THE DEFINITION AND CHARACTERISATION OF REPRESENTATIVE REACHES FOR RIVER MANAGEMENT

by

[1]Heritage, G.L., Broadhurst, L.J., van Niekerk, A.W., Rogers, K.H. & Moon, B.P.

Centre for Water in the Environment
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg
South Africa

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Project Leaders: Professor K.H. Rogers
Professor C.S. James

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[1]Department of Geography, University of Salford, Manchester M5 4WP

EXECUTIVE SUMMARY

Work within the Kruger National Park Rivers Research Programme has highlighted the complexity of the task of evaluating the physical and ecological response of the rivers in Mapumalanga Province to changes in water quality and quantity. One of the problems behind this is the complex nature of the physical environment within the bedrock influenced semi-arid river systems of the Kruger National Park and elsewhere. A method is required that will rationalise and effectively simplify this complexity, allowing sections of a river to be specified where research work could be focussed whilst still generating a fuller understanding of the nature of the system. These 'Representative Reaches' should also form the sites for longer term monitoring of environmental change and act as a focus for the evaluation of the Instream Flow Requirements of a river system.

An approach is proposed to rationalise a river system by identifying reaches that are representative of repeatable geomorphological types of the whole (e.g. pool-riffle sequence of a temperate alluvial meandering river). The identification of a set of reaches based on the morphologic unit composition provides the key to achieving this aim as it is the morphologic unit that can be directly related to the controlling catchment variables and to the ecological function of the river (Figure a).

The need for an understanding of the links between local hydraulic conditions, channel morphology and riverine ecosystem structure in the Kruger National Park was first recognised as part of an integrative holistic research programme, with the overall aim of quantifying the water demand of the environment by (Rogers *et al.* 1992). Local hydraulics and channel morphology are the primary determinants of the physical habitat, which itself influences ecosystem functioning. Therefore, it is essential to understand the mechanisms controlling local hydraulic parameters to predict the effect of altering the flow and sediment regime on a river. Given the rationalised structure of the river from the geomorphological mapping, representative examples of each geomorphic type may be monitored intensively and the hydraulic conditions extrapolated to similar unstudied areas of the river (Figure b). Hydrological data, in the form of a simulated, daily discharge regime must be translated into point discharge values, and further, into local hydraulic conditions, (flow depth, width, velocity and bed shear stress), in order to assess the impact of such a discharge regime on the form of each geomorphological type on an existing river.

This report summarises a method for the selection and characterisation of reaches along any river that are sufficient to represent the variety of geomorphological and hydraulic condition present along all, or part, of the whole river. Section 1 details the rationale behind the project and introduces the concept of representative reach selection and characterisation, section 3 applies the method to the Sabie River and details the significant results.

The principal aim of the project was to develop a method for defining representative river reaches, and for monitoring the hydraulic character at this spatial scale. This was achieved by:

Determine study reach extent

↓

Identify geomorphological components of the morphologic unit scale

↓

Look for successive associations of units at increasing spatial scales

↓

Quantify the internal morphologic composition of each unit at each scale

↓

Zone the study reach into components at the level where units are seen to repeat (i.e. channel type)

↓

Check validity of zonation with an objective statistical classification if resources are available

↓

Select a representative example of each repeating unit (representative reaches) and set up monitoring points

↓

Transfer the collected and processed hydraulic information (Qs, V, W, d) that characterises each representative reach to similar channel types along the study reach

↓

Use this information on 'whole river' functioning to begin predictive modelling of likely channel change and ecological response

Figure a. Summary diagram of the approach to the selection and characterisation of a representative reach.

- **Summarising the spatial and temporal scales on which the various physical parameters act in a riverine environment (section 1.1.1, Fig a.).**

- **Summarising the principles of channel typology and evaluating the possibility of using morphologic units as a basis for representative reach identification, given the links between the geomorphology and the physical, chemical and biological controls (section 2.2, Fig a.).**

- **Selection of specific reaches from the geomorphological study for detailed research into local control parameters (section 3.1, Fig a.).**

- **Determination of the hydraulic processes operating to maintain each representative reach (section 3.2, Fig a.).**

- **Extending the representative reach results to similar reaches to generate an overall spatial pattern of the geomorphology and hydraulic processes operating on the Sabie River (section 3.2.4, Figure a).**

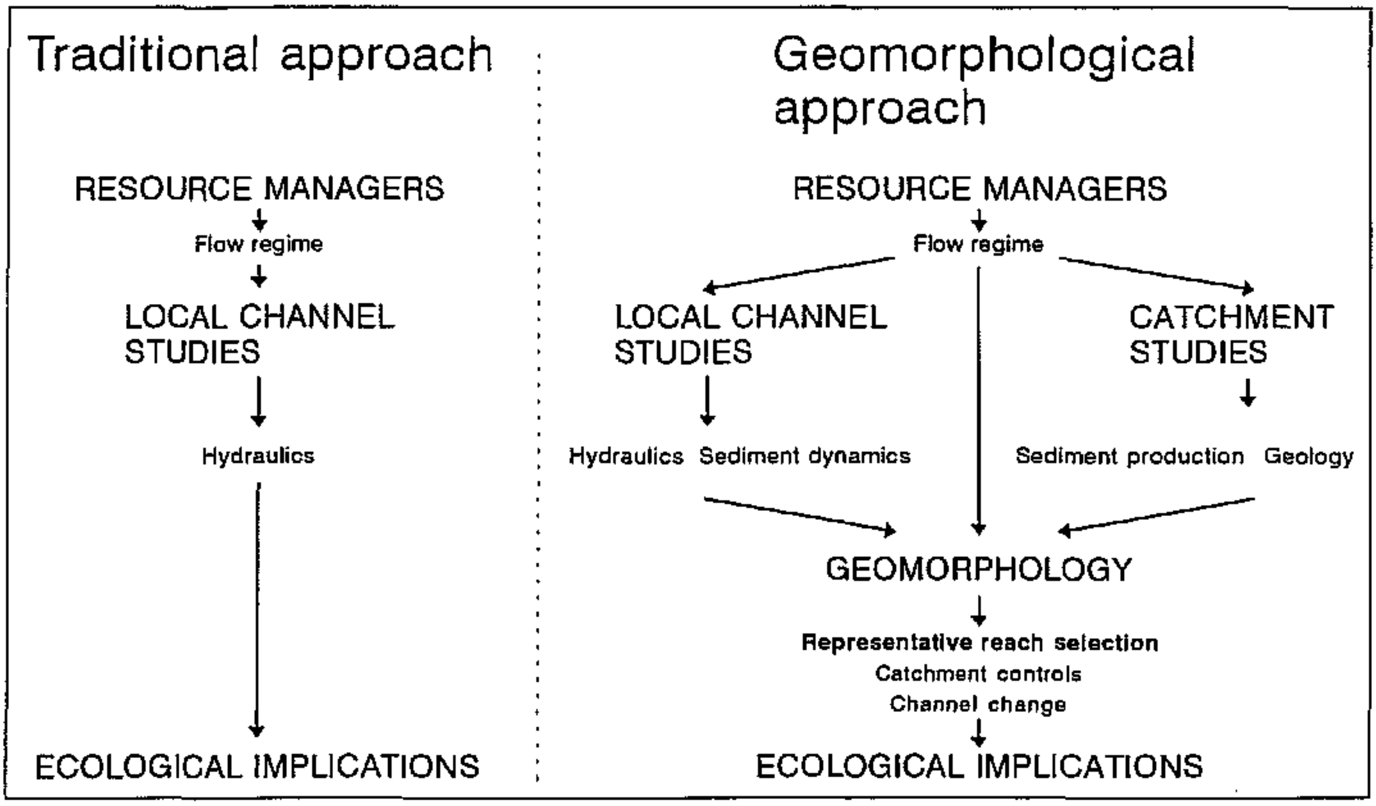

Figure b. The position of representative reach selection in the geomorphological approach to river characterisation as compared with the conventional hydraulic approach.

A review was conducted of the scales over which a variety of physical parameters operate across various river types, paying particular reference to the processes operating on the Sabie River in the Kruger National Park. Channel classification systems were fully investigated and a bottom-up agglomerative hierarchical approach was adopted, to best model associations at ecologically relevant scales in spatially complex river systems (Heritage *et al.*, in press). A summary of the research into the temporal geomorphological dynamics of the Sabie River is presented, illustrating the spatial and temporal stability, relative to other physical parameters, of geomorphic processes and associated morphologic units, that makes them the best discriminant with which to categorise and zone rivers (Table a).

It is clear that many of these physical parameters (Table a) are highly variable in space and time. The geomorphological template, is however, relatively stable, given that there is no great change in the catchment controls within the system, thus it is argued that this physical structuring would form the basis for the identification of representative reaches in any river system. The first step in achieving this is to characterise the representative reaches based on morphologic composition.

The geomorphological hierarchy proposed is flexible in that it can include a large number of morphological units that are rarely encountered in temperate alluvial river system. It is possible to extend the classification system further to include features seen on other river types. This flexibility and wide coverage allows any river to be classified systematically. Similarly, as new research is conducted into other river types the list of geomorphologic units can be extended. In order that the classification can be used more widely than for categorising active channels, valley floor features (such as bedrock pavements and terraces) are considered. The entire process may be conducted using aerial photographs and mapping the morphologic units present along the river. These should be selectively verified through fieldwork.

Table a. Spatial and temporal change characteristics of a variety of fluvial physical factors.

Factor	**Spatial change**	**Temporal change**	**Comments**
Suspended sediment	**R.** **L.** Bank collapse.	**R.** Increases during floods but no simple relationship. **L.** Affected by bank collapse.	Highly variable pattern over time that may cause short term ecological response.
Temperature	**R.** Upland/lowland distinction. **L.** Shading.	**R.** Alters with flood events. **L.**	Provides very coarse spatial pattern, ecological variation is more complex than this.
Oxygenation	**R.** **L.** Turbulence.	**R.** Turbulence pattern alters as hydraulics change. **L.** Alters diurnally.	Pattern varies spatially and temporally and may cause short term ecological response.
Dissolved substances	**R.** Varies away from coast. **L.** Local inputs cause slight variation.	**R.** Alters with flooding. **L.**	Diffuse pattern of low variability, less complex than the ecological pattern.
Geomorphology	**R.** Varies in response to geology, sediment inputs, tributaries etc. **L.** Slight alterations of local morphological composition to form complex physical template.	**R.** Robust, very rare catastrophic changes may occur. **L.** Responds to changes in sediment balance by morphologic unit change.	Pattern alters along the river in response to catchment control variability, local changes in the morphologic unit template occur on a temporal scale over which ecological response and equilibrium is significant.

R. Regional character, **L.** Local character.

Application of the representative reach approach to the Sabie River generated a geomorphological hierarchy from the scale of the morphologic unit upwards. The basic components are the morphological units, each with a distinctive character and micro-habitat (van Niekerk and Heritage, 1993). These were chosen as the primary spatial levels as it is here that the overlap with biotic preferences occurs, making it possible to infer biotic response to geomorphological change at the level of morphological unit (van Coller *et al.*, 1995). Morphological units combine variously to form different channel types. There is a functional relationship between channel types which may be grouped into reaches, where one channel type may be directly influencing the nature of the channel types up and downstream. For example, alternating braided and bedrock anastomosing channel types are common in the Sabie River immediately downstream of the western boundary of the Kruger National Park. Here, exposed bedrock in the bedrock anastomosing channel type acts as a hydraulic control, resulting in a decrease in energy in the ponded area upstream, with deposition of alluvial bars and thus the development of a braided channel type. A macro-reach may comprise one or more reaches and has distinctive geological, hydrological, sedimentological and vegetational characteristics. A zone, comprising several segments, has boundaries defined by major breaks in slope which are usually coincident with geological contacts. The river incorporates the riparian margin from source to mouth and links all of the zones. The catchment is the largest hierarchical unit and comprises all of the components of the river and its tributaries together with the intervening land surface which contributes water and sediment to the channel (Figure c).

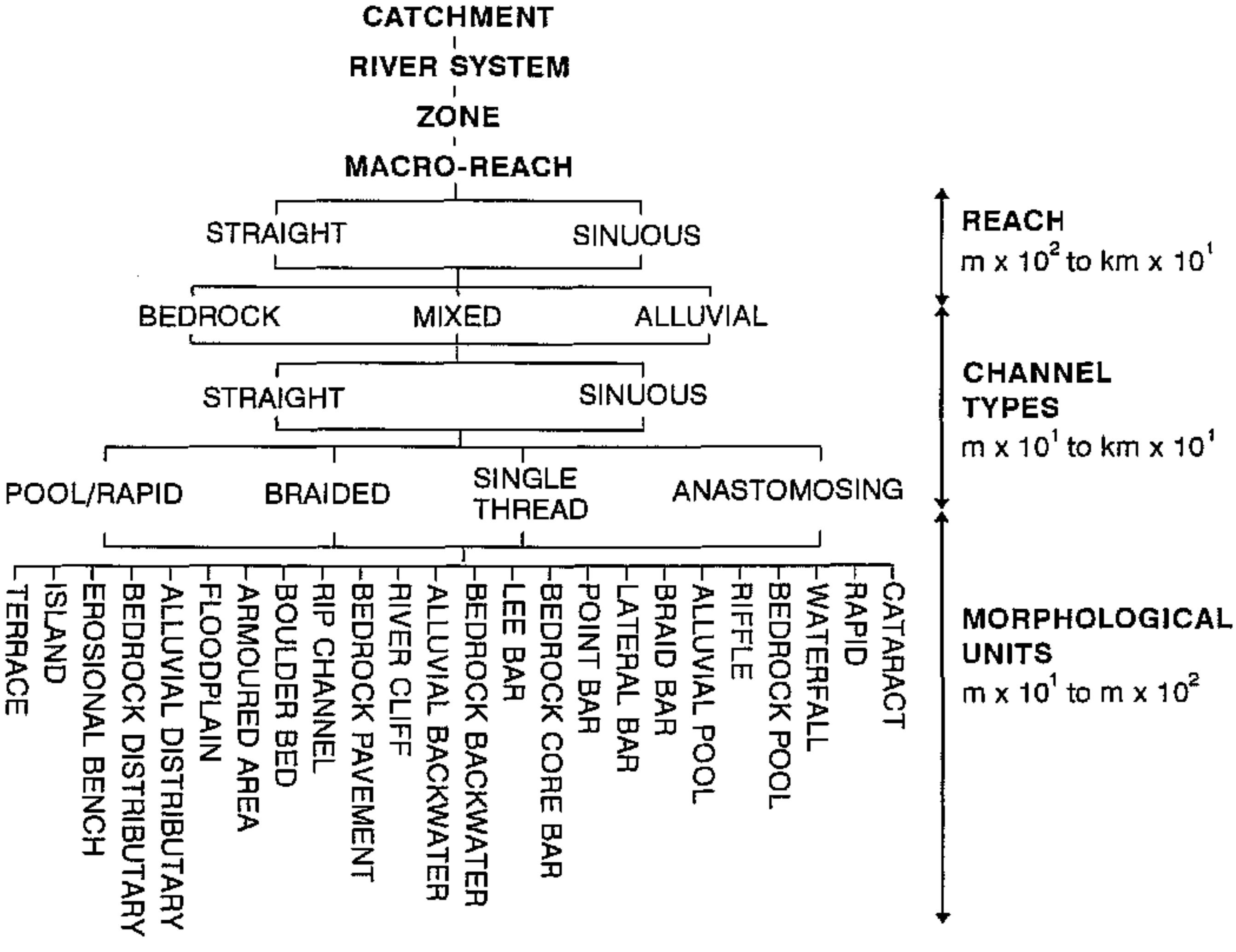

Figure c. A hierarchical classification of the Sabie River in the Kruger National Park (after van Niekerk *et al.*, 1995).

