hydraulic indices characterising hydraulic biotopes

Hydraulic Biotope	Percentile	Reynolds Number	Froude Number	Velocity-Depth Ratio	Shear Velocity	'roughness' Reynolds Number
Backwater Pool	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

6.3.7 Conclusion

Section 6.3 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 between the higher energy hydraulic biotope classes (riffle, rapid, cascade, glide and chute). Differences were noted between the hydraulic biotope classes of backwater pools, 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 backwater pools, 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.

No clear associations are shown to exist between the flow classes defined by Morris (1955) and Davis and Barmuta (1989) and the hydraulic biotope classes. This result is not suprising because of the contrasting emphasis between the bed geometry on the one hand (Morris, 1955) and the surface flow characteristics on the other (this thesis). The proportional composition of different flow types in the various hydraulic biotope classes indicate that some hydraulic biotope classes can be grouped. Before any grouping is carried out one needs to determine the ecological significance ot the various instream flow environments.

Results from this section indicate that the hydraulic biotope matrix has potential as a useful tool for the recognition of different hydraulic biotope classes. It is suggested that the matrix may need further refinement by the addition of hydraulic biotope classes in the lower energy environments (backwater pool, pool and run). There is a realisation that this refinement may not be necessary if aquatic organism distributions do not show a corresponding response to the hydraulic variations within these hydraulic biotope classes.

It would appear as though 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.

6.4 CHANNEL MORPHOLOGY, HYDRAULIC BIOTOPE DISTRIBUTION AND THE INFLUENCE OF DISCHARGE.

Having established that a number of hydraulic indices are useful variables to describe or classify hydraulic biotope classes of different spatial scales and at different discharges, the next step was to determine if there were any consistent relationships between channel morphology and hydraulic biotope class. Unfortunately site selection within this study had as its first priority different spatial scales, not morphological repetition. This, together with the fact that reach characteristics in the Buffalo River make it extremely difficult to replicate morphological units, has meant that no statistical analysis could be carried out to determine hydraulic biotope/morphology relationships or to test their spatial consistency. Only broad descriptions could be given.

Each site was divided into clearly recognisable morphological units and pie graphs plotted to represent the abundance of different hydraulic biotope classes for each of these units at each discharge. A visual analysis of these graphs allows for a quick comparison of different morphological units, or where repetition has occurred, between similar channel morphology of different spatial scales. The advantage of disaggregating each morphological unit by discharge is that it allows a quick analysis of how hydraulic biotope class composition changes with increasing discharge.

Table 6.11 presents a summary of the distribution of morphological units per site. Although there is some repetition of morphological units across sites, there are too few to make definitive statements about hydraulic biotope relationships.

Table 6.11 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					★

For ease of comparison, results for each morphological unit are presented separately and where replication has occurred comparisons are made between sites. Discharges one to four represent an increase as shown in Table 5.5.

6.4.1 Alluvial Backwater Pool

A definition of this feature is given by van Niekerk et al. (in press) as a stationary or near stationary body of water in alluvium adjacent to the active channel. An example of this morphological unit was present at transect three of the Braunschweig site (Figure 5.27). As evidenced in Figure 6.13, flows which were exceeded between 48 % and 88 % of the time (Figure 5.32 flow duration curves) made no impact on the hydraulic biotope dynamics of this morphological unit. At these relatively low flows the only hydraulic biotope class present was backwater pools. At discharge four the morphological unit is dominated by the pool class, this occurs due to the reincorporation of the side channel into the active channel.

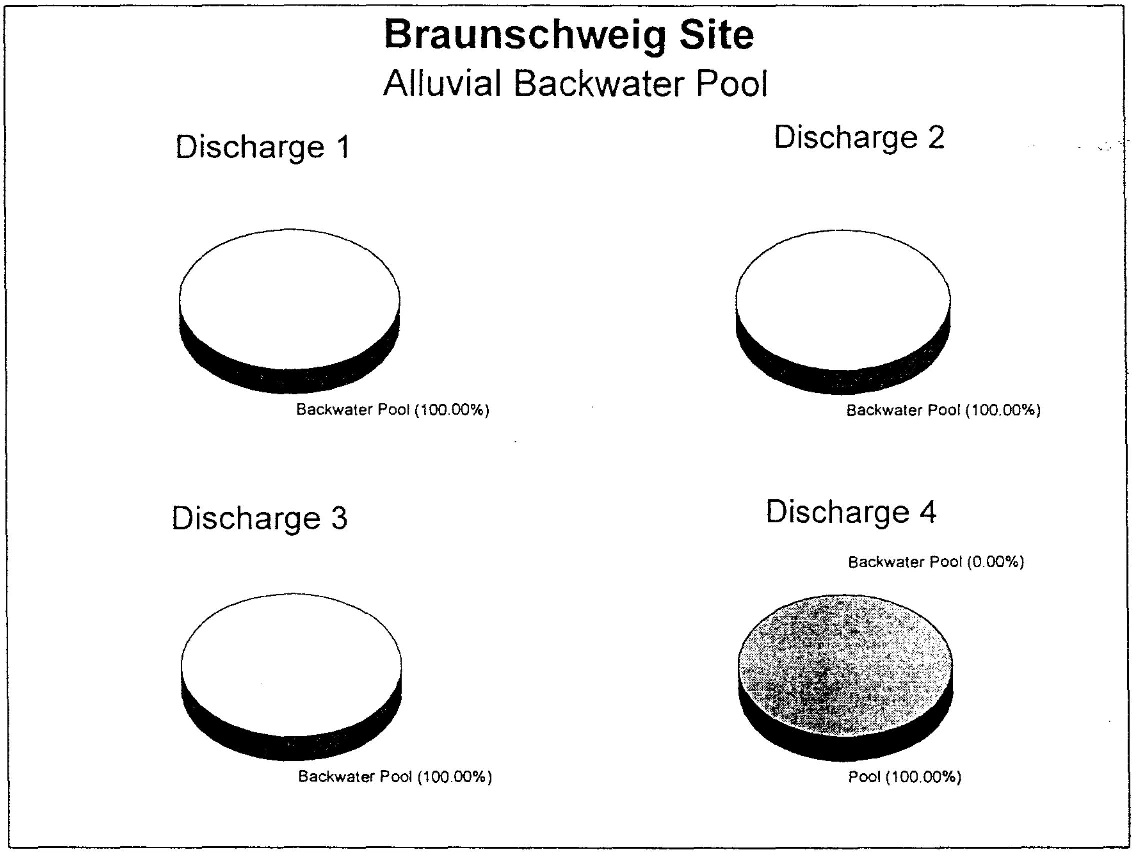


Figure 6.13 Pie graphs to show changes in hydraulic biotope class composition of an alluvial backwater pool with changing discharge.

The position of these morphological units adjacent (and very often separate) from the active channel means that they show little or no diversity in terms of hydraulics of flow until they become hydraulically reconnected. For a large portion of the low flow hydrograph, these features can be considered as consisting of a single hydraulic biotope class - backwaters. At the time of hydraulic reconnection with the active channel, it is likely that a rapid transition occurs, not only from one hydraulic biotope class to another, but also from one morphological unit to another.

6.4.2 Alluvial Pool

An alluvial pool can be defined as a topographic low point within the longitudinal profile characterised by the presence of relatively fine sediments on the bed. Two alluvial pools were present within research site 3 (Trout Pools, Figure 5.25) and were sampled at transects 1, 2, 4 and 5. The results for this morphological unit are presented in Figure 6.14.

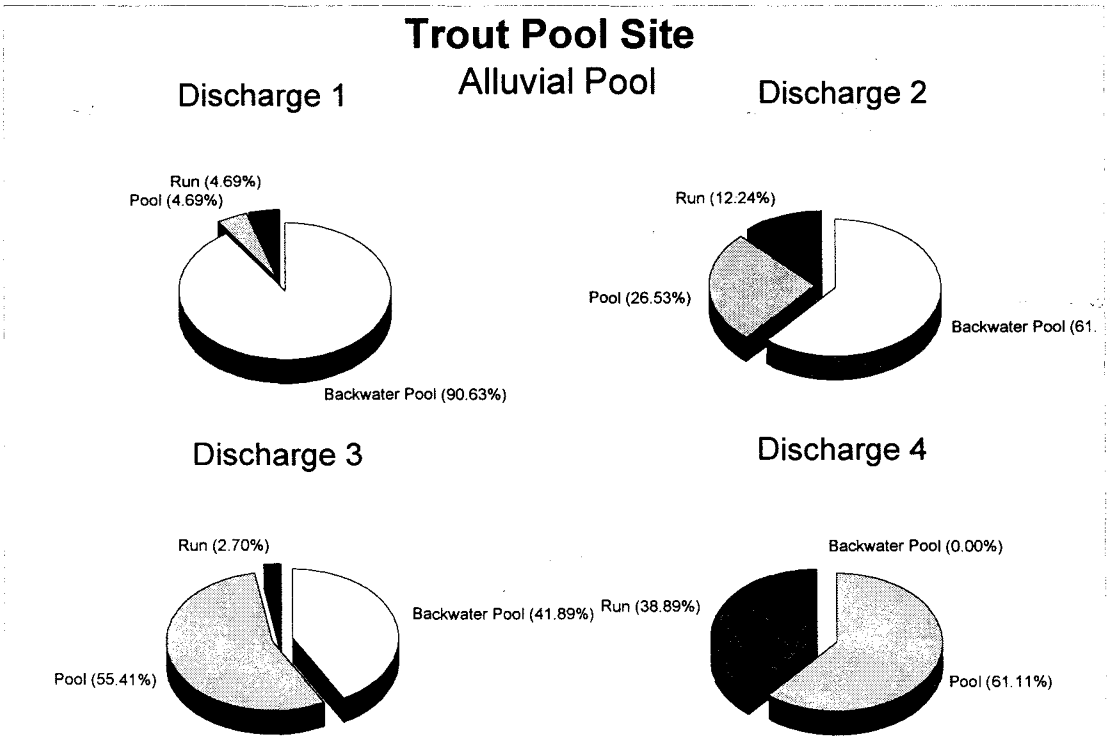


Figure 6.14 Pie graphs to show changes in hydraulic biotope class composition of an alluvial pool with changing discharge.

Three hydraulic biotope classes are present within this morphological unit namely backwater pool, pool and run. All three classes were present at the lower discharges but backwater pools disappeared at the higher discharge.

The feature is dominated by backwater pool at low flow, even though this is a fully connected morphological pool. The reason for this is that during low flows the feature is sufficiently wide and deep to provide no evidence of flowing water at the surface. As flow increases backwater is reduced and pool increases faster than run. A further increase in discharge produces further reduction in the backwater hydraulic biotope, a reduction in the run and a dramatic increase in the pool class. The final discharge shows a dramatic progression whereby backwater pool is no longer present and the feature has a 60/40 split between the pool and run class.

As evidenced by the literature review presented in Chapter Two, there is a perceived need by ecologists to differentiate between the hydraulic biotope classes of backwater pools and pools because of the aquatic organisms associated with them. From results presented here, there is evidence that a clear progression of these hydraulic biotope classes occurs with an increase (or decrease) in discharge. It is envisaged that even the short term changes in flow dynamics recorded in this study would provide hydraulic cues for aquatic organisms to redistribute themselves either laterally or longitudinally within the channel. In other words those organisms that are more easily mobilised may redistribute themselves within the morphology of the channel so as to maintain a preferred hydraulic environment (hydraulic biotope class). The more sedentary aquatic invertebrates would more likely look for refuge in the stable substratum of the bed (where it is available), until the spate has passed.

Perhaps the more important scenario to consider is not these short term changes in the flow dynamics, but rather the influence of such things as impoundments and abstractions which are likely to produce the same type of hydraulic biotope response, but of a more permanent nature.