Visual interpretation of aerial photographic records (1:10000 scale), aerial video footage taken during winter low flow conditions and extensive fieldwork provided the basis for identifying ten channel types present on the Sabie River in the Lowveld, of which five were common (bedrock anastomosing, mixed anastomosing, mixed pool-rapid, alluvial single thread and alluvial braided). Gradations between the five primary channel types were observed, creating transition states (alluvial anastomosing, bedrock single thread, bedrock pool-rapid, mixed single thread and mixed anastomosing) that could be related to the build-up of sediments (Table b). Differentiation of types was based on physical appearance and morphological unit composition (Table c).

In order to characterise the processes operating in the Sabie River the geomorphological hierarchy (van Niekerk *et al.*, 1995) was initially used to generate the five primary channel types, each of which are composed of specific morphological units, with associated flow resistance components. Individual examples of each of these 5 channel types were then chosen as 'Representative Reaches' for the river. Data from field monitoring was used to characterise the hydraulics and sediment dynamics of each representative reach, defining characteristic behavior in terms of flow resistance, water slope and sediment transport.

To identify all the flow resistance components at each representative reach and to correlate their occurrence to observed local hydraulic conditions, eight to ten cross sections per representative reach were surveyed and flow resistance components were mapped. The longitudinal spacing of the cross sections was designed to incorporate the presence of low flow hydraulic 'controls' that cause energy loss, and thus define accurately the water surface slope along a reach. These 'controls' included bedrock outcrops, major alluvial bars or tributary confluence's and major channel features, such as mid channel braid bars, meander apexes or changes in the vegetation community. In addition to the cross sectional shape survey, vegetational, sedimentological and morphological data, were collected for each cross section (see Broadhurst *et al*, 1996). This was then analysed for associations with the local geomorphology and channel hydraulics.

Following the (Barnes, 1967) method, and using the hydraulic and channel geometry parameters derived from the cross-section survey, reach flow resistance was quantified for the five representative reaches. Discrete values of flow volume and associated cross section parameters were used to generate discharge:flow resistance relationships, over the range of flows encountered on the Sabie River during the period of study.

The bedrock anastomosing representative reach had the highest flow resistance (Figure d), but showed the same trend as all of the representative reaches, with a decrease in flow resistance from low to high discharges. The alluvial representative reaches:braided and single thread, had the lowest flow resistance coefficients, with mixed anastomosing and pool-rapid reaches characterised by intermediate values. The mixed anastomosing and braided reach flow resistance increased marginally from medium to high discharges.

Table b. Channel types observed on the Sabie River in the Lowveld.

Degree of sedimentation	Channel type			
	Anastomosing	Pool-rapid	Single thread	Braided
Bedrock	primary	secondary	secondary	-
Mixed	primary	primary	secondary	secondary
Alluvial	secondary	-	primary	primary

- Channel type does not occur in nature

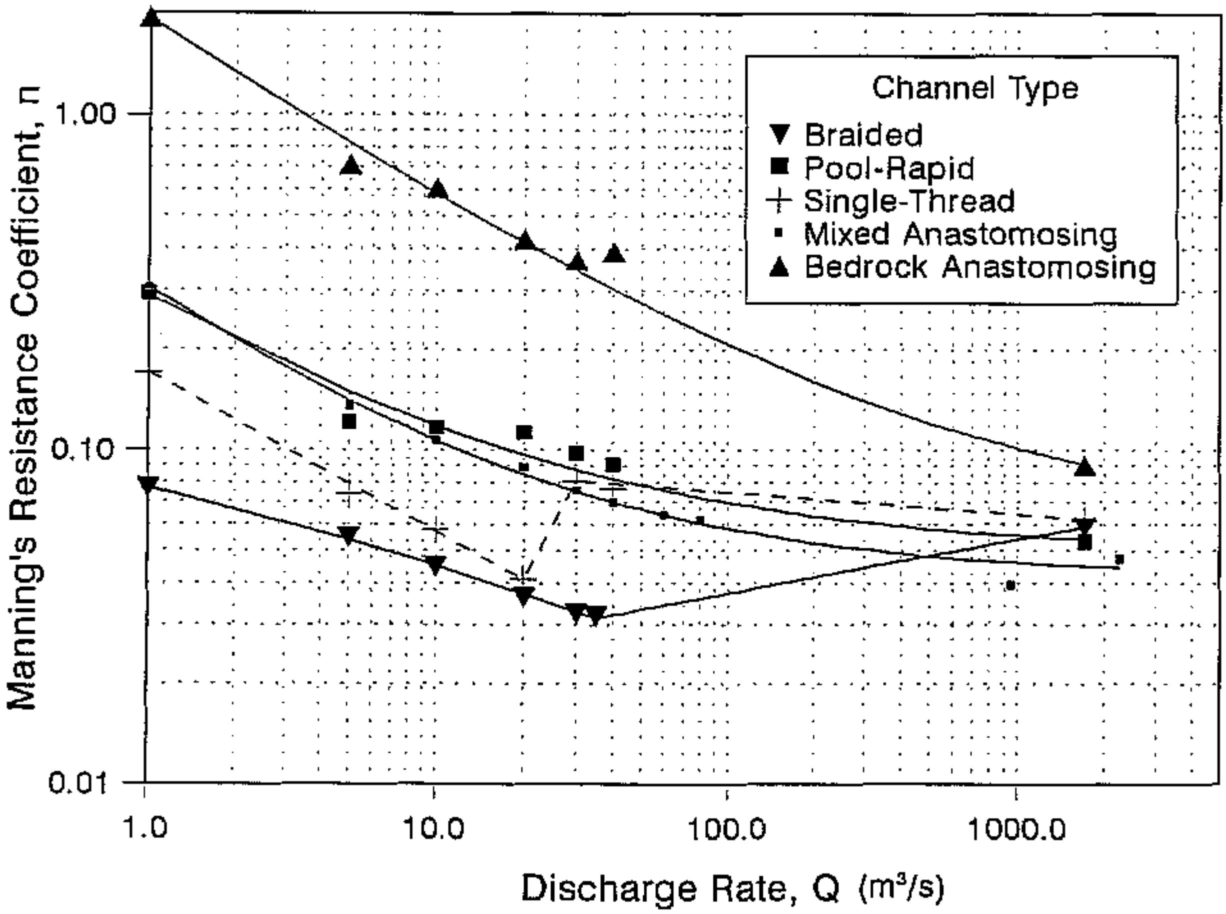

Figure d. Representative reach flow resistance characteristics with increasing discharge.

Table c. Morphological composition of the primary channel types found on the Sabie River in the Kruger National Park (after van Niekerk *et al.*, 1995).

Channel Type	Description	Morphological Units
Alluvial single thread	Uniform single channel river. Limited bedrock outcrops or braid bars associated with active channel. May be bedrock or alluvial.	Lateral bar (1), Pool (1), Rock pool (1), River cliff (2), Apical pool (2), Point bar (2), Rip channel (2), Riffle (2), Rapid (2), Floodplain (2), Terrace (2).
Alluvial braided	Multi-channel system with impermanent distributaries in alluvium. Channel convergence and divergence occurs on the scale of channel width.	Braid bar (1), Alluvial distributary (1), Lateral bar (1), Point bar (2), Rip channel (2), Cutoff channel (2), Armoured area (2), Floodplain (2), Terrace (2), Alluvial backwater (3), River cliff (3), Levee (3), Apical pool (3).
Mixed anastomosing	Multi-channel system of distributaries in bedrock and alluvium	Rock pool (1), Rapid (1), Alluvial pool (1), Bedrock core bar (1), Rock distributary (1), Alluvial distributary (1), Cataract (2), Waterfall (2), Boulder bed (2), Armoured area (2), Lee bar (2), Rock backwater (2), Alluvial backwater (2) alluvial bars (2).
Bedrock anastomosing	Multi-channel system of permanent bedrock distributaries. Sediment may accumulate on topographic highs.	Rock pool (1), Rapid (1), Bedrock core bar (1), Cataract (1), Waterfall (1), Rock distributary (1), Boulder bed (2), Armoured area (2), Lee bar (2), Rock backwater (2).
Mixed pool-rapid	System of shallow faster steeper bedrock dominated rapids and associated upstream backwater pools.	Rock pool (1), Rapid (1), Bedrock core bar (2), Lateral bar (2), Lee bar (2), Cataract (2), Boulder bed (2), Armoured area (2), Floodplain (2), Rock distributary (2), Terrace (2), Rock backwater (2), Braid bar (3), Pool (3), Riffle (3) Alluvial distributary (3),.
(1) = Definite occurrence, (2) = Probable occurrence, (3) = Rare occurrence		

Each representative reach displayed distinct low flow and regional high flow water surface slopes (Figures e and f). Under low flow conditions (Figure e) the bedrock anastomosing channel type exhibited the steepest slopes (>0.005). Mixed anastomosing reaches were also steep at approximately 0.002, ranging between 0.004 and 0.001. Pool-rapid channel types were slight less steep averaging around 0.0015, ranging between 0.003 and 0.001. Braided and single thread channels displayed the lowest low flow slopes at around 0.0004, ranging between 0.0003 and 0.0006. There was occasional overlap between representative reach slope values, but in general there was a distinct difference between representative reaches as follows:

Bedrock anastomosing	Highest slope
Mixed anastomosing	↓
Pool-rapid	
Braided	
Single thread	Lowest slope

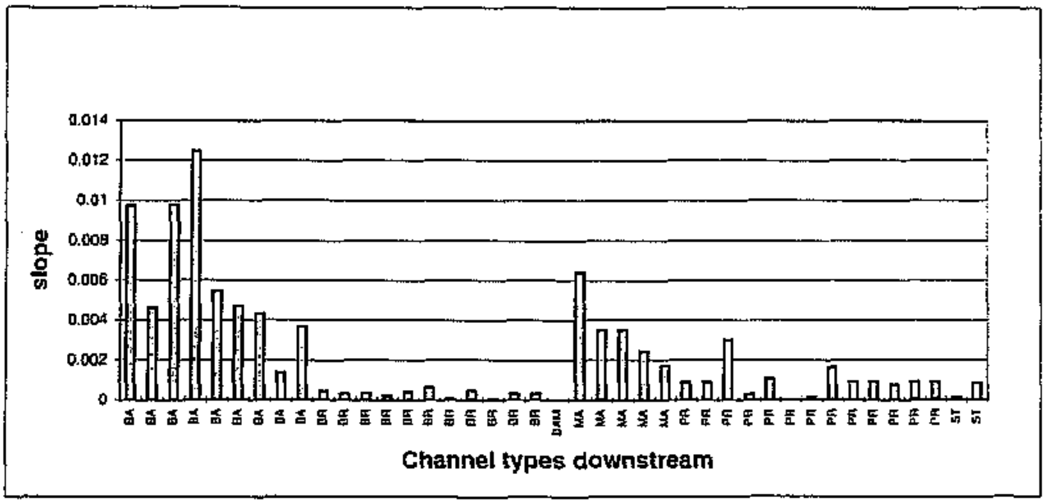

Figure e. Representative reach low flow water surface slope characteristics (BA = bedrock anastomosing, MA = mixed anastomosing, BR = braided, ST = single thread, PR = pool-rapid).

At high flows (Figure f) the water surface slopes within and between channel types, becoming similar as local controls (waterfalls, cataracts, rapids, bar deposits) are drowned out. In general the bedrock anastomosing slopes decline and the mixed anastomosing, pool-rapid, braided and single thread channel types increase to an average of 0.003.

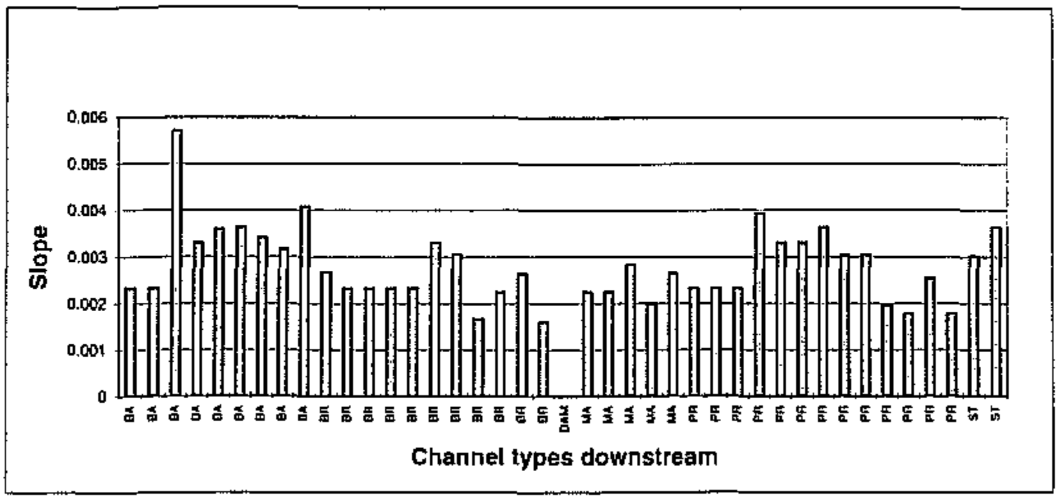

Figure f. Representative reach high flow water surface slope characteristics (BA = bedrock anastomosing, MA = mixed anastomosing, BR = braided, ST = single thread, PR = pool-rapid).

The representative reaches on the Sabie river all have distinct potential sediment transport characteristics as determined from the channel flow resistance and flow hydraulics (Figure g). At low flows the sequence of channel competence is as follows:

Single thread	Highest potential sediment transport
Braided	↓
Mixed anastomosing	
Pool-rapid	
Bedrock anastomosing	Lowest potential sediment transport

At low flow however, the volumes of sediment involved are very small, being of the order of 0.1kg.s^{-1} to 1kg.s^{-1} through the representative reaches at 30m^3.s^{-1}, hence little redistribution of sediment and channel change would be expected. This sequence alters at higher flood flows as follows:

Bedrock anastomosing	Highest potential sediment transport
Pool-rapid	↓
Single thread	
Mixed anastomosing	
Braided	Lowest potential sediment transport

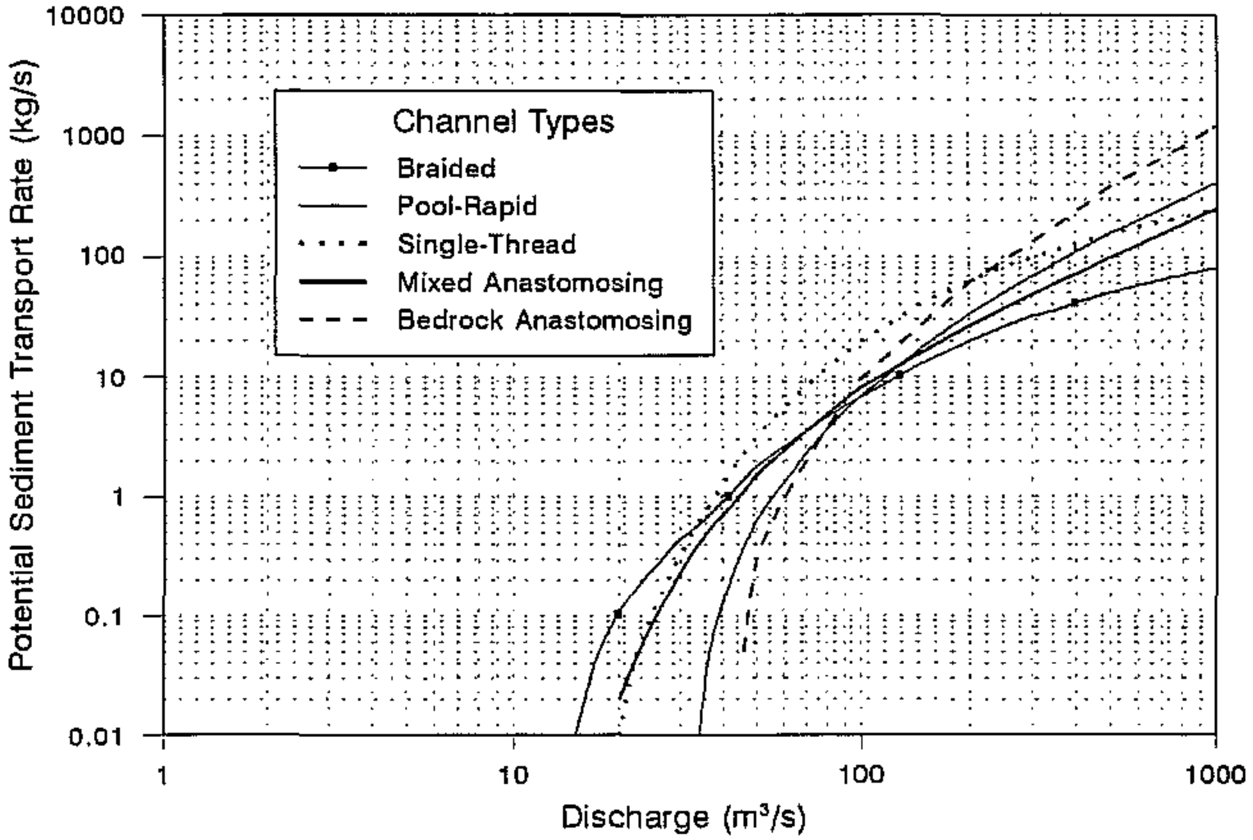

Figure g. Representative reach potential sediment transport characteristics with increasing discharge.

The last sequence is significant in terms of overall channel character and for channel maintenance. Movement of large amounts of sediment (100kg.s^{-1} to 1000kg.s^{-1} through the representative reach at 1000m^{3}.s^{-1}.) cause the bedrock anastomosing and pool-rapid representative reaches to remain clear of large volumes of sediment and this is reflected in the dominance of bedrock features in these channel types. In contrast, the braided and single thread representative reaches are less competent and are prone to sediment accumulation. It is these high flows that are important in controlling the distribution of sediment and hence the geomorphic composition of the Sabie River.

In general it is clear that each representative reach displays significantly different morphological and hydraulic characteristics (Figure h). For example, the character of a pool-rapid channel can be generalised as being dominated by bedrock , displaying moderate to high transport rates at high flows and lower rates at low flows; the water surface slope remains moderate at all flows, however the width/depth ratio changes from low at low flows to moderate at high flows. As such the representative reach approach represents the simplest and most efficient method of classifying and characterising a river channel and generates information based on the intensive study of selected reaches that may be transferred to other unmonitored sections of the river generating a complete spatial picture of the system functioning.

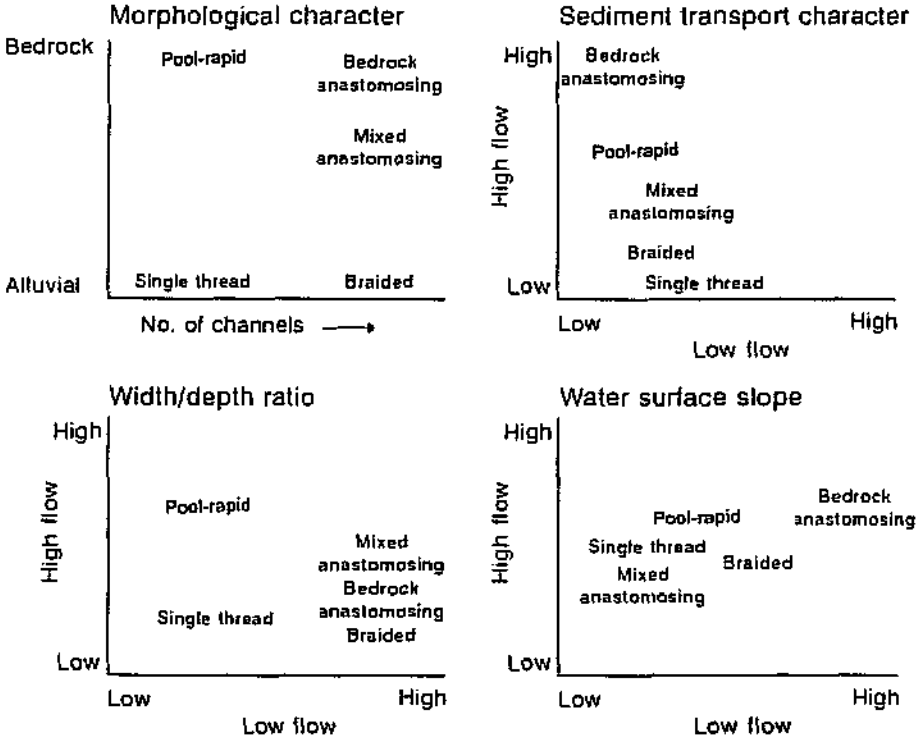

Figure h. Summary characteristics of representative reaches of different channel types on the Sabie River.

There are four major products from this research each of which is detailed fully in the main report:

i. **River rationalisation and zoning methods based on geomorphological criteria.** Qualitative and quantitative techniques are detailed that structure the river based on a bottom up hierarchical classification. The geomorphology was chosen as the best physical parameter to categorise a river system due to its spatial and temporal response characteristics and its close links with ecological change.

ii. **Appropriate methods for establishing a monitoring network, enabling hydraulic and channel geometry data to be collected at a number a physical scales.** Full descriptions of the data collection network are given together with the example network installed on the Sabie River.

iii. **Presentation of channel type scale methods to generate channel roughness and hydraulic character.**
Methods to process the raw data collected are given in order to generate representative hydraulic and sediment transport characteristics with changing discharge.

iv. **Generation of a large data base of flow resistance coefficients over a range a physical scales and fluvial environments, in addition to hydraulic and channel geometry data.**
Quantification of the flow resistance coefficients has aided an assessment of channel dynamics (Broadhurst *et al.*, in press) hence, biotic change and flow resistance values have been successfully transferred to other reaches (Birkhead *et al.*, in press). These uses of the outputs from this research form integral components of the Kruger National Park Rivers Research Programme and are of use to a variety of river scientists.

v. **Identification of Representative Reaches.**
Steps i to iv are used to identify the representative reaches on the Sabie River in the Kruger National Park and establish their character.

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1.0 INTRODUCTION TO THE PHILOSOPHY OF THE PROJECT

1.1 Background aims and objectives.

Work within the Kruger National Park Rivers Research Programme has highlighted the complexity of the task of evaluating the physical and ecological response of the rivers in Mpumalanga Province to changes in water quality and quantity (Heritage *et al.*, in press, Weeks *et al.*, 1996; Jewitt *et al.*, in press). The geomorphological study of the Sabie River faced the task of modelling channel change along 110km of very complex channel. Given the circumstances it quickly became clear that a detailed study of the whole length of river would be logistically and economically impossible. Similar experiences have been reported for the Letaba River geomorphological study (Heritage *et al.*, in press) and from many of the Instream Flow Requirement studies conducted by the Department of Water Affairs and Forestry (Department of Water Affairs and Forestry, 1996a, 1996b). Whole river hydraulic monitoring has been infrequently conducted elsewhere, however the accuracy of the quantitative outputs has received considerable criticism due to the assumptions made in interpreting between surveyed points (Hey, 1987). As such, there is a need for a less intensive approach to river investigation that still provides the information necessary to determine geomorphological and ecological functioning.

A method is proposed to rationalise a river system by identifying reaches that are representative of repeatable geomorphological types of the whole study reach (eg. The pool-riffle sequence of a temperate alluvial meandering river). This moves away from the more traditional whole reach quantification approach (Figure 1). The identification of a set of reaches based on the morphologic unit composition provides the key to achieving this aim as it is the morphologic unit that can be directly related to the controlling catchment variables and to the ecological function of the river (Figure 2). The representative reaches generated by this rationalisation are useful in three ways:

1. **They provide a method by which the river may be zoned. Knowledge of representative reach structure and function, gained from monitoring, may be applied to other unstudied but similar sections of the river with some confidence to generate a coherent morphological and process based model of the system.**

2. **They identify the key locations on the river systems that must be monitored in order to ensure that the geomorphological and ecological diversity of the system is maintained. Each representative reach can be considered as critical for the maintenance of the entire system.**

3. **The representative reach breakdown provides the basis for focussing research on key sections of channel that can be used to describe the whole system.**

Factors such as water chemistry, temperature and turbidity have been shown to be highly variable, particularly in a temporal sense (Walling and Webb, 1996). The geomorphological structure of a river system is in contrast, relatively stable and acts as the fundamental template upon which the ecosystem is structured (Rogers, 1997; Pickett and Rogers, 1997). The identification, mapping and monitoring of representative reaches via geomorphological and hydraulic studies immediately structures any river system into process based units that have an ecological significance. No rational integrated research programme can be implemented on any river system without first carrying out this task. Without performing this process the channel remains as a complex system that would require an equally elaborate, and less efficient, project design in order to gain an equivelent level of understanding.