6.4.3 Bedrock Pool

This morphological unit may be defined as a topographic low point within bedrock or large immovable boulders which is controlled locally by a bedrock obstruction across the channel. This morphological feature is very common within the Buffalo River and occurs within research sites 2, 4 and 5. Results for the three sites are presented separately, but discussed together. Results for site 2 are presented in Figure 6.15a

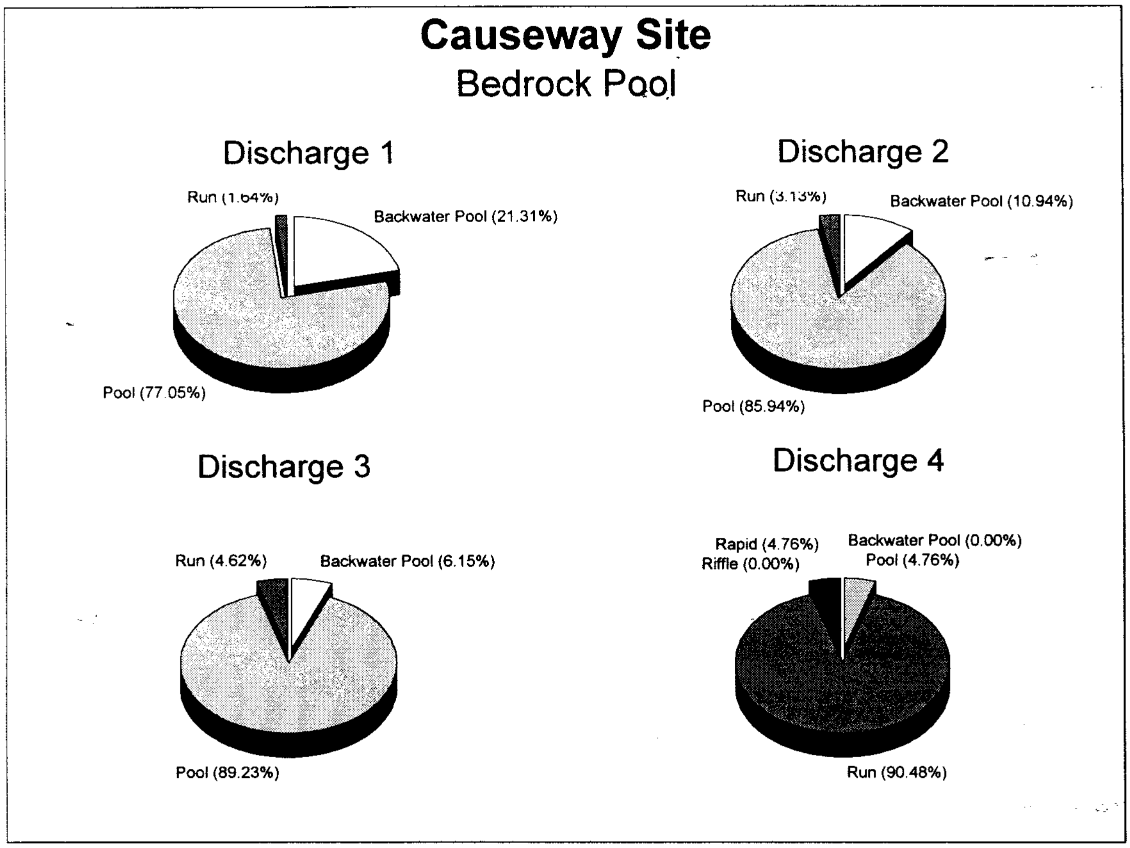


Figure 6.15a Pie graphs to show changes in hydraulic biotope class composition of a bedrock pool with changing discharge.

The bedrock pools within the causeway site are locally controlled by bedrock within the active channel margin and occur at points of local scouring, that is on the outside of bends. The features tend to be long and narrow and have beds dominated by large clasts which are well imbedded (Figure 5.23). Hydraulic biotope classes most commonly associated with this feature are backwater pools, pools and runs. At the higher discharge, rapids appear while backwater pools disappear.

Bedrock pools at the Braunschweig site are quite different from those upstream. These features occur on smooth, bedrock and span the entire channel width. They are bounded by steep deeply incised and well vegetated banks which are comprised of fine alluvium (Figure 5.27). Results for this site are presented in figure 6.15b.

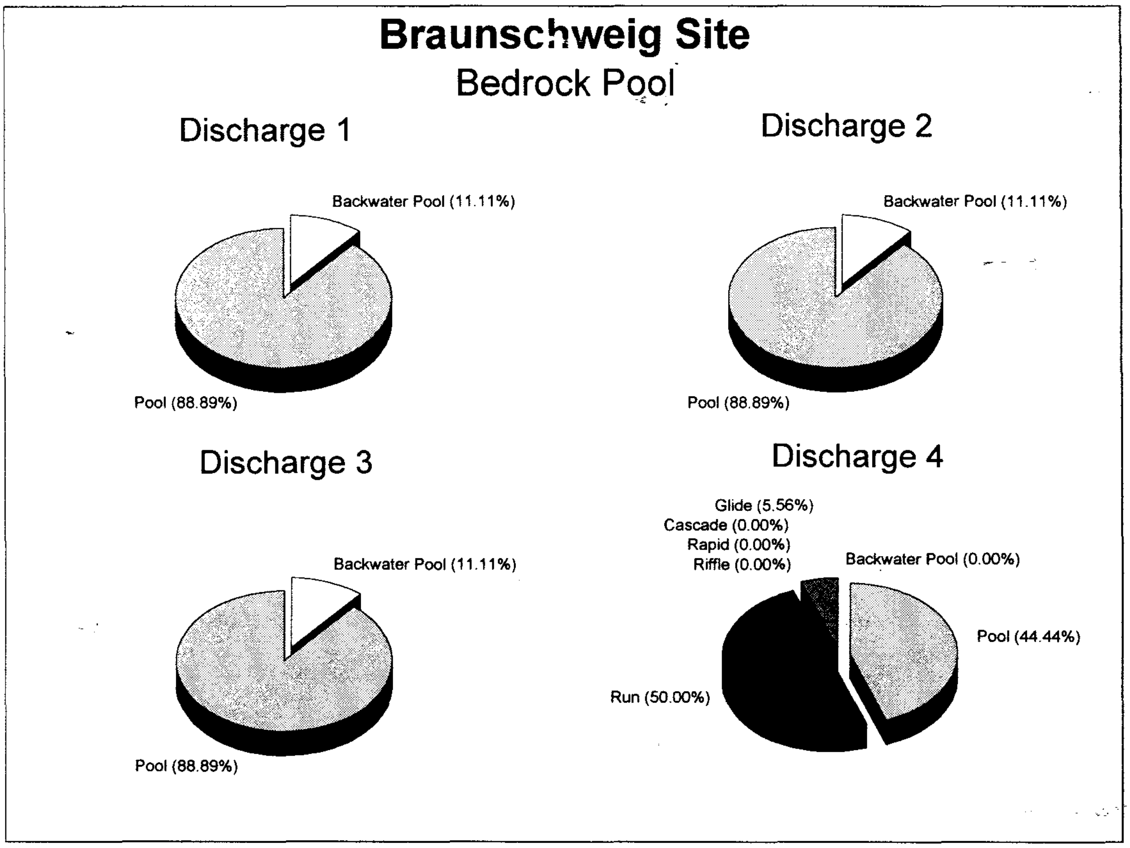


Figure 6.15b Pie graphs to show changes in hydraulic biotope class composition of a bedrock pool with changing discharge

Unlike the similar features upstream, this feature is dominated by backwater pool and pool at the lower discharges with no run present. At the higher discharges (still very low relative to the size of the channel), backwater pool disappears and run and pool dominate with a small proportion of glide appearing.

Bedrock pools at the King William's Town site are similar to those found at Braunschweig except that pools dissapear at relatively high flows and glides appear. Results for this site are presented in figure 6.15c.

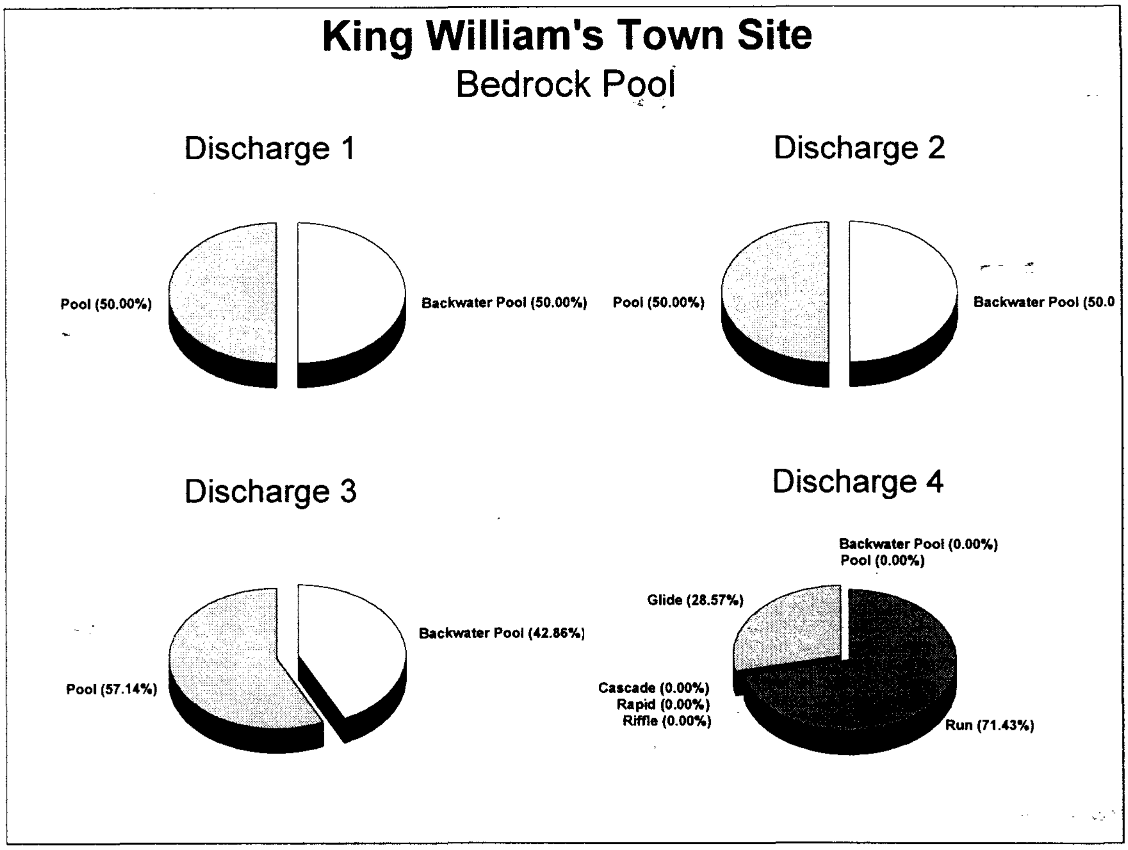


Figure 6.15c Pie graphs to show changes in hydraulic biotope class composition of a bedrock pool with changing discharge

This feature consists of pools and backwater pools at lower flows and runs and glides at higher discharges. The most important difference between this feature and similar ones upstream, is the large proportion of backwater pools at low flows and the complete absence of pools at higher flow.

The hydraulic biotope make-up of these three bedrock pools is quite similar with a dominance of pools and backwater pools at the lower discharges and with runs becoming more dominant as discharge increases. There are differences with the composition of the higher energy hydraulic biotope classes from site to site. At discharge 4 of the causeway site chutes and rapids appear, in the other two sites glides become apparent at the higher discharge. This can be explained by the substratum characteristic of roughness height between the three sites. At the causeway site the mid 50 % of roughness height is between 6 and 12 cm while at the other two sites roughness height is considerably less. It is therefore considerably easier to drown out the influence of bed material in the bedrock sites than it is in the causeway site which is dominated by boulders and cobbles.

In terms of a hydraulic biotope progression in response to increasing discharge it would be easier to separate the sites into bedrock (Braunschweig and King William's Town) and cobble/boulder bed (causeway). The bedrock sites are dominated by pool and backwater at low discharges, as discharge increases backwater pools diminish while pools increase. Backwater pools eventually disappear completely and pools are reduced and replaced by run. A further increase in discharge may lead to reduction in pool and run but the appearance of glide.

Cobble/boulder bed indicates that at low discharges, backwaters are not as common as pools and that runs are present but rare. As discharge increases, the areal extent of pools and runs increase, while backwaters are reduced. A further increase in discharge causes reduction in pools and dominance by runs with the inclusion of small proportions of rapids and chutes as large material on the channel margin becomes incorporated.

6.4.4 Plunge Pool

A plunge pool may be defined as a scour feature below falling water within bedrock or large immovable clasts. Two of the reaches sampled within this research contained plunge pools. The first was situated at the Trestle Bridge site and was part of a morphological continuum of steps and pool (Figure 5.21). The second was situated at King William's Town and occurred as a fault within resistant bedrock (Figure 5.29). Results for these two sites are presented separately (Figure 6.16a and 6.16b) but are discussed together.

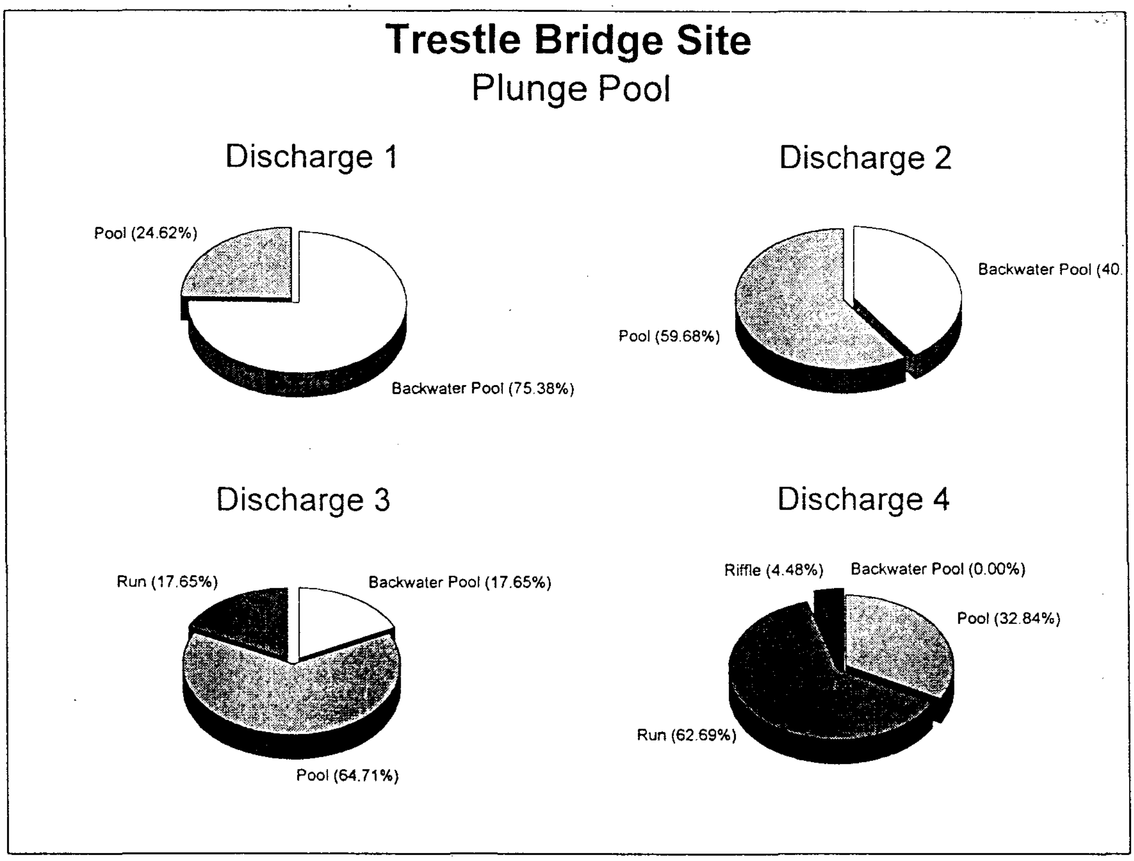


Figure 6.16a Pie graphs to show changes in hydraulic biotope class composition of a plunge pool with changing discharge.