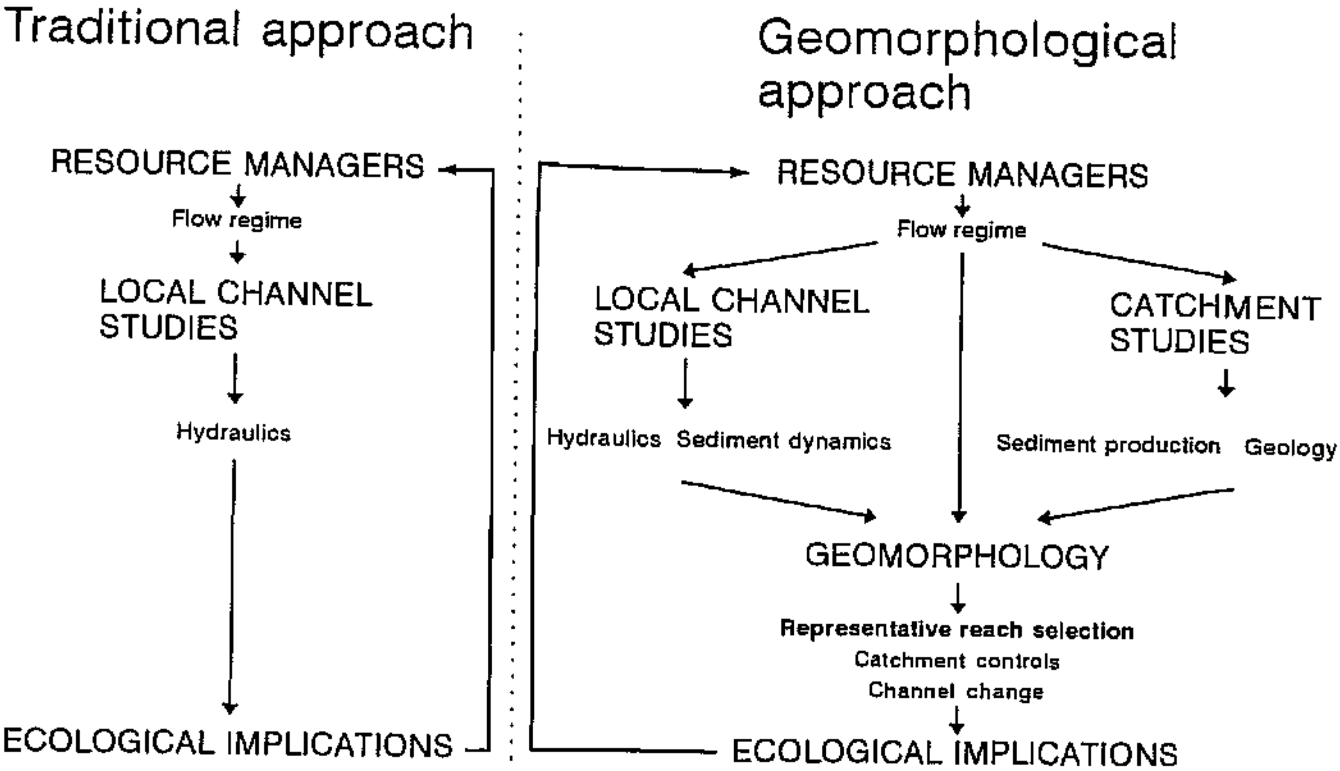

Figure 1. The geomorphological approach to defining representative river reaches.

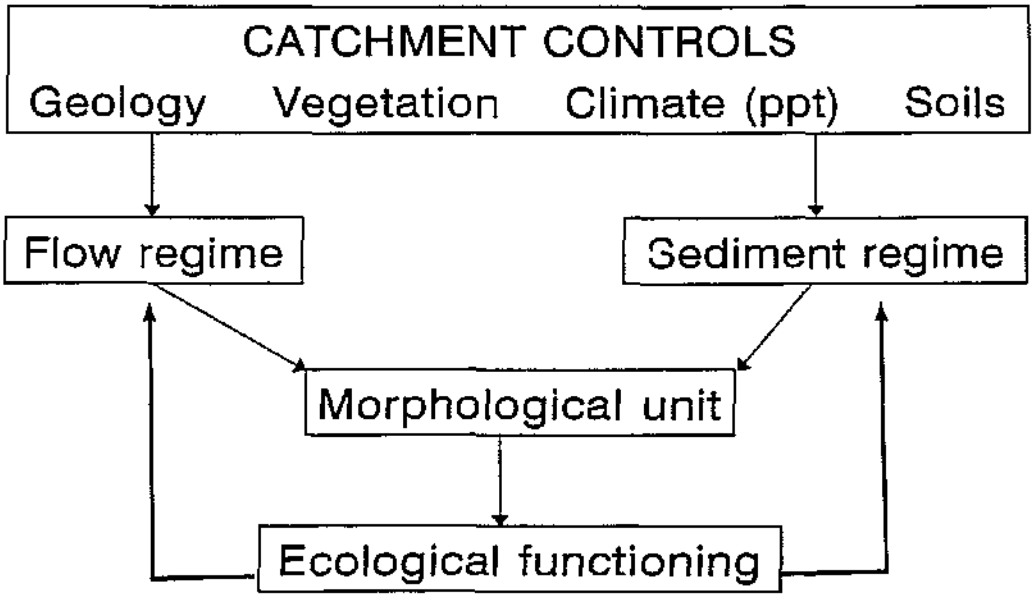

Figure 2. Linkage between catchment controls and ecological functioning through the geomorphic unit.

The need for an understanding of the links between local hydraulic conditions, channel morphology and riverine ecosystem structure in the Kruger National Park was first recognised as part of an integrative holistic research programme, with the overall aim of quantifying the water demand of the environment by (Rogers *et al.*, 1992). Local hydraulics and channel morphology are the primary determinants of the physical habitat, which itself controls ecosystem functioning. Therefore, it is essential to understand the mechanisms controlling local hydraulic parameters in order to predict the effect of altering the flow and sediment regime on a river. Given the rationalised structure of the river from geomorphological mapping, representative examples of each geomorphic type may be monitored intensively and the process characteristics extrapolated to similar unstudied areas of the river. Hydrological data, in the form of a simulated daily discharge regime must be translated into point discharge values, and further, into local hydraulic conditions such as flow depth, width, velocity and bed shear stress, to be able to assess the impact such a discharge regime would have on the form of each geomorphological type along a river. Current research in this area in South Africa is primarily concerned with riverine geomorphological classification (Wadeson and Rountree, 1995 and van Niekerk *et al.*, 1995), investigation of bedrock channel dynamics (Vogt, 1992; van Niekerk and Heritage, 1993; Heritage and van Niekerk, 1994 and Moon *et al.*, 1997) and characterisation of channel roughness (Broadhurst *et al.*, 1995; Broadhurst *et al.*, 1996).

1.1.1 The role of geomorphology in influencing fluvial geomorphological and ecological processes

Channel morphologies have characteristic hydraulic limits as the biotope work of (Wadeson, 1994) and (Newson, 1996) has demonstrated for alluvial channels. In addition, these may be directly linked to ecologically significant parameters such as substrate composition and visual cover (Heritage *et al.*, in press). A method is proposed for the selection of reaches along any channel that re sufficient to represent the variety of geomorphological and hydraulic conditions present along all or part of the whole river.

1.2 Aims

The principal aim of the project was to develop a method for defining representative river reaches, and for monitoring the hydraulic character at this spatial scale. The ideas presented are tested on the Sabie River in the Kruger National Park where physical, chemical and biological processes are monitored and modelled in order to extend the information to similar reaches along the whole river in the Lowveld. This was achieved by:

- **Channel zonation.**
- **Morphologic characterisation and definition of 'Representative Reaches'.**
- **Determination of hydraulic control processes (channel friction, sediment transport character) through an evaluation of channel roughness at the scale of channel type.**

A review was conducted of the scales over which a variety of physical parameters operate across various river types, paying particular reference to the processes operating on the Sabie River in the Kruger National Park. Channel classification systems were fully investigated and a bottom-up agglomerative hierarchical approach was adopted, to best model associations at ecologically relevant scales in spatially complex river systems. A summary of the research into the temporal geomorphological dynamics of the Sabie River is presented, illustrating the relative spatial and temporal stability of geomorphic processes and associated morphologic units that makes them the best discriminant with which to categorise and zone rivers.

The theory behind the process of representative reach selection and monitoring is detailed together with the results of the application of the method to the Sabie River. This covers geomorphic structuring, hydraulic characterisation and ecological association for the representative reaches within the River Kruger National Park. The representative reaches concept and results for the Sabie River have been utilised by a number of other studies and these are detailed to demonstrate the usefulness of the representative reaches process.

2.0 PROCEDURE FOR CHANNEL CHARACTERISATION AND ZONATION

This chapter details the steps required to achieve the aims set out in section 1.2. Rivers may be characterised by their geomorphology as this provides a more stable basis than the use of other variables such as water chemistry that change at a faster rate. The geomorphology does, however, respond to changes in the catchment over the longer term (from the annual scale upwards), these changes are often complex and have significant ecological implications (Table 1).

2.1 Zonation

Zoning is the process of dividing a system into a set of characteristic units that when combined, can be used as a spatial representation of the whole river system. Considerable research has been conducted into the zonation of physical and chemical characteristics in water courses (for examples see Walling and Webb, 1996; Webb and Walling, 1996). The physical characteristics include factors such as suspended sediment, water temperature, dissolved oxygen, solute loads and geomorphology, each of which is reviewed below to determine the one most suitable for zoning the Sabie River.

Suspended sediment is an important parameter due to its effect on the biotic system. Sources of suspended solids include, bank erosion, gullying, loss from agricultural land and mining waste. Suspended sediment loads can vary significantly between catchments and may be a function of climate, rock type, relief, tectonic activity and land use (Walling and Webb, 1996). At a more local scale within a catchment, geology, soils and land use patterns become the dominant factors influencing the spatial distribution of suspended sediment. Temporally, suspended sediment transport is highly variable often with clear water flow for most of the year interspersed with event-related rises in concentration.

Water temperature also plays an important role in influencing other factors within the river such as dissolved oxygen and the distribution of aquatic organisms (Rose, 1967). Temporal patterns in water temperature may vary on an annual regime and diurnally, in addition storm events create a response in water temperature. Spatially, the most significant temperature difference can be detected between the main channel and headwater tributaries and mean annual water temperature has been directly correlated to altitude. This phenomenon was recognised by (Weeks *et al.*, 1996 and Pollard *et al.*, 1996) in their zonation of the Sabie River into Lowveld and headwaters. On a micro-scale, temperature may vary in response to factors such as stream shading (Weatherley and Ormerod, 1990) and channel depth (Sioli, 1964).

Concentrations of dissolved oxygen have been shown to vary widely in time and space, and the concentration is inversely related to the annual cycle in water temperature. Locally the aeration of the water column is affected by channel hydraulics with oxygenation occurring over shallow turbulent reaches (Walling, 1980). Construction of river zonation patterns using this variable is therefore very difficult.

Solute loads also vary spatially and temporally and many rivers receive a large proportion of their solute load directly from atmosphere. Marine derived materials declines away from the

the coast to be replaced by solutes derived from the terrestrial environment in the form of wind blown soil and dust. Solutes are also derived from the chemical weathering of the host rock and soil. Spatial variation has been correlated to six environmental factors (Meybeck and Helmer, 1989), ranging from the presence of erodible minerals, distance to the sea, aridity, terrestrial primary productivity, the ambient temperature and rates of uplift. As a result there is considerable chemical variability between rivers. Flow conditions also influence chemical concentrations, however there is no simple dilution relationship with increasing water volumes due to complex interactions, particularly with suspended sediment loads. This degree of spatial and temporal variation also makes river zonation using this parameter very difficult.

Morphological zonation has received considerable attention recently (see van Niekerk *et al.*, 1995). Differentiation has been made on the grounds of channel size and gradient, with step-pools channels characterising upland watercourses and riffle-pool sequences in lowland alluvial channels. Channel pattern within large alluvial channels have been classified on planform shape or bar associations (Kellerhals and Church, 1989). Zonation using geomorphology provides a more static picture in both a spatial an temporal sense than using the other variables previously mentioned, all of which are influenced to a greater degree by short term hydraulic variability (Table 1).

Table 1. Spatial and temporal change characteristics of a variety of fluvial physical factors.

Factor	**Spatial change**	**Temporal change**	**Comments**
Suspended sediment	**R.** L. Bank collapse.	**R.** Increases during floods but no simple relationship. **L.** Affected by bank collapse.	Highly variable pattern over time that may cause short term ecological response.
Temperature	**R.** Upland/lowland distinction. L. Shading.	**R.** Alters with flood events. **L.**	Provides very coarse spatial pattern, ecological variation is more complex that this.
Oxygenation	**R.** **L.** Turbulence.	**R.** Turbulence pattern alters as hydraulics change. **L.** Alters diurnally.	Pattern varies spatially and temporally and may case short term ecological response.
Dissolved substances	**R.** Varies away from coast. **L.** Local inputs cause slight variation.	**R.** Alters with flooding. **L.**	Diffuse pattern of low variability, less complex that the ecological pattern.
Geomorphology	**R.** Varies in response to geology, sediment inputs, tributaries, etc. **L.** Slight alterations of local morphological composition to form complex physical template.	**R.** Robust very rare catastrophic changes may occur. **L.** Responds to changes in sediment balance by morphologic unit change.	Pattern alters along the river in response to catchment control variability, local changes in the morphologic unit template occur on a temporal scale over which ecological response and equilibrium is possible.
R. Regional character, **L.** Local character.			

It is clear that many of the physical parameters briefly described above are highly variable in space and time. However, the geomorphological template is relatively stable given that there is no great change in the catchment controls within the system, thus it is argued that this factor would form for the identification of representative reaches in any river system within which the ecology may adapt. Therefore the first step in achieving this is to characterise the representative reaches based on morphologic composition.

2.2 Morphologic characterisation

The basis of any classification system is the ordering of sets of observations or characteristics based on similarity or difference (Platts, 1980). The classification of river is invaluable in understanding the behaviour and morphology of such systems. Common morphological units can be described and their characteristics determined, this allows knowledge to be extrapolated to rivers that are physically similar (Mosley, 1987). River classification theory has been reviewed by many authors (Macan, 1961; Hawkes, 1975; Wasson, 1989; Naiman *et al*., 1990; Wadeson, 1994) and it is clear from these that most work in this area has been conducted on temperate perennial alluvial systems.

2.2.1 Selection of a method for morphological river characterisation

Many river classification systems have been proposed, however, few are generic for a range of applications, instead using physical, chemical and biological criteria on a variety of spatial scales. More recently classification systems have been formulated using a hierarchical approach which links features on a variety of scales from regional to micro-habitat (Brussock *et al*., 1985; Rosgen, 1985, 1994; Frissel *et al*., 1986; Cupp, 1989; van Niekerk *et al*., 1995). Such an approach has developed from the knowledge that different processes influence geomorphic form depending on the scale of feature being investigated, for example (Wolman and Gerson, 1978) recognise that the development of landscapes, catchments and rivers although linked, are controlled by different sets of processes. Similarly rates of change vary depending upon the spatial scale being considered. A hierarchical classification places these factors in context and defines the constraints under which a system can develop.

The majority of the hierarchies are structured from the catchment scale downwards on the basis that it is the catchment variables that control the dynamics and hence the morphology of the river (van Deusen, 1954). The spatially nested river system hierarchy developed by (Fissel *et al*., 1986) in which a system at one level forms the environment for the subsystems below it, has gained wide acceptance within the research community. Six spatial scales are identified, from drainage basin to micro-habitat level (Table 2). The classification is based on studies conducted on second and third order mountain streams with perennial flow, this is reflected in the importance placed on tributary junctions as major spatial boundaries due to their inputs of water and sediment along the main channel.

Practical classification of entire river systems using this top down approach has proved difficult on some rivers, because the interaction of many catchment variables (particularly local geology) as part of a complex interlinked system, produce a variety of morphological features that make each river system a unique entity.

Table 2. The hierarchical classification of second and third order forested mountain streams (Frissel *et al.*, 1986).

Spatial scale	**Description**
Drainage basin	The area included within the primary catchment boundary.
Stream system	All the surface waters in a watershed.
Segment	The portion of a stream flowing through a single bedrock type and bounded by a tributary junctions or waterfalls.
Reach	A length of stream segment lying between breaks in channel slope, local side slope, valley floor width, riparian vegetation and bank material.
Pool-Riffle	A reach subsystem with a characteristic bed topography, water surface slope and velocity pattern.
Microhabitat	Patches within pool-riffle systems with homogenous substrate, water depth and velocity.

The problem is most apparent when an empirical hierarchy such as that developed by (Frissel *et al.*, 1986) is imposed on a river where the catchment characteristics are very different from those of the rivers on which the classification was developed. In these situations its structural rigidity, imposed by the controls defined by the study catchment on which the hierarchy was developed, prohibits its meaningful use on rivers of a different nature. For example a top down hierarchy developed on an alluviated river, where tributary sediment inputs dominate the catchment control factors, could not then be applied to structure a bedrock influenced channel that is influenced by different catchment controls such as the underlying geology. (Mosely, 1987) notes, however, that it may prove more useful to classify rivers according to their component parts, in other words to generate a bottom-up agglomerative hierarchical system, which has the advantage of not imposing any initial hierarchical structure on the system, instead looking for morphological associations to generate the hierarchy. Such an approach has been successfully applied to the Sabie River catchment by (van Niekerk *et al.*, 1995). The identification of small scale morphological units also allows the river to be assessed on a biological basis, as many of these units are also ecologically meaningful (see Nanson and Beach, 1997; Gill, 1973). Using this hierarchical approach it is possible to identify the scales at which a variety of ecological phenomena and processes take. This can then feed directly into the management decision making process (Pickett and Rogers, 1997).

2.2.2 An agglomerative approach to river classification

The proposed classification follows that of (van Niekerk *et al.*, 1995) in adopting an agglomerative approach to the construction of the river classification hierarchy. It is argued that the catchment variables and processes act to generate the morphological features at the smallest spatial scale and that it is the association of these features that progressively build to create a complete spatial classification of the river (van Niekerk *et al.*, 1995). In order that the classification is useful more widely than for categorising active channels, valley floor features (such as bedrock pavements and terraces) are considered. The entire process may be conducted using aerial photographs and mapping the morphologic units present along the river. Fieldwork should be used to confirm the patterns observed.

The agglomerative hierarchical approach is less rigid and displays a greater array of spatial scales than previously included in other top down hierarchical classifications. Details of its spatial structure, compared with the classification systems of (Frissel *et al.* 1986; Rountree and Wadeson, 1996) reveals that morphological diversity of the Sabie River has generated three subdivisions of the reach unit of (Frissel *et al.* 1986; Rountree and Wadeson, 1996), otherwise it has the same hierarchical framework as the other two, but uses the term micropatch to distinguish the smallest physical geomorphic unit from the hydraulically influenced biotope of (Rountree and Wadeson, 1996) or the ecological microhabitat of (Frissel *et al.*, 1986) (Table 3). The use of the term micropatch is consistent with the terminology used in landscape ecology and patch dynamics, two interlinked paradigms which explicitly deal with issues of scale in ecology.

Table 3. Comparison of hierarchical classification systems.

Frissel *et al.* (1986)	Rountree and Wadeson (1996)	van Niekerk *et al.* (1995)
Drainage basin	Catchment	River system
Stream system	Catchment	Zone
Segment	Segment	Macro-reach
Reach	Reach	Reach Planform Channel type
Pool-riffle	Morphologic unit	Morphologic unit
Micro-habitat	Biotope	Micro-patch

The hierarchy is also flexible and has been supported by an independent statistical analysis of data from the Sabie River (section 3.1.2). It can include a large number of morphological units that are rarely encountered in temperature alluvial river systems. It is possible to extend the classification system further to include features seen on other river types. The classification may be applied to rivers which are superimposed or antecedent, and also to others which are cut into alluvium where terraces and berms may be present. Flexibility and wide coverage allows any river to be classified systematically. Similarly as new research is conducted into other river types so the list of geomorphologic units can be extended.

Having established the geomorphic structure of the river the scale of investigation can be determined from the smallest unit in the hierarchy that repeats long the river. Morphologic units may occur in all channel types. Channel types are seen to repeat along the length of a river, but reach units often consist of unique combinations of channel types. Hence, the representative reach scale of investigation should be set at the scale of channel type. It should be stressed here that the term 'representative reach' is used in the context of defining the study length of a river and does not necessarily relate to the same spatial scale as the reach unit in the morphological hierarchy (Table 3), hence the 'representative reach' length can be equivalent to that of channel type. A single example of each of these constitutes the representative reaches. This allows the river to be zoned on the basis of channel type to form the baseline spatial scale for further investigation of the hydraulic processes that are acting to generate the channel types and influence the ecology. The importance of these hydraulic processes is discussed below.

2.3 Process characterisation

Following the process of identifying the geomorphological components of a river system and zoning the river on the basis of geomorphological similarity, single examples of each can be chosen as 'representative reaches'. It is then necessary to characterise the variables controlling the physical nature of each representative reach, principally flow resistance, water surface slope and sediment dynamics. This process is detailed below:

2.3.1 Representative reach flow resistance quantification

The local hydraulics of a channel influences its physical form through the erosion and deposition of sediment, in addition features such as water velocity, flow depth and wetted perimeter influence the biotic communities within the system. The local hydraulics are reflected in the flow resistance of the channel. The following steps are necessary to characterise the roughness of a river at this scale:

a) Identification of the flow resistance components.

Representative reaches should be determined from objective classification of the geomorphology (Section 2.2.2). There are a variety of factors controlling flow resistance within each representative reach, such as the type of vegetation community found, the channel geometry and the sedimentary or lithological characteristics of the channel bed and banks. A comprehensive geomorphological, sedimentological and vegetational survey should be undertaken for each channel type that characterises the study river, to identify all these flow resistance components. This would involve the mapping of morphologic units, cross-section surveys, bed-material sampling and characterisation and vegetation surveys (see Broadhurst *et al.,* in press, Heritage *et al.,* in press).

b) Evaluation of different methods for assessing flow resistance.

A literature review identified flow resistance estimation methods which were most appropriate at the scale of representative reach. The (Barnes, 1967) method has become the accepted approach for reach characterisation of channel roughness from multiple cross-section and flow level data, a comprehensive review of the evaluation process for the Sabie River is contained in (Broadhurst *et al.*, in press).

c) Establishment of hydraulic monitoring networks.

Hydraulic data should be collected at each of the representative reaches, covering the range of channel types identified. This should occur over a range of discharges, for use in quantifying flow resistance. To identify all the flow resistance components at each channel type and to correlate their occurrence to observed local hydraulic conditions, eight to ten cross sections per channel type should be surveyed and flow resistance components mapped. The longitudinal spacing of the cross sections was designed to incorporate the presence of low flow hydraulic 'controls' that cause energy loss, and thus to define accurately water surface slope along a reach. Flow stages should be surveyed and related to the peak discharge recorded by the nearest gauging structure.

d) Quantification of flow resistance.

The data obtained from field investigations should be used to determine the flow resistance characteristics. Results quantified for each channel type can then be transferred to other unstudied but similar environments on the river to produce a whole river picture of hydraulic and geomorphic processes.

Following the geomorphological hierarchy outlined above, it is possible to characterise the study river at the scale of channel type. Several cross sections, comprising a channel type must be analysed. The Barnes, (1967) method is outlined below.

Reach flow resistance may be expressed as a friction factor, most commonly Manning's 'n', Chezy C or Darcy-Weisbach f.

Manning:

$$Q = \frac{A R^{\frac{2}{3}} S_f^{\frac{1}{2}}}{n} \qquad 1$$

Chezy:

$$Q = A\, C\, (R\, S_f)^{\frac{1}{2}} \qquad 2$$

Darcy-Weisbach:

$$Q = A \left(\frac{8 g R S_f}{f} \right)^{\frac{1}{2}} \qquad 3$$

where Q is the discharge, R is the hydraulic radius is the channel area (A)/wetted perimeter, Sf is the water surface or friction slope and g is the acceleration due to gravity.

A value of the friction slope, S_f, to be used in total resistance equations, Manning's n, Chezy C or Darcy-Weisbach f (equations 1 to 3) is only available between sections, as it is defined by:

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - k(\Delta h_v)}{L} \qquad 4$$

where h_f is the friction head loss, L is reach length, Δh is the change in elevation of the water surface between the upstream and downstream cross sections, Δh_v is the change in velocity head between the upstream and downstream cross sections and $k(\Delta h_v)$ approximates the energy loss due to acceleration or deceleration in a contracting or expanding reach. Following convention, k is assumed to equal zero for contracting reaches and 0.5 for expanding reaches (Chow, 1959). The velocity head, h_v, at a cross section is equal to $\alpha V^2/2g$, where α is the velocity head coefficient, which indicates the uniformity of velocity across the section.

As no detailed knowledge of the change in velocity across the sections under investigation is known, it can be assumed that α equals 1. This follows a precedent set by (Chow, 1959) and followed by others calculating flow resistance coefficients (Barnes, 1967; Jarrett, 1984; Hicks and Mason, 1991). However, several studies have shown that values for α can far exceed unity, with values of greater than two attributed to expanding sections displaying flow separation (Streeter, 1942), (a phenomenon commonly found on the Sabie River).

A representative value of flow resistance for a multiple section reach at a given discharge can be obtained by equating the friction head loss calculated from the friction slope (equations 1 to 3) with the friction head loss given by equation 4. This uses the method adopted by (Barnes, 1967) and followed by (Jarrett, 1984) and (Hicks and Mason, 1991). Therefore,

$$h_f = h_{f_{1,2}} + h_{f_{2,3}} + \ldots\ h_{f_{(m-1),m}} \qquad 5$$

and from the Manning's equation (equation 2) and the continuity equation Q=AV:

$$h_f = n^2 Q^2 \left(\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \ldots \frac{L_{(m-1).m}}{Z_{(m-1).m} Z_m} \right) \qquad 6$$

where m is the number of cross sections (with the mth cross section being furthest upstream), m-1.m represents the difference in value of the parameter in question between cross section m-1 and cross section m, $Z = AR^{2/3}$, and a representative value of Z, following the convention given by Barnes, (1967) for the reach between two adjacent cross sections is given by the average $(Z_1 Z_2)^{1/2}$.

From equations 5 and 6:

$$h_f = (h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + \ldots k_{(m-1).m}\Delta h_{v_{(m-1).m}}) \qquad 7$$

and therefore, from equation 7:

$$n = \frac{1}{Q}\left(\frac{(h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + \ldots k_{(m-1).m}\Delta h_{v_{(m-1).m}})}{\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \ldots \frac{L_{(m-1).m}}{Z_{(m-1)} Z_m}}\right)^{\frac{1}{2}} \quad \mathbf{8}$$

In a similar fashion, Hicks and Mason, (1991) derived a representative value of Chezy C from:

$$C = Q\left(\frac{\frac{L_{1.2}}{X_1 X_2} + \frac{L_{2.3}}{X_2 X_3} + \ldots \frac{L_{(m-1).m}}{X_{(m-1)} X_m}}{(h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + \ldots k_{(m-1).m}\Delta h_{v_{(m-1).m}})}\right)^{\frac{1}{2}} \quad \mathbf{9}$$

where $X = AR^{1/2}$

An equivalent expression for Darcy-Weisbach friction factor has also been derived (Broadhurst *et al.*, 1996)

$$f = \frac{8g}{Q^2}\left(\frac{(h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + \ldots k_{(m-1).m}\Delta h_{v_{(m-1).m}})}{\frac{L_{1.2}}{(Y_1 Y_2)^{\frac{1}{2}}} + \frac{L_{2.3}}{(Y_2 Y_3)^{\frac{1}{2}}} + \ldots \frac{L_{(m-1).m}}{(Y_{(m-1)} Y_m)^{\frac{1}{2}}}}\right) \quad \mathbf{10}$$

where $Y = A^2R$

Using equations 8, 9 and 10, total flow resistance coefficients can be quantified over a channel type representative reach. Section 3 of this document details the application of this technique to the Sabie River.

2.3.2 Characterisation of representative reach water surface slope

Data collected as part of the stage level monitoring for the flow resistance exercise can be used to define the water surface slope character for each representative reach. The water levels at various discharges should be plotted against channel distance to determine the slope.

2.3.3 Characterisation of representative reach geometric characteristics

Data collected as part of the stage level monitoring for the flow resistance exercise can be used to define the geometric character (width, depth, wetted perimeter, hydraulic radius and flow velocity) for each representative reach. This may be achieved by simply plotting the cross-section data for different flows and measuring off the relevant parameters.