Plunge pools at the Trestle Bridge site consisted of four hydraulic biotope classes through the range of measured discharges; backwater pool, pool, run and riffle. A relatively clear progression is evident with increasing discharge.

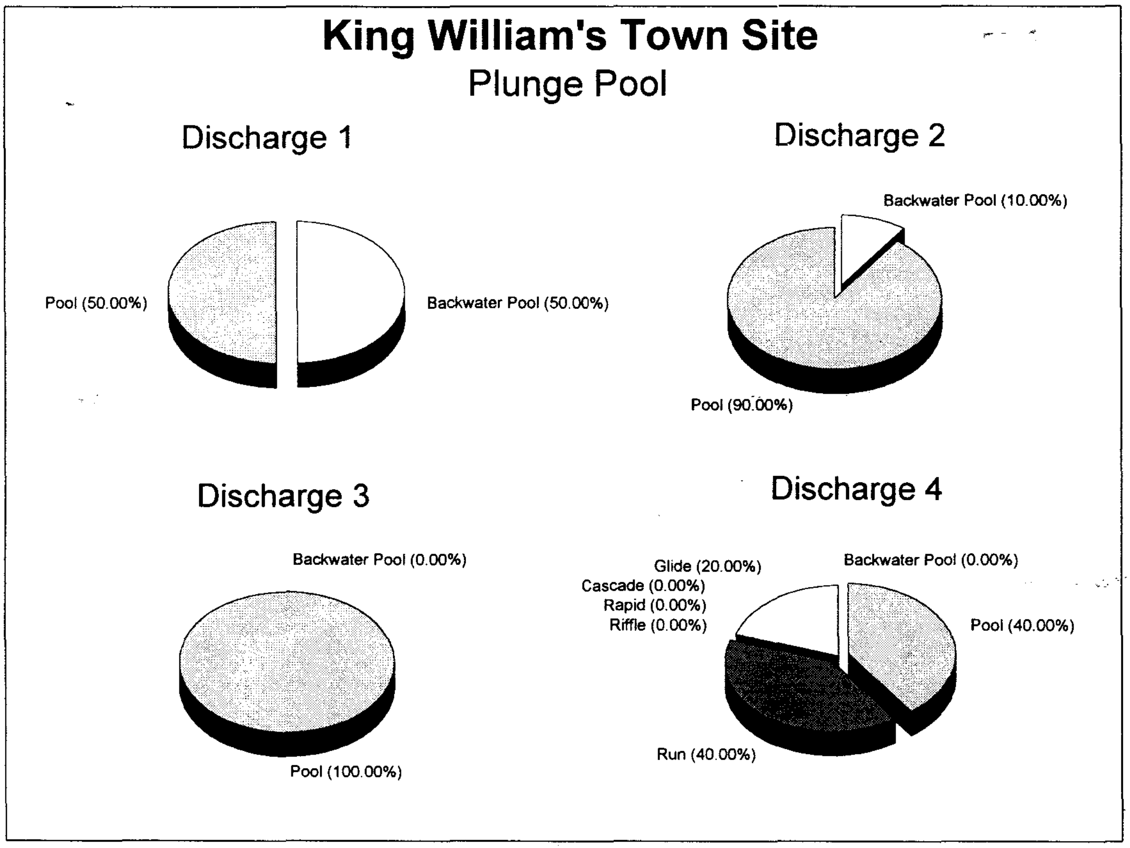


Figure 6.16b Pie graphs to show changes in hydraulic biotope class composition of a plunge pool with changing discharge

Plunge pools at the King William's Town site consisted of four hydraulic biotope classes; backwater pool, pool, run and glide. A similar progression was observed as that for the upstream site with the main difference being the appearance of glides instead of riffles.

The progression from backwater to pool to run at lower discharges appear to be similar for the two different sites. At a higher discharge, the ability of the flow depth to drown out the influence of bed material roughness determines whether class progression occurs from run to riffle (large substratum) or from run to glide (unfractured bedrock). Plunge pools are not dissimilar to bedrock pools, except that in this morphology pools are maintained at high flows.

6.4.5 Bedrock Pavement

A bedrock pavement is defined by van Niekerk *et al.* (in press) as a laterally extensive outcrop of bedrock over the macro channel floor. The nature of the geology of this catchment (sandstones, mudstones and intrusive dolerite dykes), the relatively steep nature of the longitudinal profile and the relatively recent local uplift means that in many areas of the channel, incision has occurred to the depth of resistant bedrock. This bedrock is fairly smooth with the occasional local faulting causing small steps which act as local controls. It is across these controls that transects were taken and measurements made. The relatively horizontal and gently sloping nature of this material does not allow its recognition as rapid morphology and is therefore referred to as bedrock pavement. This morphology was only sampled at the Braunschweig site although it is common throughout the lower reaches of the Buffalo River. The results of this morphology are displayed in Figure 6.17.

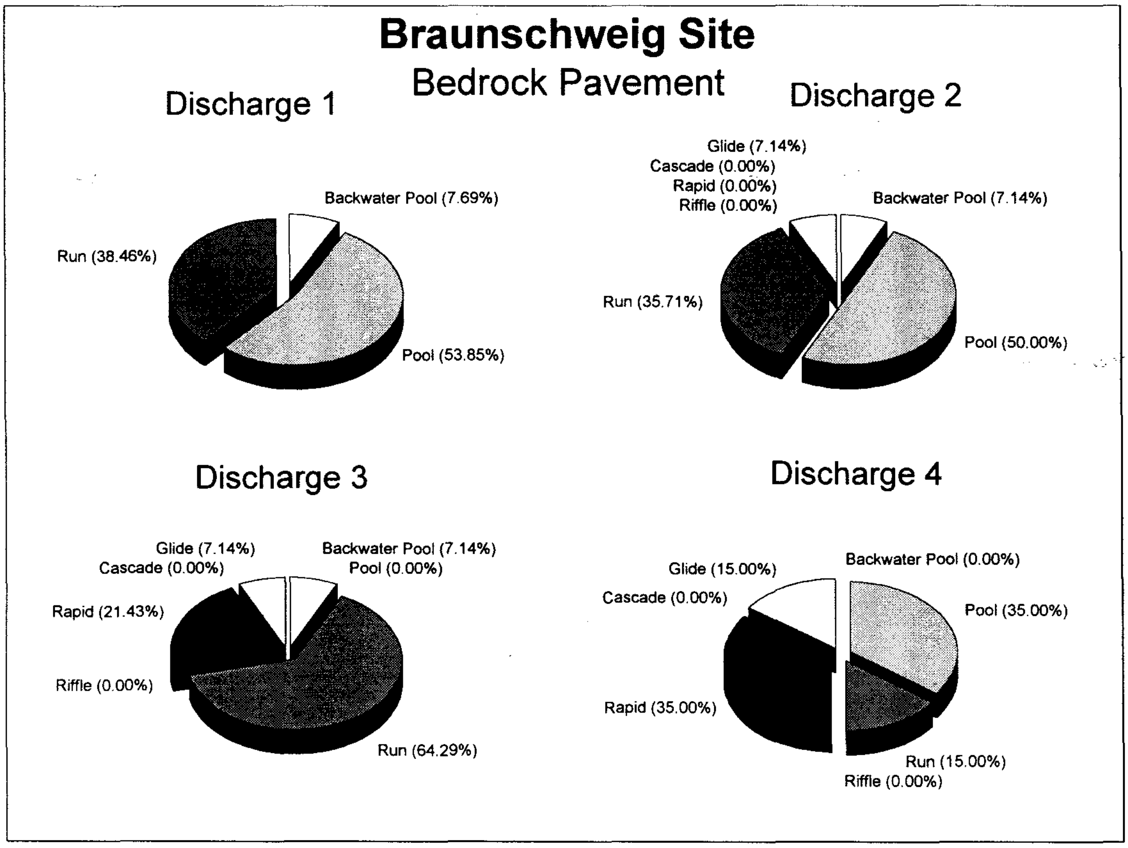


Figure 6.17 Pie graphs to show changes in hydraulic biotope class composition of a bedrock pavement with changing discharge.

Five hydraulic biotope classes are found within this morphological unit namely backwater pools, pools, runs, glides and rapids. All five of these classes were apparent by the time discharge three measurements were made.

The hydraulic biotope class composition of this feature is interesting because it does not show clear differences between the lower energy classes of the lower discharges (1, 2 and 3) and the higher energy classes of the higher discharge (4), even though they are clearly apparent in the previously mentioned morphological units.

The class progression for this feature shows a domination by pools and runs at low discharge with a small proportion of backwater pools. As discharge increases a portion of the pool and run is decreased to be replaced by glide while backwater remains the same. A further increase sees the complete removal of pool and the new dominance of runs, some of which appears to become rapid. Glide and backwater pools remain unchanged. The final discharge sees the re-emergence of pools (as the active channel becomes larger), runs become less dominant while the proportion of rapids and glides increases.

The high diversity associated with small increases in discharge can be related to the shape of this morphological unit. Being relatively flat and acting as a local geomorphological control or high point, flow at low discharge is only present through low points (perhaps a single narrow trapezoid niche). As discharge increases, water overflows this niche gradually covering more and more of the bedrock pavement until the entire width of the channel is covered. This flow is shallow and hydraulically diverse as it is easily influenced by small bedrock protrusions.

6.4.6 Plane Bed

Plane bed morphology is defined by Montgomery and Buffington (1993) as features that lack any rhythmic bedforms and that occur at gradients and relative roughness intermediate between pool-riffle and step-pool morphology. Particles are large relative to the flow depth and are responsible for the "chaotic" appearance of the water surface. This morphology is common in the upper reaches of many South African rivers and was sampled at the Causeway site of the Buffalo River (Figure 5.23). Results for this morphology are presented in Figure 6.18.

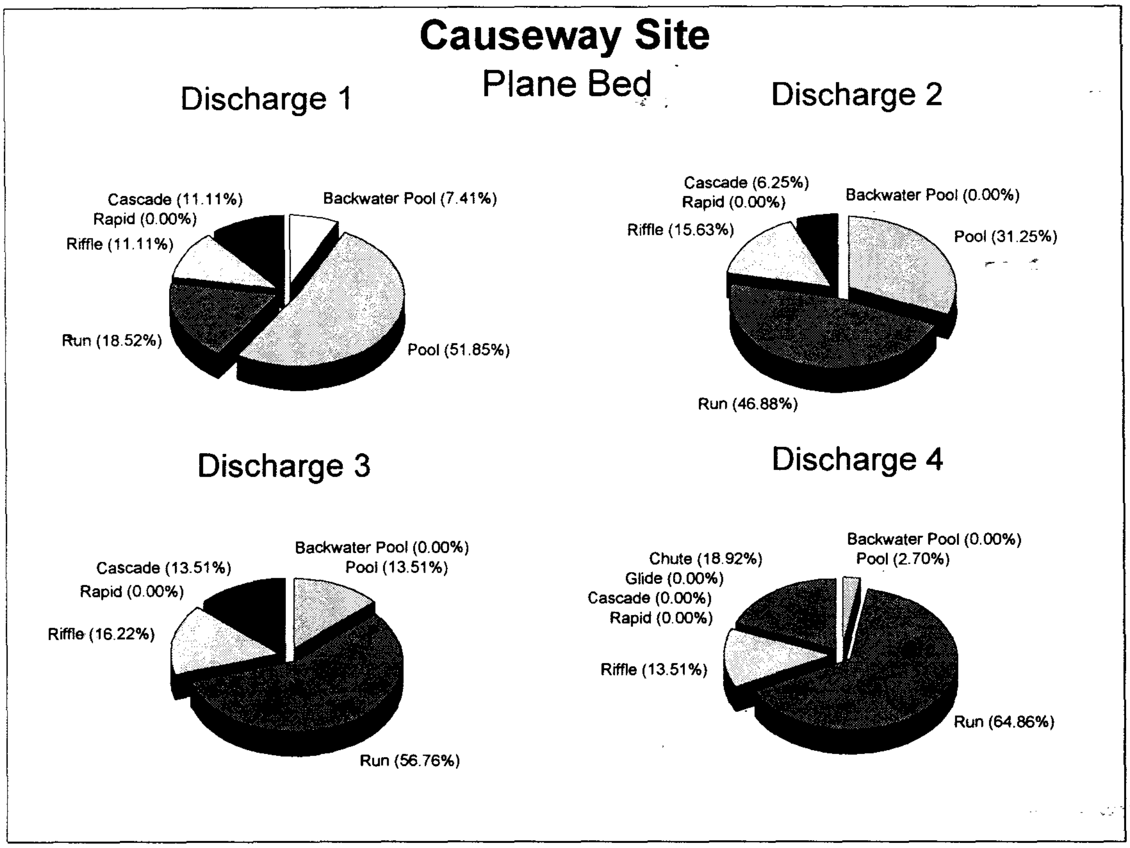


Figure 6.18 Pie graphs to show changes in hydraulic biotope class composition of a plane bed morphology with changing discharge.