2.3.4 Characterisation of representative reach sediment transport characteristics

Data collected as part of the stage level monitoring for the flow resistance exercise can be used to define the sediment transport character for each representative reach. The Ackers and White (1973, 1993) equations can be used to quantify transport rates as discharge changes:

Initially the dimensionless grain size D_{gr} is calculated from equation 11.

$$D_{gr} = D_i \left[\frac{\gamma S}{\rho_w \upsilon^2} \right]^{1/3} \qquad \textbf{11}$$

where D_i is the grain-size of the bed-material (usually D_{50}), S is the water surface slope, $\gamma = (\rho_s - \rho_w)g$, ρ_w is the density of water (1000kgm^{-3}), ρ_s is the density of sediment (2650kgm^{-3}), g is gravitational acceleration (9.81ms^{-2}) and v is the kinematic viscosity of the fluid at 10° Celsius (T):

$$\upsilon = \frac{1.79 \times 10^{-6}}{1 + 0.03368T + 0.000221T^2} \qquad \textbf{12}$$

Where D_{gr} <60 (fine sediments) the following parameters are then calculated:

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53 \qquad \textbf{13}$$

$$A = 0.14 + \frac{0.23}{\sqrt{D_{gr}}} \qquad \textbf{14}$$

$$m = 1.34 + \frac{9.66}{D_{gr}} \qquad \textbf{15}$$

$$n = 1 - 0.56 \log D_{gr} \qquad \textbf{16}$$

These are then used to compute the particle mobility F_{gr}:

$$Fgr = \frac{\rho_w^{1/2} v_* n}{(\gamma S D_i)^{1/2}} \left[\frac{V}{\sqrt{32}\log\left(\frac{10d}{D_i}\right)} \right]^{1-n} \qquad 17$$

where $v_* = \sqrt{gdS}$, V is the average flow velocity (ms^{-1}) and d is the average flow depth (m).

The dimensionless sediment transport rate is then calculated using equation 8:

$$G_{gr} = C\left(\frac{F_{gr}}{A_i} - 1\right)^m \qquad 18$$

Ai is substituted for A when considering the rate of transport for a particular grain size fraction:

$$A_i = A\left(\frac{D_{50}}{D_i}\right)^{0.2} \qquad 19$$

Finally the dry weight sediment transport rate is calculated using equation 10:

$$q_b = \left[\frac{G_{gr}}{\left(\frac{v_*}{V}\right)^n} \right] \rho_s D_i V \qquad 20$$

3.0 APPLICATION OF THE REPRESENTATIVE REACH SELECTION PROCEDURE AND PROCESS CHARACTERISATION OF THE SABIE RIVER

The Sabie river was selected for this study to test the geomorphological and hydraulic characterisation method detailed in chapter 2. The Sabie River rises on the Great Escarpment and flows eastwards for 210 km to its confluence with the Incomati River in Mozambique (Figure 3). It drains an area of 6252 km^2 in South Africa and a total area of 7096 km^2 and flows through the Kruger National Park for approximately 110 km of its length. Rainfall varies from 2000 $mm.a^{-1}$ in the mountainous upstream portion of the catchment to 400 $mm.a^{-1}$ close to the Mozambique border. The flow regime of the Sabie River is characteristic of semi-arid systems in which extremes of discharge occur with low winter baseflows of 1 to 2 $m^3.s^{-1}$, occasional high summer flood flows in excess of 100 $m^3.s^{-1}$ and very rare major floods of the order of 1000-1500 $m^3.s^{-1}$. During non-drought years, several summer mid-range flows of the order of 20 to 40 $m^3.s^{-1}$ occur. During drought periods summer and winter baseflows are reduced and summer high and intermediate flows are less frequent.

The Sabie River in the Kruger National Park is incised into the Post African I and II surfaces, which consist of gneiss west of the conservation areas, separated from the basalt in the east by a narrow band of Karoo Sequence sediments. This has resulted in a large degree of bedrock control within the macro-channel. The longitudinal profile of the Sabie River in the Lowveld is highly irregular on large and small scales.

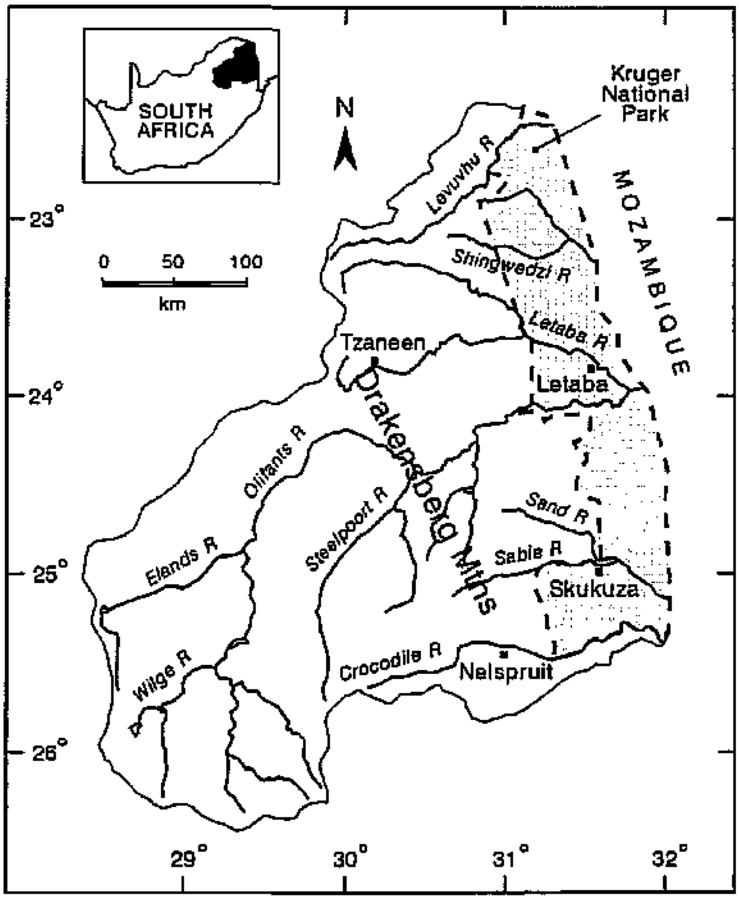

Figure 3. Location of the Sabie River, Mpumalanga Province, South Africa.

3.1 Representative reaches on the Sabie River in the Kruger National Park

Examination of detailed cross-section profiles and referring to the geologic history of the Lowveld Region (Partridge and Maud, 1987) shows that the Sabie River consists of a macro-channel and one or more active channels (Figure 4). The macro-channel extends across the width of the incised 'valley' and contains the full extent of sedimentary deposits and riparian vegetation within the 'valley'. Flow within the macro-channel is normally confined to smaller active channels. Extensive alluvial deposits occur in places; in other areas bedrock features dominate. The active channels carry water throughout the year and some seasonal channels become active during the higher summer flows. Sediment deposits occur in the active channels and along their edges, although bedrock outcrops frequently, controlling the upstream water surface slope.

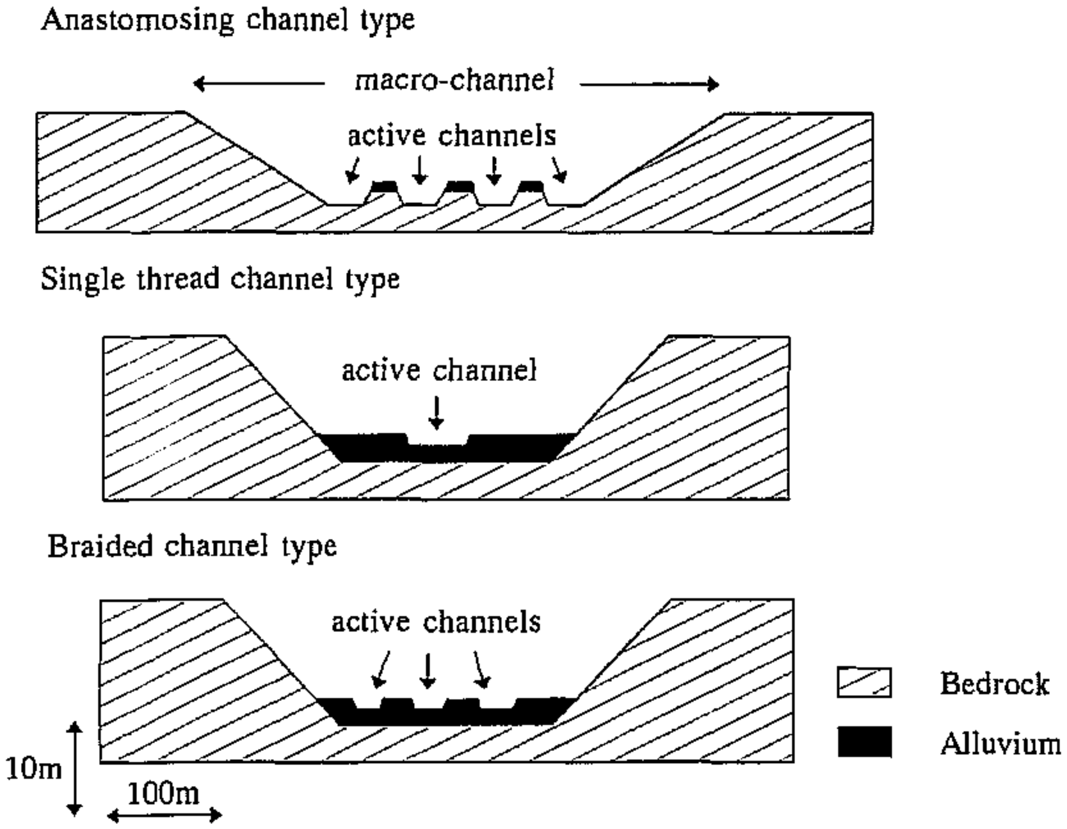

Figure 4. Channel forms in the incised macro-channel of the Sabie River in the Kruger National Park.

3.1.1 A hierarchical classification of the Sabie River in the Lowveld

In agglomerative hierarchical river classifications a spatial hierarchy is constructed from associations between the smallest units, allowing simultaneous consideration of all characteristics of the object that are considered to be important (Mather, 1976). By determining spatial geomorphological associations from the scale of morphological unit upwards, using an agglomerative approach, the physical structure of the system becomes apparent and the finer scale components of the physical system become better defined. These can subsequently be related to wider catchment influences, such as tributary junctions and geological boundaries, to describe the broader scale levels of the hierarchy, thus generating a complete picture of the geomorphological structure of the river system.

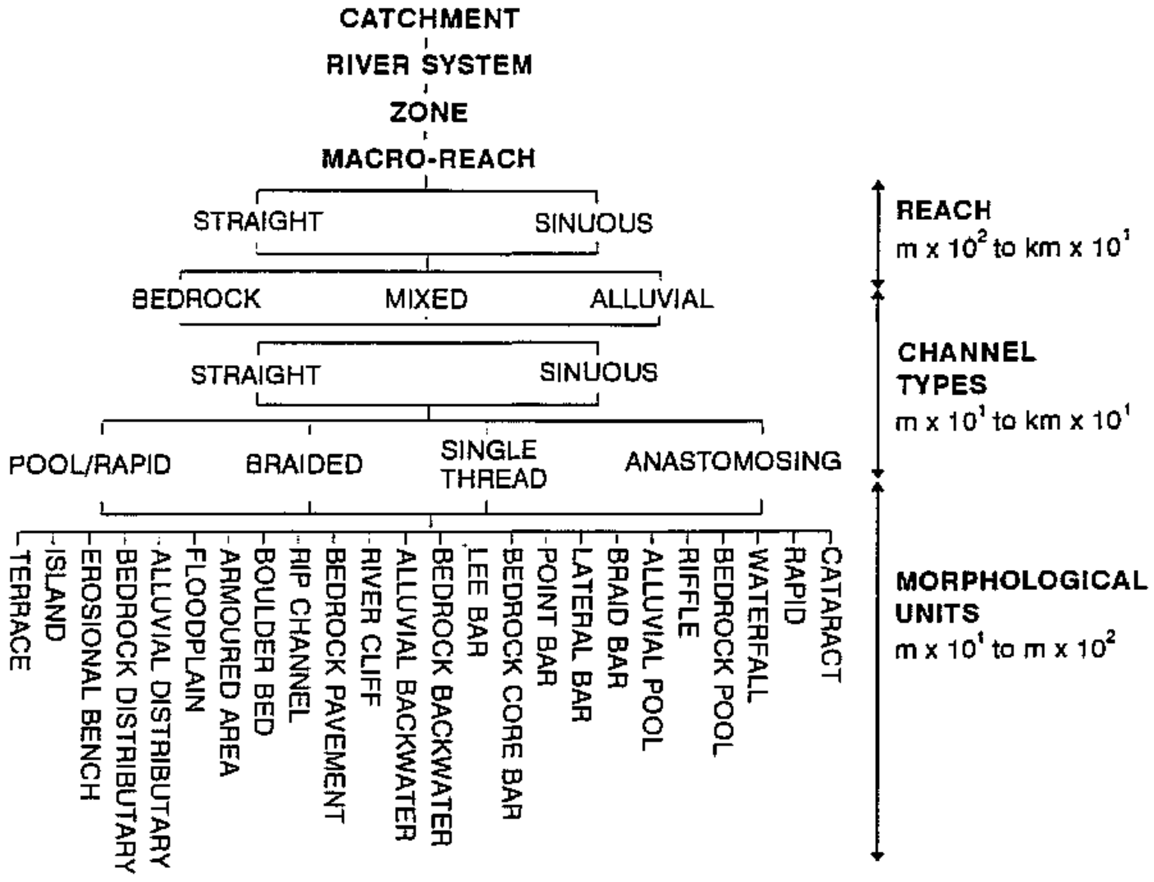

Figure 5. A hierarchical classification of the Sabie River in the Kruger National Park.