Hydraulic biotope classes associated with this morphology are backwater pools, pools, runs, cascades chutes and riffles.

Hydraulic biotope class progression appears to follow the following pattern: at low discharge the feature is dominated by pools with a small proportion of backwater pool, cascade, riffle and run present. An increase in discharge sees the removal of the backwater class and an increase in the run and riffle class while cascade decreases. A further increase in discharge leads to a reduction in pools and an increase in runs, riffles and cascades. A further large increase in discharge causes a reduction in pools and riffles, an increase in runs, the removal of cascades and the appearance of chutes. Cascades are drowned out and replaced by riffles (standing waves on the water surface), and the larger clasts on the channel margin start to re-direct flow creating chutes.

6.4.7 Step

Steps may be defined as features which consist of large clasts organised into channel spanning accumulations that separate pools containing finer material. These steps consist of water seeping under and around the large clasts during low flows, but are overtopped to create small falls during higher flows. These are common features of the upper reaches of the Buffalo River and were sampled at the Trestle Bridge site (Figure 5.21). Results for this morphological unit are presented in Figure 6.19.

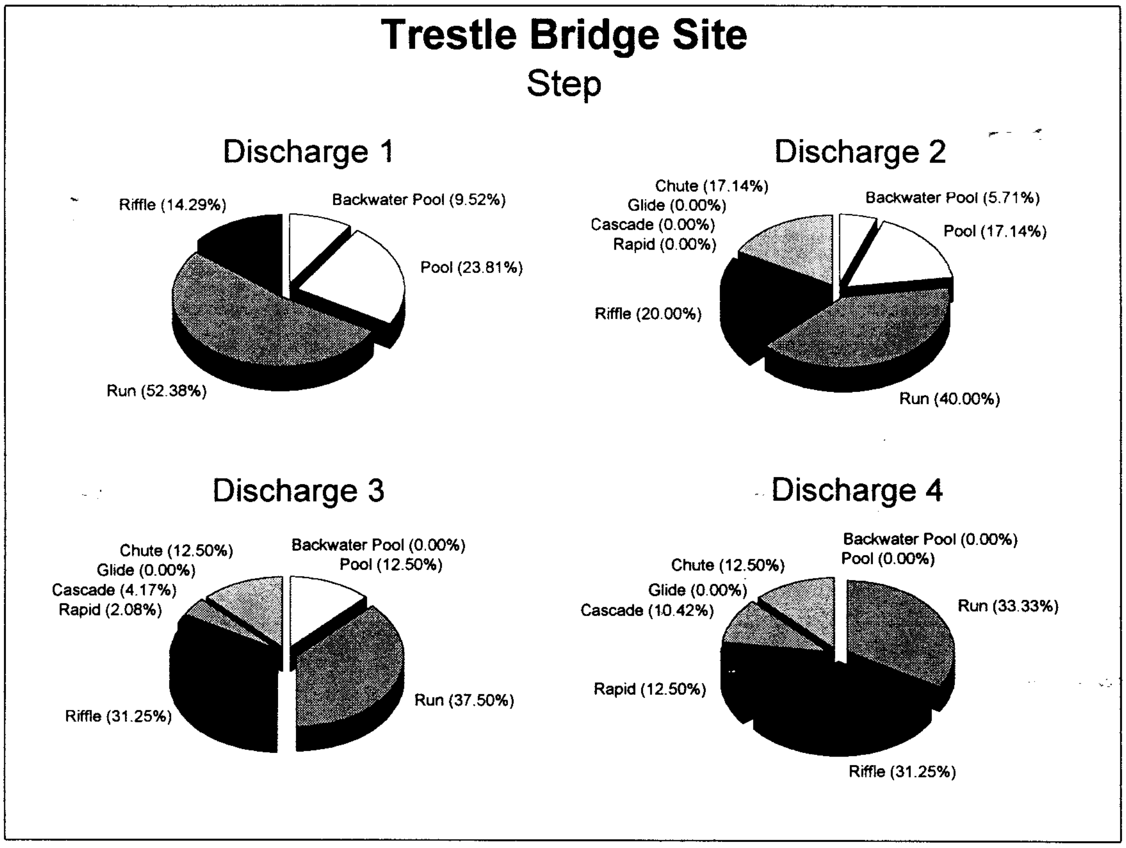


Figure 6.19 Pie graphs to show changes in hydraulic biotope class composition of a step morphology with changing discharge

The step morphology provides the most diverse array of hydraulic biotope classes. Seven classes can be recognised; backwater pool, pool, run, riffle, rapid, cascade and chute. The only hydraulic biotope class missing is the glide and this is never likely to be present at this site because of the high roughness heights measured.

The hydraulic biotope progression observed at this site is similar to those mentioned earlier with backwater pools, pools and runs being reduced while riffles, rapids, chutes and cascades increase with increasing discharge. Runs again appear to be an intermediate class between high and low energy classes.

6.4.8 Riffle

These may be simply defined as the accumulation of coarser sediments as topographic high points within a riffle-pool sequence. The size of the largest bedload material in pool-riffle channels is a fraction of the bankful flow depth and is traditionally thought of as a feature that is covered even by low base flow conditions. In South Africa the extremely high variability of flow together with the large substratum size means that large areas of these features are often uncovered during base flow conditions and appear as transverse bars.

The Trout Pool reach was recognised as having a clearly defined succession of riffles interspersed with pools (Figure 5.25). Results for this site are presented in Figures 6.20.

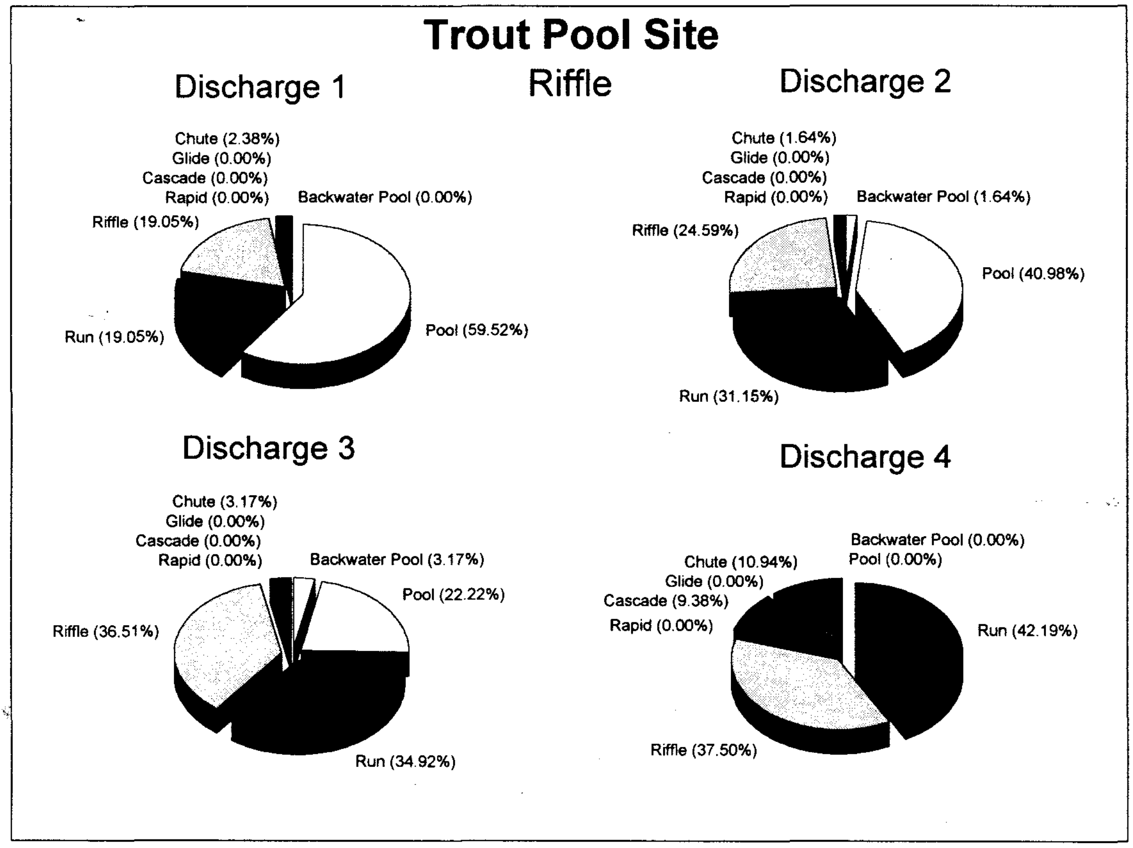


Figure 6.20 Pie graphs to show changes in hydraulic biotope class composition of riffle morphology with changing discharge.

The riffle morphology observed at the Trout Pool site was well represented by the presence of four transects across two separate riffles. Hydraulic biotope classes present within the morphology of this site include backwater pool, pool, run, riffle, chute and cascade.

An interesting feature of the above results are the way in which the riffle class never obviously dominates the feature as one might expect it to. At the lower discharge the feature is dominated by pools with an equal proportion of runs and riffles and a small amount of chutes. As discharge increases the proportions of riffles, runs and pools start to even out. A further increase sees riffle and run obtaining equal dominance while pool is reduced with chute only increasing slightly. The final discharge shows riffle and runs having taken over equal dominance (about 40 % each) while chutes and cascades make up an equal portion of the remaining 20 %.

6.4.9 Rapid

A rapid may be defined as a steep bedrock section which has concentrated flow dominated by high velocities (van Niekerk *et al.*, in press). The King William's Town site was the only reach which included this morphology in the sampling framework. The rapid at this site is very local and occurs as a result of a dolerite intrusion across the channel (Figure 5.29). Results for the rapid morphology are presented in figure 6.21.

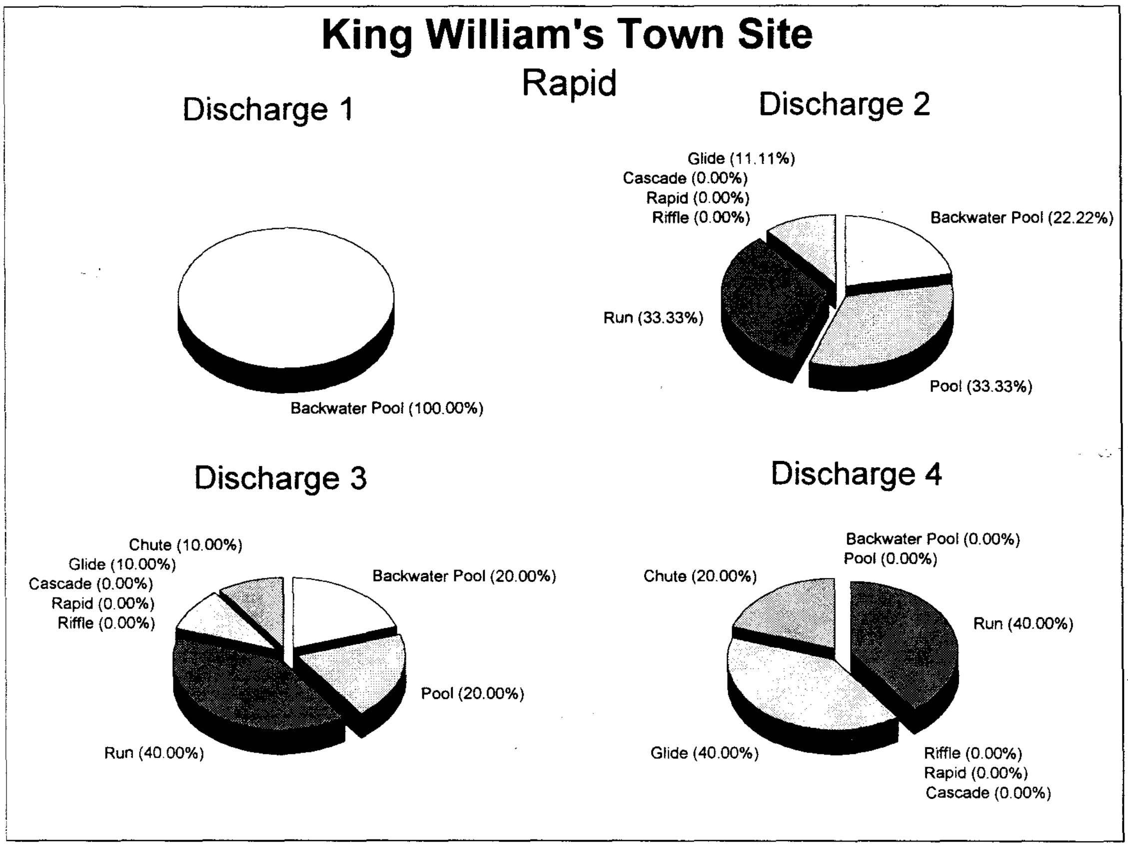


Figure 6.21 Pie graphs to show changes in hydraulic biotope class composition of rapid morphology with changing discharge.

This morphological unit consisted of five hydraulic biotope classes; backwater pool, pool, run, glide and chute. Hydraulic biotope diversity increases from discharge 1 through to discharge 3 and then is reduced again at the higher discharge 4.

An interesting observation about this morphological unit is the fast change in class structure as a response to increasing discharge. This result is similar to that experienced for bedrock pavement at the Braunschweig site and probably occurs for the same reason. A hydraulic biotope progression occurs such that initially backwater pools form behind the high points of the intrusion at low discharge. As discharge increases, local concentrations of flow spill over into narrow channels within the bedrock and pools, runs and glides appear. Further increases of flow provide a wider area of flow across the bedrock and further concentrations of flow within small confined channels. Glides remain constant and run areas increase while chutes now appear where flow constrictions are occurring. The areas of pool and backwater pool diminish. At the final discharge, flow is occurring across the width of the rapid and as a result pools and backwater pools disappear. Run areas remain fairly consistent as a proportion of the morphological unit while glides and chutes increase.

6.4.10 Conclusion

Section 6.4 attempts to determine whether there are any specific associations between the general physical make up of the river channel (channel morphology) and the distribution of hydraulic biotope classes. This section also assesses the influence of discharge on this distribution.

Backwater pools, pools and runs were the three hydraulic biotope classes which showed no associations with specific morphological units, they were equally as common in all channel morphology. Glides were specifically associated with smooth beds consisting of unfractured bedrock. This 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. 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 backwater pools, pools, runs, riffles and chutes at low discharges. At high discharges the pattern changes to run, riffle, cascade and chute. On the other hand a bedrock pavement has different associations; at low discharges backwater pools, pools and runs are common. At higher discharges this changes to pools, runs, rapids and glides.

6.5 SUMMARY AND SYNTHESIS

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 recognition of different hydraulic biotope classes appears to be extremely useful as it can be applied at a number of different spatial and temporal scales. Statistical analysis of results suggest that generally 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; the patterns of change are determined by the original associations between morphological units and hydraulic biotope classes.

CHAPTER SEVEN
ECOLOGICAL SIGNIFICANCE OF THE HYDRAULIC BIOTOPE

7.1 INTRODUCTION

This chapter provides a justification for the development of the hydraulic biotope concept described in this research by providing a qualitative assessment of its ecological significance within the Buffalo River.

As described in Chapter Two, there are many published ecological studies which regard it necessary to sub-divide a stream into a mosaic of patches, each one subjectively recognised on the basis of any number of different criteria. Common criteria used for the recognition of these patches or 'habitats' are the substratum and/or hydraulic characteristics of the river at that point. Southwood (1977) defines a habitat as the place that an organism occupies in time and space, a definition that implies a fine scale of resolution for study. A cursory examination of the ecological literature indicates that the 'habitat scale' of study is used infrequently in ecological research. The more practical, and therefore more common scale of ecological research considers one which incorporates communities of organisms. This has been termed the biotope and is defined by Udvardy (1959) as the location of the community in time and space.

The broader 'biotope' scale has the potential to provide a link between the smallest geomorphological scale feature (the morphological unit) and its associated ecology. The more semantically correct term is the 'hydraulic biotope' and is the one used in this research to define this scale based link. A distinction is made between these two terms because of the implied relationships that are made when referring to one or the other. Traditionally it is the characteristics of the hydraulic and physical environment that are intuitively used by ecologists to recognise different sampling areas. These are the variables that appear to be the primary factors influencing the distribution of aquatic communities.

As evidenced in Chapter Two, the distribution of macroinvertebrate assemblages in streams is frequently discussed in terms of the nature of the physical environment in which they are found (Boulton *et al.*, 1988; Statzner *et al.*, 1988; Wetmore *et al.*, 1990; Jowett & Richardson, 1990) There is, however, conflicting evidence for and against the association of species assemblages with particular hydraulic biotopes, the outcome of results tending to be a function of the scale at which hydraulic biotope classes are recognised. Chutter (1970), Scullion *et al.*, (1982), Ormerod (1988), Palmer (1991) and Emery (1994) are some researchers who have presented findings that indicate a strong association between species assemblages and particular hydraulic biotope classes. On the other hand authors such as Wright *et al.*, (1983) and Jenkins *at al*, (1984) report a lack of such associations.

Some authors have indicated the ecological significance of instream flow environments at the scale of the hydraulic biotope. Gorman and Karr (1978) made an observation that most fishes are 'habitat' (hydraulic biotope) specialists while Northcote (1978) recognised that many fish utilise specific locations within stream channels throughout their life cycles in response to spawning, feeding and overwintering requirements. These relationships between the hydraulic biotope and such aspects as biotic distributions, trophic and life history adaptations have been noted by many authors (Linduska, 1942; Cummins & Lauff, 1969; Rabeni & Minshall, 1977 and Hynes, 1970). Some authors have extended these relationships to the structure and dynamics of stream communities (Reice, 1974; Dudgeon, 1982; Mc Auliffe, 1983; Wever & Warren, 1986).

The remainder of this chapter draws on previous research carried out by aquatic ecologists in the Buffalo and other rivers and attempts to show the ecological significance of the hydraulic biotope classes defined in this study. Problems exist from one study to another due to subjective definition of habitat or hydraulic biotope classes together with the inconsistent use of terminology and poor descriptions of substratum, velocity and depth. These problems hinder direct comparison between this and other studies and therefore only allow broad generalisations to be made.

7.2 THE BUFFALO RIVER

A number of ecological studies have been carried out in the Buffalo River but only one of these attempts to relate species distribution to biotope classes found within the river channel. As part of a study carried out by Palmer (1991), an attempt was made to determine what associations exist between macroinverterbrate assemblages and subjectively defined 'biotopes' in three reaches of the Buffalo River. In this study three sites were selected within the upper, middle and lower reaches of the Buffalo River. At each site 'biotopes' were broadly identified as either being erosional (turbulent flow) or depositional (still water). Within these broad conditions, specific 'biotopes' were subjectively defined (Table 7.1).

Table 7.1 Classification of biotopes by Palmer *et al.* (1991).

Palmer *et al.* Location	Location within this study	Erosional biotopes	Depositional biotopes
Site 1	Segment 2 Reach 2 (Site 2)	Riffles Leaf packs in riffle Waterfalls	Stony backwater Sediments
Site 2	Segment 3 Reach 5 (Site 4)	Riffle Marginal vegetation in current	Stony backwater Marginal vegetation out of current Sediments

Macroinvertebrate samples were collected seasonally from different 'biotopes' in summer (February), autumn (May), winter (August) and spring (November). On each sampling occasion three separate replicate samples were collected in each class. Samples from all 'biotopes' and seasons were classified using two-way indicator species analysis (TWINSPAN).

The following results were obtained from this study: a difference was noted between the species assemblage structure of the headwater and lower reaches. Within the headwater site a distinction was made between the species assemblage of the waterfall class and the rest of the stream. Within the riffle-pool sequence of channel morphology a seasonal shift in species assemblage was more apparent than a 'biotope' association. In the lower reaches there were clear associations between species assemblages and 'biotopes'.

In a discussion of her results (Palmer, 1991 p66), the following points were made: "The dimensions of the headwater stream were considerably smaller than the middle/lower reaches. At site 1 the stream was very narrow , and the subjectively recognised biotopes formed a mosaic of small patches. Physical conditions in these patches changed frequently, due to variable discharge, which fluctuated from occasional spates to a seasonal absence of surface flow. This contrasted with the middle and lower reaches (22 - 30m wide), where biotopes formed larger discrete units, and changes in discharge were more gradual and less frequent".

As noted by Palmer (1991), by subjectively distinguishing between erosional and depositional 'biotopes', it is implicitly recognised that water velocity and substratum are important factors which differentiate between 'biotopes' in the Buffalo River.

7.2.1 The hydraulic biotope connection

An obvious problem with trying to link the findings presented in this thesis with those of Palmer *et al.* (1991) is the inconsistent use of 'biotope' terminology between the studies. Palmer *et al.* (1991) use many of Allen's (1951) definitions which are referred to in Chapter Two. Results presented in the previous chapter of this research indicate that associations appear to exist between channel morphology and hydraulic biotope classes. These relationships are used to determine which classes recognised in this study match the broader 'biotope' classes of the Palmer *et al.* (1991) study.

Two of the sites studied by Palmer *et al.* (1991) fall within study reaches of this research. Site 1 recognised by Palmer *et al.* (1991) falls within segment 2, reach 2 (Figure 5.23) and is comprised of plane bed and bedrock pool morphology. Site 2 falls within segment 3, reach 5 and is comprised of bedrock pavement, bedrock pool and alluvial backwater pool morphology. The biotope classes recognised by Palmer *et al.* (1991) and the related hydraulic biotope classes recognised in this study are presented in Table 7.2.

Table 7.2 Biotope classes recognised by Palmer *et al.* (1991) and their equivalent hydraulic biotope classes recognised within this study.

Palmer *et al.* (1991) Site 1	Wadeson (this thesis) Seg 2, Reach 2	Palmer *et al.* (1991) Site 2	Wadeson (this thesis) Seg 3, Reach 5
Riffles	Riffle Cascade Chute	Riffles	Rapid Cascade Glide
Leaf packs in Riffles	Run	Marginal vegetation in current	Run
Stony Backwater	Backwater pool	Stony Backwater	Backwater pool
Waterfall	Cascade	Marginal vegetation out of current	Pool
Sediments	Run Backwater pool Pool	Sediments	Run Backwater pool Pool

Table 7.2 clearly demonstrates that the broad definitions of hydraulic biotope classes as used by Palmer *et al.* (1991) are of a much coarser scale than those used in this study. Despite this coarse scale (or perhaps because of it), associations were clearly noted by Palmer *et al.* (1991) in the lower reaches between hydraulic biotope classes and species assemblages. In the upper reach, the only distinction that could be made was between the waterfall hydraulic biotope and the rest. Reasons for lack of consistency between the upper and lower reaches are given by Palmer *et al.* (1991) as being related to problems of scale. The upper reach consisted of a complex mosaic of patches which are extremely dynamic and respond to abrupt changes in discharge. On the other hand the lower reaches had a more consistent and easily recognisable hydraulic biotope pattern. These results can be compared to an investigation carried out by King *et al.* (1987) in a small western Cape stream. Headwaters of this stream were of a similar scale to that studied by Palmer (1991) in the Buffalo River. The scientists in this study could not distinguish between different hydraulic biotopes at this scale. It is suggested that the complex mosaic of hydraulic biotope classes in these small scale streams do not allow for easy recognition using traditional subjective methods.

A relatively simple third year research project was carried out by Gordon (1995) in conjunction with the research presented in this thesis. The aim of this study was to determine if there were any associations between invertebrate families in three different hydraulic biotope classes (pools, riffle and runs) within three separate morphological riffles situated in the headwaters of the Buffalo River. Limited results from this study led him to conclude that the family *Simuliidae* could be considered as diagnostic of the riffle class while the families *Libellulidae* and *Aeshnidae* were characteristic of the pool class. No family associations were observed for the run. The evidence presented in this work was far from conclusive but clearly indicated the potential of a more rigorous and objective approach to hydraulic biotope classification for the description of macroinvertebrate species assemblage distributions within any scale of study.

7.3 RELATED ECOLOGICAL STUDIES

7.3.1 Blackflies in the Buffalo River

In a study carried out by R.Palmer in 1991, the effects of impoundments on the distribution of Blackflies (*Simuliidae*) in the Buffalo River were assessed. Although no specific associations were sought between the Blackflies and various hydraulic biotopes, the research methodology implicitly assumes a relationship to exist. Sixteen sample sites were selected within the Buffalo River, each of which was dominated by the hydraulic biotope "stones in current", a term introduced by Chutter (1970). These sites were recognised as having either relatively large alluvial material or fractured bed rock within fast and noisy flowing water. This class was selected because as Palmer (1991c, p15) indicates "stones in current are typical blackfly habitat".

It must be recognised that the hydraulic biotope type "stones in current" within the Buffalo River incorporates a diverse array of substratum and hence a large number of the hydraulic biotope classes recognised in this research, including run, riffle, rapid, cascade and chute. Photographs presented in the thesis of Palmer (1991c) indicate that sample sites were dominated by bedrock. These sites appear to be dominated by three hydraulic biotope classes: rapid, chute and cascade.

A puzzling result presented by Palmer (1991c) indicate that Blackflies in the Buffalo River constitute between 5% and 35% of the total number of "riffle" dwelling invertebrates. By comparison Blackflies in the Orange / Vaal system constitute over 80% of the "riffle" dwelling fauna. The implications of these statements are that a comparison is being made between Blackfly distributions within the same hydraulic biotope classes. After considering various aspects of water quality, the author is unable to explain the differences between these two systems.