The basic components are the morphological units, each with a distinctive character and micro-habitat (van Niekerk and Heritage, 1993). These were chosen as the primary spatial level as it is here that the overlap with biotic preferences occurs, making it possible to infer biotic response to geomorphological change at the level of morphological unit (van Coller *et al.*, 1995). Morphological units combine variously to form different channel types. There is a functional relationship between channel types which may be grouped into reaches, where one channel type may be directly influencing the nature of the channel type up and downstream. For example, alternating braided and bedrock anastomosing channel types are common in the Sabie River immediately downstream of the western boundary of the Kruger National Park. Here, exposed bedrock in the bedrock anastomosing channel type acts as a hydraulic control, resulting in a decrease in energy in the ponded area upstream, with deposition of alluvial bars and thus the development of a braided channel type. A macro-reach may comprise one or more reaches and has distinctive geological, hydrological, sedimentological and vegetational characteristics. A zone, comprising several segments, has boundaries defined by major breaks in slope which are usually coincident with geological contacts. The river incorporates the riparian margin from source to mouth and links all of the zones. The catchment is the largest hierarchical unit and comprises all of the components of the river and its tributaries together with the intervening land surface which contributes water and sediment to the channel (Figure 5).

The geomorphological structure of the Sabie River is detailed from the lowest level in the hierarchy (morphologic unit), through channel types and reaches up to the spatial scale of macro-reach

3.1.1.1 Sabie River morphologic unit characteristics

The interaction of bedrock and alluvium along the Sabie River has generated a very varied assemblage of morphological units in the active and macro-channel (Table 4).

Table 4. Character and location of the morphological units found on the Sabie River in the Kruger National Park.

Sediment influence	Location in the channel	
	Macro-channel	Active channel
Bedrock influenced channel	Pavement Bedrock core bar Bedrock backwater	Isolated rock Rapid Bedrock pool Bedrock distributary Cateract Waterfall
Alluvial influenced channel	Terrace Macro-channel lateral bar Anastomosing bar Alluvial backwater Floodplain Island	Lateral bar Point bar Lee bar Alluvial pool Alluvial distributary Riffle/pool Braid bar River cliff Rip-channel Boulder bed Armoured area

A brief description of the principal morphological units identified on the Sabie River follow:

i. **Cataract**

Step-like successions of small waterfalls related to the local geology. The feature represents a major hydraulic control influencing the upstream water surface slope and is seldom drowned out at high discharges.

ii. **Rapid**

Steep bedrock sections representing areas of more resistant lithology where the river has exploited structural weaknesses to create a series of smaller steep channels within the rock.

iii. **Waterfall**

Abrupt vertical discontinuity in channel slope, again the result of bedrock influence where a resistant rock outcrop is slowly being eroded by headward retreat.

iv. **Bedrock pool**

Topographic low area upstream of a bedrock control containing no consolidated or unconsolidated sediment.

v. **Riffle**

Accumulation of coarser sediment as a topographic high point as part of a pool-riffle sequence that may occur between meander inflections in a sinuous channel or approaching the confluence of two distributary channels in a braided system.

vi. **Pool**

Topographic low point characterised by finer sediments, as part of a pool-riffle sequence that may occur at meander inflections in a sinuous channel or downstream of the confluence of two distributary channels in a braided system.

vii. **Braid bar**

Accumulation of unconsolidated sediment in mid-channel causing the flow to diverge over a scale that approximates to the channel width. Characteristically these features are destroyed and reformed with each major flood.

viii. **Lateral bar**

Accumulation of unconsolidated sediment attached to the side of the channel, may occur sequentially downstream as alternate bars. Sediment may be routed through these units , however the unit position remains fixed through time.

ix. **Point bar**

Accumulation of sediment on the inside of a meander bend. Formed as a result of the local flow and sediment transport pattern in a sinuous channel. Sediment may be routed through these units , but the unit position remains fixed through time.

x. **Bedrock core bar**

Accumulation of finer consolidated sediment on top of bedrock in bedrock anastomosing areas. Accumulation occurs as a result of vertical accretion during the falling stage of major floods as suspended sediment is deposited, this process is often aided by the growth of vegetation.

xi. **Lee bar**

Accumulation of unconsolidated sediment in the lee of flow obstructions such as rocks or tree stumps. Sediment may be routed through these units , but the unit position remains fixed through time.

xii. **Bedrock backwater**

Stationary or near stationary bodies of water in bedrock, adjacent to, but isolated from, the active channel. Contains no consolidated or unconsolidated sediment.

xiii.**Alluvial backwater**

Stationary or near stationary bodies of water in alluvium, adjacent to, but isolated from, the active channel.

xiv.**River cliff**

Vertical or near vertical alluvial erosion face. Most characteristically found on the outer bank of the apex of a sinuous bend in an alluvial channel but may occur anywhere there is active erosion of consolidated sedimentary deposits.

xv.**Apical pool**

Deep section of channel located on the outer bend of a meander, associated with point bars.

xvi.**Rip-channel**

High discharge distributary channel on the inside of point and lateral bars. Formed as a result of the river cutting a channel along the shortest downstream route at higher flows.

xvii.**Boulder bed**

Accumulation of locally derived material exceeding 0.25m.

xviii.**Armoured area**

Accumulation of coarser sediments due to winnowing of finer material at intermediate flows.

xix.**Floodplain**

Extensive lateral accumulation of finer sediment as a result of flood deposition by lateral or vertical accretion. The active floodplain is associated with the bankfull flow condition of alluvial channels in stable equilibrium conditions.

xx.**Alluvial distributary**

Individual active channel in an alluvial braided or anastomosing system containing consolidated and/or unconsolidated sediment.

xxi.**Bedrock distributary**

Individual active channel in a bedrock anastomosing system containing no consolidated and/or unconsolidated sediment.

xxii.**Island**

Large mid-channel accumulation of consolidated sediment at a level coincident with any floodplain deposits. These features are inundated less frequently than in-channel bar deposits.

xxiii.**Terrace**

Relic floodplain or valley floor deposits above the present river level representing a former floodplain level prior to downcutting by the river.

3.1.1.2 Sabie River channel type characteristics

The morphological units combine to form the channel types found on the Sabie River in the Kruger National Park. Interpretation of the associations of morphological units from aerial photographic records (1:10000 scale), aerial video footage taken during winter low flow conditions and extensive fieldwork provided the basis for identifying ten channel types present on the Sabie River in the Lowveld (Table 5), of which five were common (bedrock anastomosing, mixed anastomosing, mixed pool-rapid, alluvial single thread and alluvial braided). Gradations between the five primary channel types were observed, creating transition states that could be related to the build-up of sediments (alluvial anastomosing, bedrock single threat, bedrock pool-rapid, mixed single thread and mixed anastomosing). Differentiation between channel types, based on physical appearance and morphological unit composition is detailed in Table 6.

Table 5. Occurrence of channel types observed on the Sabie River in the Lowveld.

Degree of sedimentation	Channel type			
	Anastomosing	Pool-rapid	Single thread	Braided
Bedrock	principal	secondary	secondary	-
Mixed	principal	principal	secondary	secondary
Alluvial	secondary	-	principal	principal
- Channel type does not occur in nature				

The principal channel types are described below:

i Bedrock anastomosing

These channels were first identified on the Sabie River by (van Niekerk and Heritage, 1993) and are dominated by bedrock features (Figure 6, Table 6). Chemical differences in the host rock have generated resistant areas where the rivers less able to erode vertically (Cheshire, 1996). Distributary channels exploit weaknesses along fractures and joints within the bedrock, to create a widely spaced multiple distributary pattern. Typically, the incised macro-channel is widened to extend across an area three to four times the average width of the river and this effect may extend over several kilometres, but is variable as the size of the feature is a function of the local geology. Numerous steep gradient active channel bedrock distributaries exist within the incised channel, describing a tortuous route over the resistant rock. Such channels have a fixed planform as defined by the weaker pathways through the resistant outcrop (Cheshire, 1996). These distributaries display very few alluvial features within their bedrock channels. Bedrock features include pools, rapids, cataracts and small waterfalls, with sediment accumulation being restricted to lee bar deposits downstream of bedrock obstructions, armoured clastic lags and fine deposits in low energy areas.

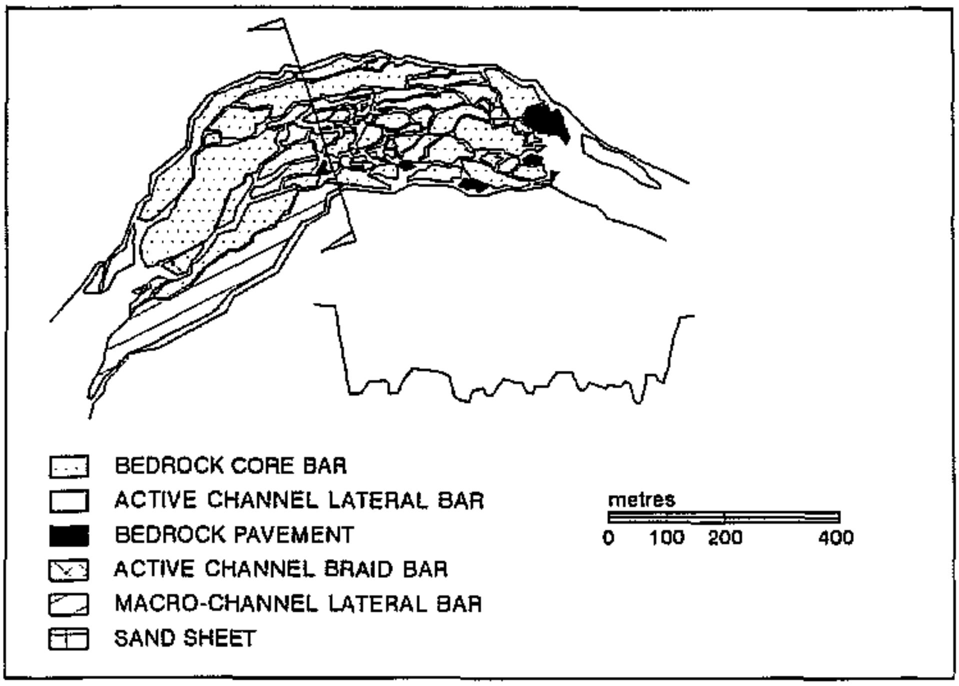

Figure 6. Characteristic geomorphology, planform and cross-sectional form of a bedrock anastomosing channel type in the Sabie River (after Heritage *et al.*, in press).

Distributaries at different elevations may be active at the same flow as there is almost no lateral water table and flow is a function of upstream conditions. Elevated bedrock areas are common and may exist as exposed bedrock pavements and as areas of limited sediment build up termed bedrock core bars (van Niekerk *et al.*, 1995). These bedrock core bars are characterised by an accumulation of basal sands overlain by finer sediments on top of bedrock areas above the active distributaries. They probably result from early deposition of sands transported out of these channels during moderate flood events and fine sediments during waning flows. The process of sedimentation is aided by the growth of *Breonadia salicina*, a riparian tree that germinates in bedrock cracks and reed growth. Fines may be deposited from suspension as the river rapidly loses energy when it floods across the over-wide incised macro-channel and the bars grow through a process of vertical aggradation.

ii Mixed pool-rapid

This channel type is also dominated by bedrock features (Figure 7, Table 6), created by differential resistance to fluvial erosion on the Sabie River. Detailed field investigation of the geological controls has revealed a number of reasons for this, including localised chemical differences similar to the bedrock anastomosing situation and differing lithologies (Cheshire, 1996). Similar findings concerning geological control on the geomorphology of a bedrock influenced river comes from the study of the Burdekin Gorge, Australia, where lithological variation was found to be responsible for small scale erosional features (Wohl, 1992). These factors create pool-rapid sequences within the active channel, the scale of which is dependent on local geological variability and channel gradient. Typically, the rapids are free of sediment apart from occasional boulders and small scale bedrock core bars. The pool areas are more variable, ranging from sediment free bedrock areas to sediment lined pools, incorporating a variety of bar types. Aerial photographic evidence dating back to the, 1940s indicates that the pools are highly susceptible to sedimentation as flow energy is rapidly reduced in the backwaters of the bedrock rapids.

The active pool-rapid channels typically occupy only a portion of the macro-channel. Large scale sedimentary features associated with infrequent high magnitude flows have covered much of the bedrock across the rest of the incised channel.

iii Alluvial single thread

This channel system is analogous to both the straight and meandering channel types of (Leopold and Wolman, 1957). Essentially no differentiation is made regarding channel sinuosity due to the somewhat arbitrary nature of the definitions. Single threat channels have developed in alluvial sections of the Sabie River, where the freedom to make planform adjustments is restricted to the width of the incised macro-channel (Figure 8, Table 6). Typically, these channel types contain a considerable range of the features noted in temperate alluvial single thread channels.

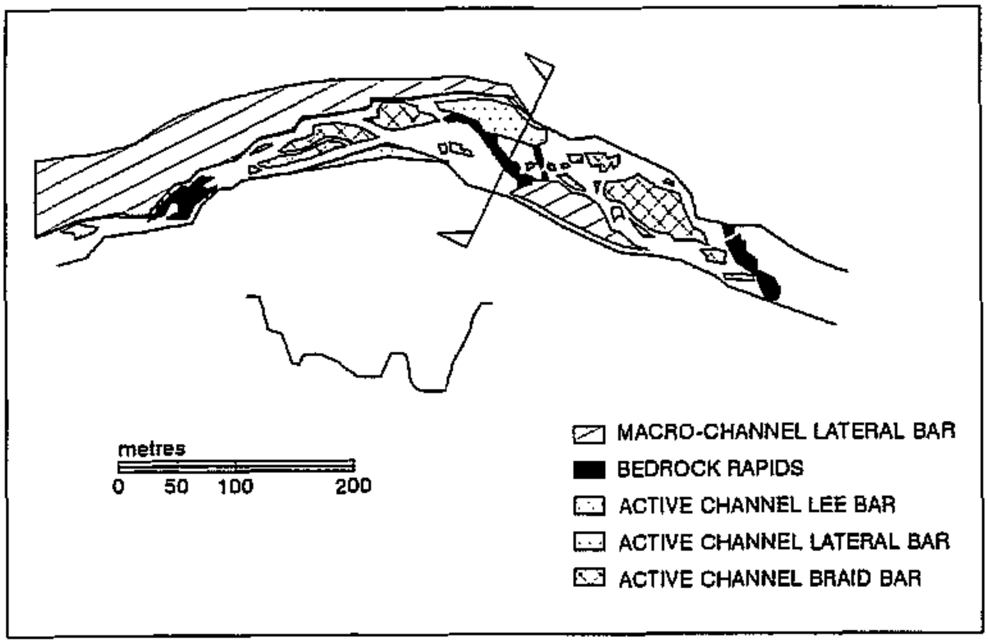

Figure 7. Characteristic geomorphology, planform and cross-sectional form of a bedrock pool-rapid channel type in the Sabie River (after Heritage *et al.*, in press).