The Orange / Vaal system is the longest river system in southern Africa (2300 km), is relatively flat and is dominated by alluvial substratum. The Buffalo River on the other hand is a very short, steep, system (140 km), deeply incised into bedrock. The morphological units of these two systems and corresponding hydraulic biotopes are likely to be quite different. A suggestion may be made that Blackflies prefer the "riffle" conditions provided by an alluvial system (morphological riffles) rather than a bedrock system (morphological rapids, bedrock pavement etc). This theory is supported by a visual analysis of the results presented for blackfly abundance down the Buffalo River channel (Palmer, 1991c; Figure 7.2, p146). These results indicate that blackfly abundance is considerably higher in the upper reaches of the Buffalo River, a site at which true riffle morphology occurs.

Although the above assumptions are broad generalisations and may be based on a false premise, they serve to illustrate the importance placed on different hydraulic biotopes by ecologists for the explanation of species distributions. It also demonstrates the potential of using a more rigorous technique (such as the one outlined in this thesis) for the recognition of hydraulic biotope classes in studies of this kind.

7.3.2 Species diversity and abundance between riffles and runs

An honours project completed by Emery in 1994, looked at the species diversity and abundance of macroinvertebrates within two hydraulic biotope classes (riffles and runs as defined in this thesis) in the Molenaars River, western Cape. A specific aim of this study was to determine whether the species composition and abundance of these two hydraulic biotopes changed under different flow conditions.

In direct contrast with results published for a New Zealand stream by Pridmore and Roper (1985), Emery (1994) found that under base flow conditions riffles could be considered as having significantly greater diversity and abundance of macroinvertebrates than runs. Emery (1994) concluded that these findings could be related to a higher variability of flow hydraulics within riffles as evidenced by a high variability of Froude numbers.

Emery (1994) noted that hydraulic and ecological sampling of these two hydraulic biotopes during a spate produced different results from those experienced during base flow conditions. During a spate, riffles and runs become less distinguishable in terms of their hydraulic characteristics and in terms of their species compositions and abundance. Furthermore a period of recovery was observed after the spate in which both hydraulic and species assemblage conditions returned to base flow conditions.

Unfortunately no effort was made to re-define the hydraulic biotopes under different flow conditions. It would appear as though changes in macroinvertebrate distribution can be partially attributed to changing hydraulic conditions. From results presented in the previous chapter, these hydraulic changes bring about transformation of hydraulic biotope classes.

7.4 THE HYDRAULIC BIOTOPE AS A TOOL FOR THE ESTIMATION OF INSTREAM FLOW REQUIREMENTS

As suggested earlier in this thesis, with further development the hydraulic biotope concept may provide an essential component of a cheaper and easier alternative for the estimation of instream flow requirements than that already offered by the IFIM and PHABSIM. This statement assumes that as this chapter suggests, the hydraulic biotope will be found to have ecological significance.

A simple example is given here to demonstrate the potential use of the hydrulic biotope as a management tool to help determine the instream flow requirements. This example considers the flow requirements of a length of channel between Maden Dam and Rooikrans Dam. For the succesful implemenatation of the hydraulic biotope concept, all levels of the hierarchical geomorphological model need to be considered. It is assumed in this example that the whole model has been applied to the Buffalo River catchment as it has been demonstrated in this research.

7.4.1 Below Maden Dam (segment 2, reach 5)

Maden dam is situated in the montane forests of the Amatola Mountains on the 520m contour. This area of the catchment produces 8% of the total runoff and approximately 5% of the potential sediment production (Figure 5.18). The resultant sediment-runoff ratio is low. The dam is the primary water supply for King William's Town and is the site for the oldest Trout fishing club in Africa. In a study by O'Keeffe *et al.* (1987) the river upstream of Maden Dam was given a very high conservation status of 83% - 88%. The dam is managed so that no releases are made for downstream users, this is one of the major reasons for a drop in conservation status to 37% - 45% downstream of the dam. A top spillway ensures that larger flood events can pass through.

Only one reach exists between Maden Dam and Rooikrans Dam and consists of a bed morphology dominated by rapids and bedrock pools. Results from this thesis indicate that at a low discharge (flows that are exceeded 90% of the time, Figure 5.31) these features are likely to show little hydraulic variability and therefore provide poor hydraulic biotopes for aquatic organisms (mostly backwater pool and pool). An increases in discharge to a flow that is exceeded 50% - 70% of the time is likely to produce much greater hydraulic diversity. This increases would allow the incorporation of glide, chute and run hydraulic biotopes within the rapid morphology. In morphological pools runs would become a more dominant hydraulic biotope.

Obviously the idea of environmental flow releases is considerably more complex than indicated here. A number of different aspects need to be considered before releases can be made including the seasonal flow requirements for different biota, the influence of water temperature etc. The hierarchical model and the hydraulic biotope concept provide a useful framework within which these and many other aspects can be considered.

7.5 CONCLUSION

The implication of the findings of limited studies mentioned above, together with the results presented in the previous chapter of this research, is that the hydraulic biotope concept is valid. In other words ecologically significant flow environments can be recognised and defined using their hydraulic and substratum characteristics. Palmer *et al.* (1991) recognised that the traditional method of subjectively identifying hydraulic biotopes was useful as a basis for stratified sampling programmes within larger streams. These authors conclude that it cannot be assumed that distinct faunal groups will necessarily be found in different hydraulic biotopes in headwater streams where such hydraulic biotopes are spatially adjacent and may be subject to seasonal variation in discharge. Gordon (1995) uses a more rigorous, objective technique (the hydraulic biotope matrix) in this same headwater stream and concludes that at this finer scale of resolution, associations do appear to exist between macroinvertebrate species distribution and hydraulic biotope class. Although this was a very limited study, it is reasonable to suggest that even better associations may have been found if species assemblages had been considered.

It is suggested that the argument presented by many ecologists that velocity and substratum are extremely important differentiating factors to explain species assemblage distributions (and hence hydraulic biotope classification) is likely to hold true for all spatial scales within the fluvial environment. As shown in the research results of this thesis, hydraulic biotope classes at the point scale can be defined in terms of their hydraulic characteristics. It is suggested that the use of a classification index such as the hydraulic biotope matrix presented in Chapter Two, could provide a scale independent technique for more rigorous stratified sampling programmes.

It is important to note that it is well recognised by all ecologists that velocity and substratum are only two variables influencing species distribution within the lotic environment. Other variables of importance include water quality and predation. The evidence presented in this thesis suggests that hydraulic biotopes may be classified according to their hydraulic and substratum characteristics and that they may be easily identified. This technique makes no assumptions about the distributions of species assemblages within hydraulic biotope classes. A brief review of a very small portion of the ecological literature clearly indicates that the technique may provide a useful framework for any sampling programme which attempts to link biotic distributions within streams to the present flow and sediment regimes. The technique may have some predictive potential by allowing extrapolation to those flow or sediment regimes likely to be imposed in the future.

CHAPTER EIGHT
SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

The initial justification for the development of a hierarchical geomorphological model was that such a system would provide river managers, researchers and conservationists with a tool that would allow rivers to be categorised or classified with respect to their geomorphic characteristics at both the catchment and the channel scale. It was envisaged that the model would aid the prediction of channel adjustment and associated 'habitat' transformations in response to changes in flow and sediment yield.

One of the original aims in the development of the model was to develop a link between the biotic and physical components of the river system. An early idea was that the lowest level of the hierarchy (the morphological unit) would provide the necessary scale based link. This idea was encouraged by the regular reference in the literature, and in conversation with ecologists, to terminology common to fluvial geomorphology (riffle, pool etc). A more detailed analysis of the literature, together with consultation with ecologists, emphasised the fact that although terminology was sometimes similar or the same, the scale of feature being referred to and its temporal stability was considerably different. This provided the impetus for the development of the hydraulic biotope concept described in this thesis.

A number of objectives were addressed to fulfil the original aim:-

- Review the habitat terminology used in the ecological literature.
- Develop a common language of communication between geomorphologists and South African lotic ecologists.
- Develop an objective technique for the recognition of hydraulic biotopes.
- Review the hydraulic literature of open channel flow to determine the most appropriate hydraulic indices to describe the flow characteristics of hydraulic biotopes.
- Carry out pilot studies to determine the feasibility of using scale independent hydraulic indices as quantitative measures to characterise hydraulic biotopes.
    - Consider variations in discharge.
    - Consider variations in scale.
    - Consider variations in substratum.
- Carry out a detailed sampling programme to determine the feasibility of using hydraulic indices as quantitative measures to characterise hydraulic biotopes. Include hydraulic indices which characterise the micro-flow environment.
    - Consider variations in discharge.
    - Consider variations in scale.
    - Consider variations in substratum.
- Assess the ecological significance of the hydraulic biotope concept.

○ Apply the hierarchical geomorphological model to the Buffalo River catchment.

All of these objectives have been met within the this research and will be discussed separately.

8.2 ECOLOGICAL REVIEW

A review of the ecological literature relating to the description and definition of 'habitat' terms provides a number of interesting revelations. The term habitat refers to the abiotic environment of a species and as such implies a fine scale of resolution. Inconsistent with this definition is the use of the term 'habitat' by ecologists with often refers to a scale of feature that incorporates community requirements. This scale of feature is recognised by some authors as a 'biotope' . Neither of these terms were adopted for this research because of the implied biotic interaction and association. The term 'hydraulic biotope' was adopted and is defined as a spatially distinct instream flow environment characterised by specific hydraulic attributes.

Common denominators in the definition of 'habitats' are velocity, depth and sometimes substratum. Problems with the use of these variables are that they are scale dependant and therefore non transferrable. A further review of the ecological literature indicated that some authors have recognised the potential of scale independent hydraulic indices to characterise sampling sites. An immediate understanding from these findings was that 'habitats' are temporally and spatially unstable.

'Habitats' are recognised at a number of different spatial scales by ecologists. The scale of recognition is largely determined by the size and mobility of the aquatic organism being studied. A common feature of ecological studies is that the majority of researchers consider a scale of $1m^2$ as the smallest that can be reasonably sampled.

Some implications from the findings in the ecological literature were that 'habitats' cannot generally be equated to the morphological units except in large rivers where flow and substratum conditions are relatively uniform. Morphological units consist of a number of different 'habitats' (hydraulic biotopes), whose distribution within the morphological unit varies with discharge and sediment dynamics. An important understanding was that morphological units are relatively stable in comparison to hydraulic biotopes.

8.3 A DICTIONARY OF HYDRAULIC BIOTOPE TERMS

One of the realisations while carrying out an ecological literature review was that a large numbers of subjective terms are used by researchers to describe ecologically significant flow environments. These terms are poorly defined and arbitrarily applied.

Consultation with South African ecologists provided an ideal opportunity for the standardisation of terms and definitions. This has been a developmental procedure with numerous changes being made along the way. The most recently accepted terminology and definitions are given in Table 2.5.

8.4 AN OBJECTIVE TECHNIQUE FOR THE RECOGNITION OF HYDRAULIC BIOTOPES

Early in this research it was recognised that together with a need for a standardised terminology to describe hydraulic biotopes, there was a need for an objective technique to identify them. At a workshop held in Citrusdal (Western Cape), ecologists, geomorphologists and hydraulic engineers formalised such a technique. The resultant hydraulic biotope matrix is a first attempt to group the variables of velocity, depth and particle size into eight easily recognisable classes of 'flow type' and 'substratum'. Limited testing of the hydraulic biotope matrix indicates that it has potential as a classificatory tool for the consistent recognition of hydraulic biotopes by researchers from many different fields and with various levels of expertise.

The hydraulic biotope matrix was recognised by the workshop participants as an initial 'working' method that requires further development and testing.

8.5 CHANNEL HYDRAULICS FOR ECOLOGISTS

The most commonly used variables to quantify hydraulic biotopes are velocity and depth. These scale dependent variables are non transferrable from one site to the next. A review of the ecological and hydraulic literature indicated the potential of dimensionless, scale independent variables to characterise hydraulic biotopes. Following the example of Gordon *et al.* (1992), a discussion of open channel flow considers the use of hydraulic indices outside the engineering domain for which they were developed. The potential of hydraulic indices to provide quantitative measures of hydraulic biotope conditions are considered.

Two broad hydraulic conditions which are considered are the mean- and micro-flow components of a column of water. Indices discussed include the Froude number, Reynolds number and velocity-depth ratio (mean-flow) and the 'roughness Reynolds number, shear velocity and thickness of the laminar sub-layer (micro-flow).

8.6 INITIAL ASSESSMENT OF THE USE OF HYDRAULIC INDICES TO CHARACTERISE HYDRAULIC BIOTOPES

Initial verification of the hydraulic biotope as a valid concept considered the use of the Froude number and Reynolds number as quantitative measures to characterise hydraulic biotopes identified from the visual characteristics of the flow. Three pilot studies were initiated to include the influence of discharge, scale and substratum.

8.6.1 The Great Fish River

An exploratory analysis was carried out in the Great Fish River to try to obtain a better feel for the hydraulic biotope and to ascertain whether the concept was worth developing further. Results indicated that the Froude number was a good index to quantify the variability of mean flow conditions experienced in different hydraulic biotopes. The Reynolds number showed no such relationships. Changes in discharge brought about changes in classification of the hydraulic biotopes and concomitant changes in the variability of Froude numbers. Froude number values were shown to closely approximate those observed in a similar study carried out in New Zealand (Jowett, 1993).

8.6.2 The Olifants River

A study in the Olifants River, Western Cape, provided the opportunity to carry out a more detailed analysis of the changing hydraulic characteristics of mean flow in a sand bed channel as a response to changing discharge. For this study hydraulic biotopes were classified at a point rather than at a transect.

The hydraulic biotope concept was found to hold true for sand bed channels but differences were observed in the variability of Froude numbers in this study and those measured in the gravel bed of the Great Fish River. Differences were accounted for by the relatively homogeneous nature of the substratum offering little frictional resistance to the flow in the Olifants River. An important feature which distinguished the sand bed of the Olifants River from the gravel bed of the Great Fish River was the importance of bedload movement at all discharges.

Some changes that were observed in the hydraulic biotope characteristics in response to changes in discharge were that pools exhibited the most changeable environment with increased variability and median values of Froude number. Riffles were the least changeable showing a small loss in variability but a consistent mean value of Froude.

8.6.3 The Molenaars River

A study in selected reaches of the Molenaars River, Western Cape, provided an opportunity to carry out some exploratory research on the influence of changes in substratum and scale on hydraulic biotope dynamics. The study provided an opportunity to collect detailed data for the calculation of both near bed and average flow conditions.

Again the hydraulic biotope concept was found to hold true in this study as illustrated by a clear distinction between the variability of Froude number between different hydraulic biotopes. As in previous studies areas of overlap were observed between the different hydraulic biotope classes. This pattern of data distribution indicated a continuum of flow hydraulics rather than clearly defined boundaries. The additional collection of substratum size data allowed the calculation of 'roughness' Reynolds number. A similar pattern of variability was observed between this index and the Froude number. This allowed for the statement that near bed flow conditions can also be considered as being spatially distinct. Conclusions made from these findings were that the hydraulic biotope provides a useful and easy means of defining different hydraulic biotope classes.

A multiple range analysis of grouped data demonstrated that the Froude number most clearly differentiates between the different classes. Some classes were considered to be the same using this method; pools with backwater pools, riffles with chutes and cascades with chutes.

Based on the findings from the two previous studies, differences were expected in the hydraulic values characterising similar hydraulic biotopes within different sedimentological environments. These results were confirmed by a broad division of hydraulic biotopes into those observed in reaches dominated by large clasts (boulder and bedrock) and those observed in reaches dominated by smaller clasts (sand to cobble).

A discriminant analysis technique was used to determine which hydraulic index (or group of indices) best discriminates between the different hydraulic biotope classes. Froude number on its own was shown to be very good (62%) while Froude number with Reynolds number was slightly better (64%). The addition of a 'roughness' Reynolds number provided only slight improvement (65%). Conclusions from this are that the hydraulic indices of mean flow may be sufficient for the classification of hydraulic biotopes.

An important output of this study was guidelines to establish a detailed sampling strategy in the Buffalo River. Depending on the hydraulic biotopes being sampled, between 4 and 12 sampling points were considered necessary for the incorporation of a good range of variability.

8.7 APPLICATION OF THE HIERARCHICAL GEOMORPHOLOGICAL MODEL TO THE BUFFALO RIVER CATCHMENT

The hydraulic biotope concept forms an important ecological link between the lotic environment and the physical processes working within the catchment which determine the morphology, sediment and flow regime of that environment. The hierarchical geomorphological model was applied to the Buffalo River catchment to demonstrate how catchment variables such as climate and geology influence such things as runoff, land use and soil characteristics. These variables influence the next level of the hierarchy by providing inputs of sediment and discharge into the channel network. All factors together influence the channel morphology which has an association of hydraulic biotopes. The distribution of these biotopes is dependent on the flow characteristics.

One of the important uses of the hierarchical geomorphological model is that it provides a framework within which we can make qualitative assessments of the influence of changing variables on the channel morphology and associated hydraulic biotopes. The model is currently being used in South Africa as a management tool to assess the impacts of impoundments on the downstream morphology and hydraulic biotope characteristics.

8.8 DETAILED SAMPLING PROGRAMME IN THE BUFFALO RIVER

A detailed study was initiated in the Buffalo River catchment in order to further develop and verify the hydraulic biotope concept. As with previous studies an assessment of the influence of discharge and scale on hydraulic biotope classification was considered. Additional requirements within this study were for the assessment of associations between channel morphology and hydraulic biotopes, and for a more rigorous assessment of the relationship between mean- and micro-flow characteristics.

Analysis of grouped data showed that the Froude number and velocity-depth ratio are the best indices to characterise mean flow while the 'roughness' Reynolds number and shear velocity are the best to characterise the micro-flow. Comparison between this and other studies showed similar results. As with other studies a progression of hydraulic biotopes appears to exist with lowest values and least variability being experienced within backwater pools and the highest values and large variability being experienced in glides.

Analysis of roughness height across different reaches indicated that substratum size was different from one reach to the next. In contrast to previous findings, no significant differences were observed between the hydraulic biotopes of these different reaches as characterised by the Froude number. Hydraulic indices describing micro-flow conditions indicated differences between the pool and riffle classes between reaches.

Conclusions that may be made from this are that hydraulic biotopes within selected reaches of the Buffalo River were consistently recognised and consistently defined in terms of their hydraulic characteristics, despite differences in scale and substratum.

An assessment of the influence of discharge on the hydraulic indices describing hydraulic biotopes showed that differences are recognised in the hydraulic biotopes of the lower energy environments (backwater pool, pool and run). No significant differences were observed in the higher energy environments. A conclusion made here is that the hydraulic biotope matrix may not be sensitive enough for the recognition of hydraulic biotopes in the low energy environments.

A discriminant analysis was carried out to determine which hydraulic indices would best discriminate between the different hydraulic biotope classes. Unlike the Molenaars study, the relatively easily calculated indices of Froude number and velocity-depth ratio provided the best result with only limited improvement by the addition of shear velocity.

Morris (1955) and later Davis and Barmuta (1989) have developed a classification system to describe near bed flows in rough conditions ($Re_* > 70$). This technique relies on the measurement of height and spacing of roughness elements on the channel bed. Relationships between 'flow type' and hydraulic biotope class were examined. A visual assesment of pie charts illustrated that no clear relationships were found to exist between the two classification systems. Some hydraulic biotope classes were shown to have distinct differences in the proportional composition of the different flow types. These results suggest that it may be possible to group some hydraulic biotope classes using 'flow type' as the defining variable. The presence of many different flow types in all hydraulic biotopes indicates a high degree of hydraulic variability within the various classes.

A summary table was presented to show the 25th, 50th and 75th percentile values for the various hydraulic indices used to characterise hydraulic biotopes in this study. These values may act as guidelines for the classification of instream environments when hydraulic values are known or to predict hydraulic characteristics from observed flow type and hydraulic biotope classification.

The final aim of this study was to determine potential associations between morphological units and hydraulic biotopes. Some hydraulic biotopes were found to be common to all morphological units (backwater pools, pool and runs). The rapid class was shown to be associated with bedrock pavement, bedrock pool and plane bed morphology. Cascades, chutes and riffles were associated with plane bed, step and riffle morphologies. Closely related to these associations were the patterns of progression from one class to another in response to increasing discharge.

8.9 THE ECOLOGICAL SIGNIFICANCE OF THE HYDRAULIC BIOTOPE CONCEPT

The ecological significance of the hydraulic biotope concept has been implied throughout the research. Detailed ecological studies carried out in the Buffalo and other South African Rivers highlight the potential of the hydraulic biotope concept as a framework for biogeographical studies and as a tool for the assessment of conservation status, management priorities, etc. An important conclusion from this part of the study is that there is a need for the standardisation and acceptance of a technique such as this so that comparisons can be made within and between rivers.

8.10 LIMITATIONS

8.10.1 Hydraulic biotope matrix

The developmental nature of this research has meant that a number of revelations have occurred at the most untimely moments. One of the most important of these was the recognition that intuitive classification of hydraulic biotopes by ecologists could be more rigorously and objectively defined by producing a matrix of flow type against substratum. The hydraulic biotope matrix presented in this research was only formalised in January 1995, three years into the research programme. The development of this matrix was a result of the subjective assesment of instream flow conditions, it is felt therefore that although the identification of hydraulic biotopes classes prior to the formalisation of the matrix was carried out quite loosely, they were still valid.

8.10.2 The importance of substratum

Although substratum was recognised as an important component for the identification and classification of hydraulic biotopes, data analysis did not take substratum into account. For example a feature classified as a run was not subdivided into the different substratum components of gravel run or cobble run. This could have important implications for the comparison of hydraulic indices between different hydraulic biotopes as it is felt that more conclusive results may have been obtained if hydraulic biotope classes had been sub-divided further into both flow and substratum classes.

It is suggested here that if any further work is carried out in this field, care should be taken to ensure a detailed classification is made of hydraulic biotopes based on both flow type and substratum.

The classification of hydraulic biotopes assumes that flow conditions observed at the surface are the result of the vertical intrusion of substratum into the flow beneath the sampling point. It is obvious that this is not always so, particularly in river channels dominated by large substratum and or fast flow.

The classification of hydraulic biotopes in this research did not account for the lateral distubance of surface flow by upstream obstructions or by wind. Wherever possible the influence of these factors were taken into account and a subjective assesment made as to the influence of these factors on observed flow conditions. The further development of the hydraulic biotope concept needs to make allowances for the influence of lateral disturbances.

8.10.3 Equipment

A further limitation to this research was the possible error introduced by the use of an outdated 'spinning cup' flow meter. This equipment was notoriously fragile, often stiffening or even seizing in the field. It is also very bulky and time consuming to obtain a reading. As discussed in Chapter Three, these factors together with the predominance of shallow water justified the collection of only one reading at a point.

The measurement of roughness height proved to be difficult because of the lack of a well defined method or standard apparatus. The frame designed for this research proved to be adequate but not without problems. It was expensive to make (aluminium), and costly to use because of the need for water proof paper. It was extremely heavy and cumbersome making it difficult to manipulate in high flows. It was extremely time consuming collecting this data because of the need to take two profiles at a point, each of which had to be transferred to water proof paper.

8.11 FUTURE DIRECTIONS

Because of the fairly new and developmental nature of this research, there is considerable scope for its expansion. It is envisaged that areas of expansion can be divided into three groups; geomorphology, lotic ecology and conservation.

8.11.1 Fluvial geomorphology

Evidence presented in this thesis implies a relationship between channel morphology and the hydraulic biotope, this evidence is far from conclusive and needs to be tested further. Research needs to be extended to determine to what extent associations can be made between morphological units and hydraulic biotopes. These associations need to be tested over much wider spatial and temporal scales so that a full range of substratum and morphology is considered at a wide range of discharges.

8.11.2 Lotic ecology

A strong association between species assemblage and the hydraulic biotope is implied in much of the ecological literature. These relationships need to be tested under different flows, in different substratum and at different spatial scales. This is an enormous task complicated not only by the wide array of aquatic organisms which can be observed, but also by the influence of other variables influencing species distribution such as predation and water quality. A number of ecological studies have already been initiated using the hydraulic biotope concept, most of these are being undertaken within the Freshwater Research Unit of the University of Cape Town.

8.11.3 Conservation

The hydraulic biotope concept has potential as a component of a cheap alternative to the assessment of instream flow requirements. It is felt by this author that ideally it should form part of a catchment based model which recognises the integrated nature of inputs and outputs within the system. The hierarchical geomorphological model described in this research provides a useful framework because the spatially nested levels that comprise the model allows one to enter at the most appropriate level, that level determined by the scale of resolution required. All levels of the hierarchical model are undergoing constant change and development as new ideas and data becomes available. The model is gaining wide acceptance in South Africa and is more and more regularly being used as a tool for the prediction of the influence of impoundments on both the morphological and hydraulic biotope characteristics of the downstream channel. A similar approach to the use of hydraulic biotopes as an alternative to IFIM and PHABSIM is being undertaken by Newson and Padmore in the U.K, funded by the National Rivers Authority.

8.12 SUMMARY

This study was concerned with the development of a scale based link between lotic ecology and fluvial geomorphology, a task made difficult by an apparent lack of compatibility between spatial and temporal scales of research between the two disciplines. Fluvial geomorphologists consider relatively stable channel form features (morphological units) as the finest level of resolution worth studying while lotic ecologists are more concerned with constantly changing 'habitats' within these morphological units.

It was recognised that indices developed by hydraulic engineers could provide useful quantitative, scale independent values for the characterisation of hydraulic biotopes and thus provide the essential link between the different scales of research.

This research shows that it is possible, from simple observations of water surface and channel bed characteristics, to identify hydraulic biotopes which represent spatially distinct in-stream flow environments. Different hydraulic biotopes have been shown to have distinct hydraulic characteristics in terms of velocity/depth ratio, Froude number, Reynolds number, shear velocity and 'roughness' Reynolds number, that is both mean-flow and micro-flow environments. The distribution of hydraulic biotopes varies with morphological units, but the association is discharge dependent.

Studies presented in this research indicate that the most useful indices to characterise hydraulic biotope characteristics are the Froude number, Reynolds number and velocity-depth ratio. Research results consistently indicate that the Froude number provides the single best index for the classification of hydraulic biotopes. The collection of velocity and depth data are all that are necessary for the calculation of indices characterising mean flow, for this reason it is suggested that these are the values used to discriminate between hydraulic biotopes of an unknown class.

As with the Froude number and the velocity-depth ratio, the 'roughness' Reynolds number and shear velocity showed good relationships with the hydraulic biotope classes. These results suggest that different hydraulic biotope classes can be considered to be hydraulically distinct in terms of both the mean flow and micro flow characteristics. The variables required for the calculation of 'roughness' Reynolds number and shear velocity include a roughness height (k) or a water surface slope or a velocity profile (if it approximates a log linear relationship). These variables are time consuming to obtain and it is suggested from the results here, unnecessary for the classification of hydraulic biotopes.

Changes in both discharge and substratum characteristics have been shown to influence the variability of hydraulic indices describing hydraulic biotopes. Changes in discharge appear to have a greater influence on the hydraulic biotopes associated with the low energy environments (backwater pool, pool and run) while large variations in substratum produce changes in the hydraulic variability of all hydraulic biotope classes. The large degree of overlap between different classes indicates a continuum of hydraulic biotopes. The pattern of progression for this continuum appears to be consistent at all discharges and in all substratum.

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APPENDIX ONE

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

APPENDIX TWO

REACH ANALYSIS FORM

River Reach Analysis

Recorder [ ] Date [ ]

River Name [ ]

River Reach: Contour [ ] to Contour [ ]

Map Sheet: [ ]

Latitude [ ] Longitude [ ]

SITE DESCRIPTION

Sketch map showing location of x section, landmarks and key morphological / biotope units.

Photographs

	Film No	Shot No
Upstream		
Downstream		
Overview		

REACH ENVIRONS

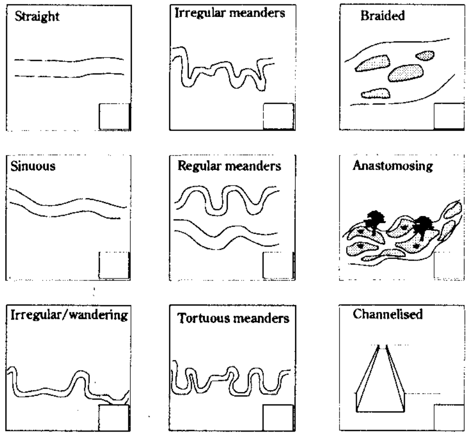
Water level at time of sampling:

Dry [ ] Isolated Pools [ ] Low Flow [ ] Medium Flow [ ] High Flow [ ] Flood [ ]

Channel Type:

	Mud	*Sand/ gravel*	*Gravel/ sand*	*Gravel/ cobble*	*Cobble/ boulder*	*Boulder/ bedrock*	*Bedrock*
Alluvial							
Bedrock							

Channel Pattern:
(more than one may apply)



Riparian Land Use:

PROPORTION:	*Low*	*Mod*	*High*
Natural			
Nature Reserve			
Grazing Veld			
Grazing Pasture			
Orchards			
Other			

	Low	*Mod*	*High*
Plantation Indig			
Plantation Alien			
Urban Residential			
Urban Indust			
Rural Residential			

Local Disturbance:

IMPACT:	*Low*	*Mod*	*High*		*Low*	*Mod*	*High*
Borrow Pit				Roads			
Bridge				Clearfell/plough			
Storm Discharge				Dams / Weirs			
Water Extraction				Channelisation			
Large W.Debris				Grazing			
Other							

RIPARIAN VEGETATION:

		Reeds & Grasses	Shrubs	Trees
Density	sparse			
	open			
	dense			
Position	toe			
	mid			
	top			
Diversity	indig			
	mix			
	alien			
Age	young			
	mature			
	old			
Lateral Extent	wide			
	medium			
	narrow			

2.

CHANNEL MORPHOLOGY:

Reach Type:
(more than one may apply)

Cascade High gradient streams within a confined valley. Energy dissipation is dominated by jet and wake flow, hydraulic jumps and turbulence around individual large (cobble/boulder) clasts.

Step - Pool Occur within confined valleys and are characterised by large clasts (cobble / boulder) organised into discrete channel spanning accumulations that form a series of steps seperating pools containing finer material. Pool spacing is 1 to 4 channel widths.

Plane - bed Occur within unconfined valleys. They lack well defined bedforms and are characterised by long stretches of of relatively planar channel bed occasionally punctuated by channel spanning rapids. The flow around particles that are large relative to the flow depth produces multiple current threads of approximately the same depth and width, uniformly distributed across the channel. Occur at gradients and relative roughness intermediate between pool-riffle and step-pool reaches.

Pool - Riffle Occur within unconfined valleys and have an undulating bed that defines a sequence of bars, pools and rifles. The term riffle applies to the entire shallow channel area (including bars).

Regime Occur in unconfined valleys in either sand or gravel. The channel exhibits a succesion of bedforms with increasing flow velocity ie; sand beds:- plane bed to antidunes. The channel is characterised by a low relative roughness.

Planar Bedrock A contiguous alluvial bed is absent but some alluvial material may be temporarily stored in scour holes or behind flow obstructions. Absence of significant falls or rapids.

Bedrock fall A steep channel where water flows directly on bedrock with falls and pools which leads to free surface instability.

Pool - Rapid Occur in unconfined valleys. Channels are characterised by long pools upstream of channel spanning bedrock intrusions (rapids). Sediments are deposited upstream of the local control in the form of braid and lateral bars. (Van Niekerk et al 1994).

Morphological Unit:

Cascade ☐ Step ☐ W/fall ☐ Cataract ☐ Rapid ☐ Plunge pool ☐

Bedrock pool ☐ Alluvial pool ☐ Riffle ☐ Braid bar ☐ Point bar ☐

Lateral bar ☐ Lee bar ☐ B-rock backwater ☐ Alluvial backwater ☐

Sand bed ☐ Vegetated island ☐ Unvegetated island ☐

Biotopes:

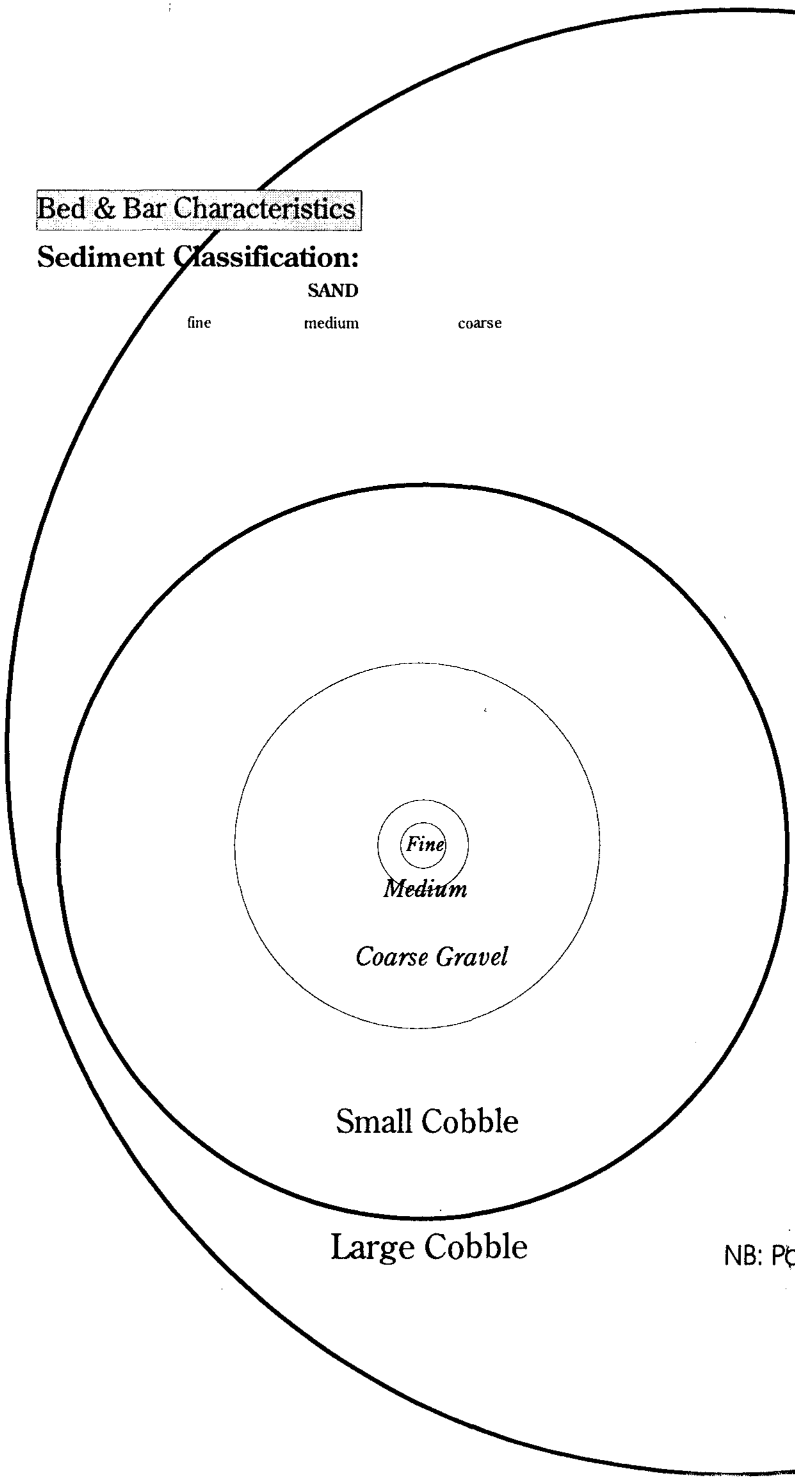
B-rock pool ☐ Alluvial pool ☐ Plunge pool ☐ B-water pool ☐

Riffle ☐ Rapid ☐ Cascade ☐ Chute ☐ W-fall ☐ Run ☐

3.

Bed & Bar Characteristics

Sediment Classification:



Dominant substratum class:

	mud	sand			gravel			cobble		boulder	
		fine	medium	coarse	fine	medium	coarse	small	large	small	large
Thalweg (lowest point)											
Bar											

Bedrock: left bank ☐ right bank ☐ bed ☐

Gravel / Cobble Shape:

sphere ☐ disk ☐ blade ☐ rod ☐

Bed Compaction:

armoured ☐ loosely packed ☐ no packing ☐

Bed Stability:

scouring: ☐
stable: ☐
aggrading: ☐

Bar Type:

none ☐
lateral ☐
lee ☐
point ☐
mid channel ☐
tributary ☐

NB: Page reduced therefore no longer right dimensions

4.

Bank Condition:

Overall condition:

LEFT BANK

	high	*moderate*	*low*	*minimal*
Overall instability				
Susceptibility to erosion				

Location of instability

Bends	☐	Floodplain Scours	☐	Obstacles	☐
Seepage & Runoff points	☐	Irregular	☐	All along	☐

RIGHT BANK

	high	*moderate*	*low*	*minimal*
Overall instability				
Susceptibility to erosion				

Location of instability

Bends	☐	Floodplain Scours	☐	Obstacles	☐
Seepage & Runoff points	☐	Irregular	☐	All along	☐

Aquatic Habitat:

Channel

large woody debris	
submerged veg	
floating veg	
tree roots	
rock/boulder/cobble	
permanent pool >1m	

Banks

LEFT		RIGHT
	canopy cover	
	vegetation overhang	
	root overhang	
	bank overhang	

Overall Habitat Rating:

High ☐	**Moderate** ☐	**Poor** ☐
High diversity of depth & substrate No disturbance Abundant diverse cover	Low diversity of depth & substrate Moderate disturbance Low diversity of cover	No diversity of depth & substrate High disturbance No cover or low diversity

APPENDIX THREE

SUMMARY METHOD FOR REACH ANALYSIS

Reach Analysis

Desk Study
This involves the digitising of both the perennial and ephemeral sections of the main channel of a selected stream network, together with the contour intersections, at the finest scale of resolution available. The computer software GIS ArcInfo is used for this purpose. This data base is then imported into a spread sheet (Quattro Pro) so that the raw data of channel length between contours, and contour height can be manipulated.

From the raw data channel gradient is calculated between contour intersections together with the percentage change in gradient between one section of river (between two contours) and the one preceding it (i.e. percentage gradient change down the channel). The resultant data is imported into a statistical software package and frequency distribution curves are drawn. Visual analysis of these curves allows the recognition of those gradients which are anomalous within the longitudinal profile. These points are then transferred back to the plot of longitudinal profile and are assumed to represent the points along the channel at which significant changes in slope occur. These points are considered to be situated within an area in which a *natural* reach break occurs.

To account for anthropogenic disturbance, visual analyses of available maps and aerial photographs are carried out. Features such as dams, stream diversions, canals etc are marked as additional reach boundaries.

Field Verification
Field verification is carried out through a subjective assessment of the following broad data groups:

- Reach Environs; this considers such aspects as channel type and channel pattern together with the local catchment and riparian conditions.
- Site Description; this places a specific area of data collection within the broader reach.
- Channel Morphology; this considers individual channel form features together with their pattern of distribution within the reach.
- Bed and Bar Characteristics; this focuses on the size, shape and packing of the dominant substratum groups.
- Bank Condition; considers the degree and position of channel instability.
- Aquatic Habitat; this considers the degree of disturbance, availability of various forms of cover and the diversity of hydraulic biotopes available.