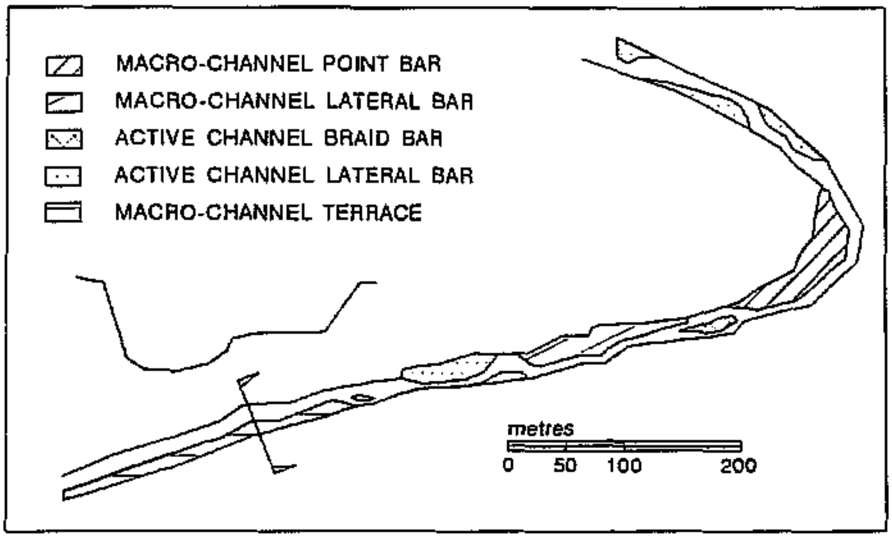

Figure 8. Characteristic geomorphology, planform and cross-sectional form of an alluvial single thread channel type in the Sabie River (after Heritage *et al.*, in press).

iv Alluvial braided

These channels are defined as alluvial systems that exhibit channel splitting and rejoining over a distance of a few distributary widths. The geomorphological features present largely consist of ephemeral deposits of sediment (Reading, 1986). Problems exist with defining the number of active braid channels, as this varies with discharge (Rust, 1978). Winter low flow aerial photographic records were used in this study and this flow level formed the basis of our discrimination. The degree of braiding in the Sabie River, as defined by the number of braid channels, is low and appears restricted to the deposition of mid-channel and lateral bars within the active channel, the banks of which are well protected by vegetative cover (Figure 9, Table 6).

Geomorphological diversity is lower than for those channel types directly influenced by bedrock. There is a significant reduction in the frequency of bedrock features, these being restricted to a small area of reduced rapids. Alluvium was present over bedrock in the form of bedrock core bars and in the active channel as mid-channel and lateral deposits; all pools showed some degree of alluviation. The macro-channel areas were dominated by lateral alluvial features with only very rare outcrops of bedrock.

v Mixed anastomosing

The mixed anastomosing channel types are sections of the macro-channel displaying multiple bedrock and occasional alluvial distributary channels that divide and rejoin over a distance much greater than the distributary width. The planform of the active channels appears to be relatively stable , with the river largely reverting to its old course following floods greater than the capacity of the active channels. This stabilisation is aided by the reduction in winter base flow variation during dry cycles and the consequent growth of vegetation adjacent to the active channels (Figure 10, Table 6). Extensive reed growth (*Phragmites mauritanus*) between the active distributaries increases channel resistance during flows higher than the capacity of the distributary channels and promotes bar growth by the vertical accretion of sediment.

vi Other channel types

Variability between sediment transport competence and sediment delivery determines the relative dominance of bedrock and sedimentary features. This factor is emphasised on the Sabie River by the incised nature of the macro-channel, confining all flows and deposits within its bounds, and the variable nature of the flow regime. Large infrequent flows can scour deposits in some areas and deposit sediments in others. Intermediate floods may redistribute sediments and perennial flows may further rework active channel deposits. Thus, bedrock dominated channel types may display areas of sedimentary influence giving the channel a 'mixed' bedrock-alluvial appearance (Table 6). It is such transition states that link to form the continuum of channel form between bedrock and alluvial systems.

Examples of these less common or less well defined channel types observed on the Sabie River in the Kruger National Park include alluvial anastomosing, which represents the final alluvial stage of bedrock anastomosing evolution; bedrock pool-rapid, which represents the initial state in the sequence through mixed pool-rapid to mixed single thread/mixed braided and finally alluvial single thread/alluvial braided (Table 5).

Having identified that there are 5 principal channel types on the Sabie River the 120km of channel in the Kruger National Park was zoned (Figure 11) and a single example of each type was chosen to form the 'representative reaches' for the river in the Kruger National Park.

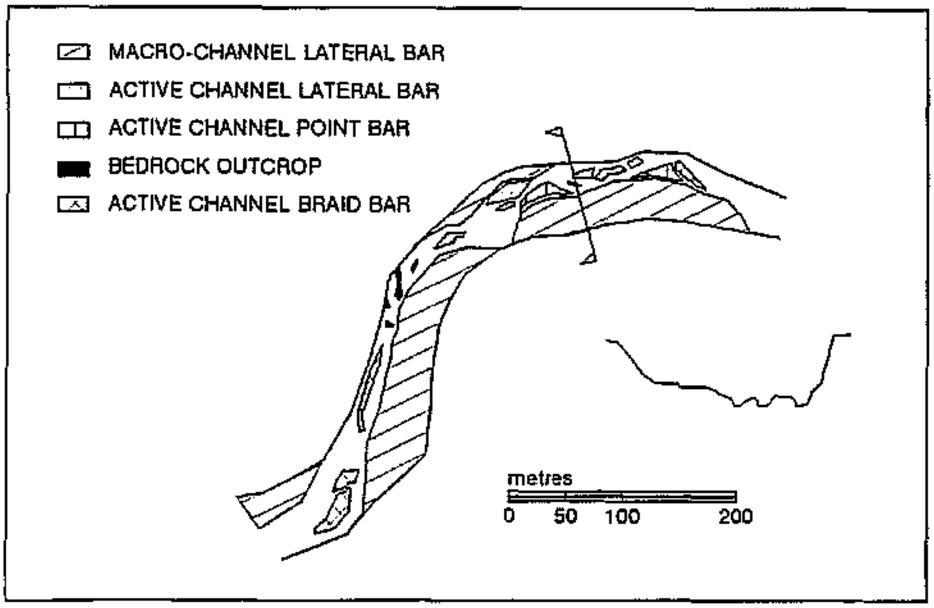

Figure 9. Characteristic geomorphology, planform and cross-sectional form of a braided channel type in the Sabie River (after Heritage *et al.*, in press).

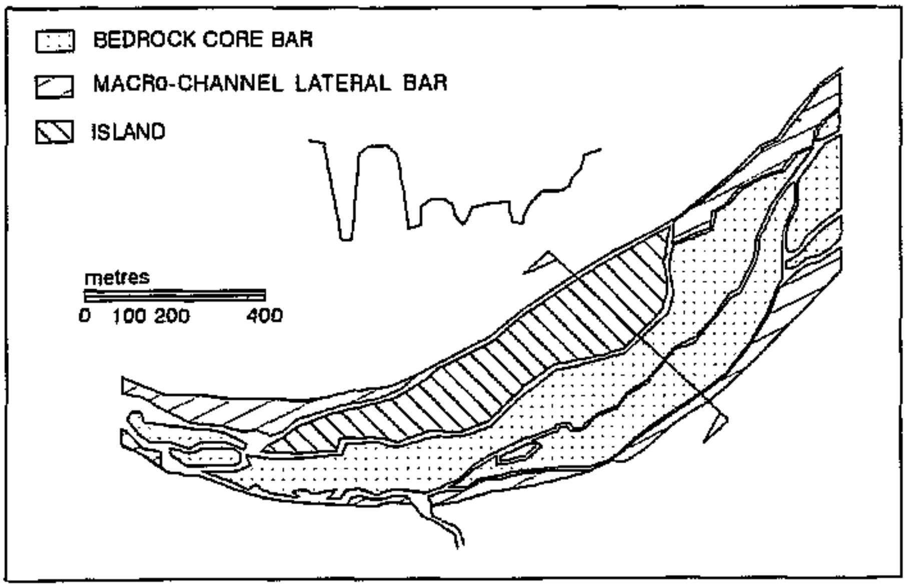

Figure 10. Characteristic geomorphology, planform and cross-sectional form of a mixed anastomosing channel type in the Sabie River (after Heritage *et al.*, in press).

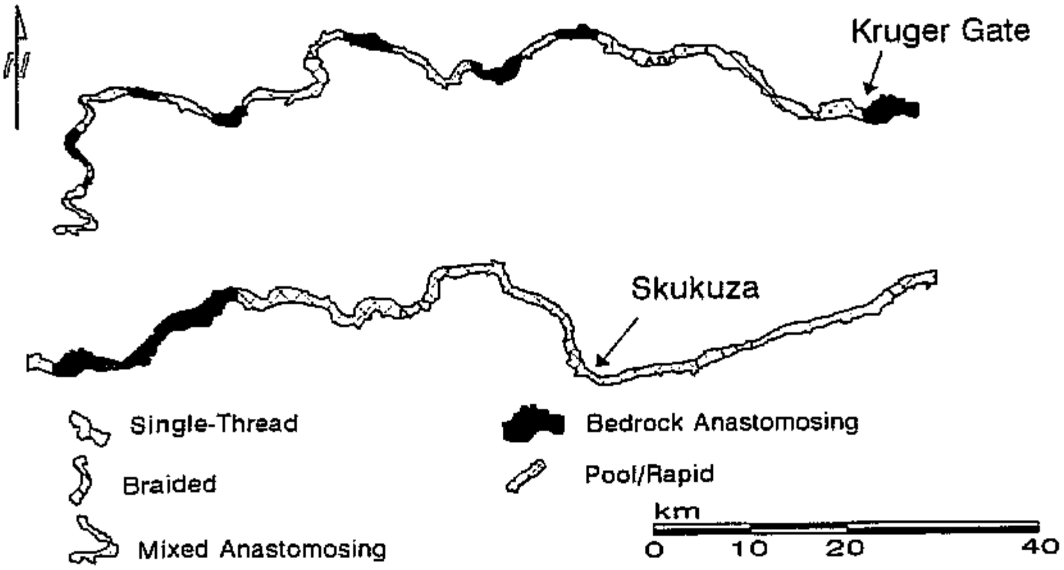

Figure 11a. Channel types along the Sabie River (western boundary of the KNP to Skukuza).

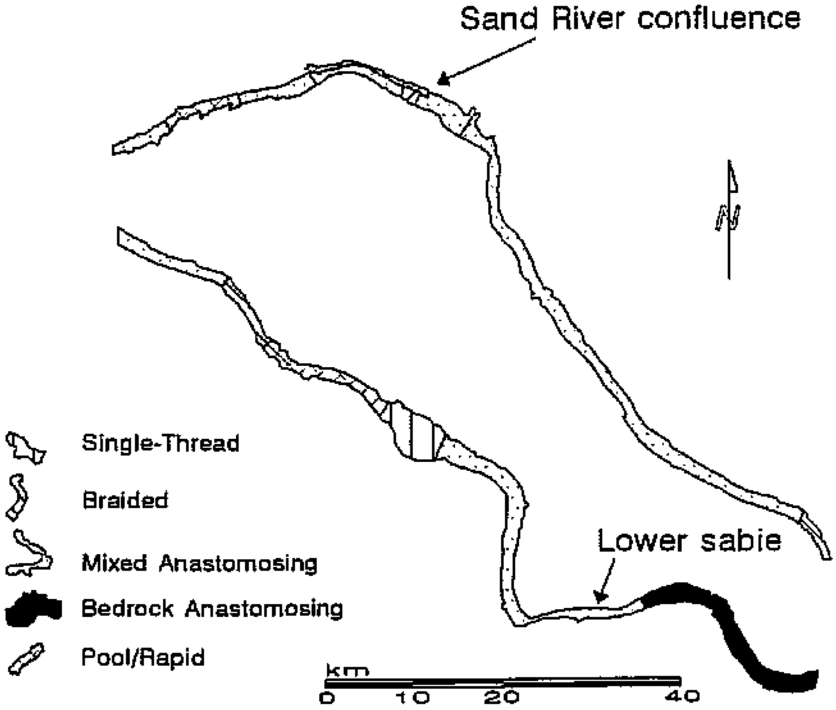

Figure 11b. Channel types along the Sabie River (Skukuza to Lower Sabie restcamp).

Table 6. Morphological composition of the primary channel types found on the Sabie River in the Kruger National Park (after van Niekerk *et al.*, 1995).

Channel Type	Description	Morphological Units
Alluvial single thread	Uniform single channel river. Limited bedrock outcrops or braid bars associated with active channel. May be bedrock or alluvial.	Lateral bar (1), Pool (1), Rock pool (1), River cliff (2), Apical pool (2), Point bar (2), Rip channel (2), Riffle (2), Rapid (2), Floodplain (2), Terrace (2).
Alluvial braided	Multi-channel system with impermanent distributaries in alluvium. Channel convergence and divergence occurs on the scale of channel width.	Braid bar (1), Alluvial distributary (1), Lateral bar (1), Point bar (2), Rip channel (2), Cutoff channel (2), Armoured area (2), Floodplain (2), Terrace (2), Alluvial backwater (3), River cliff (3), Levee (3), Apical pool (3).
Mixed anastomosing	Multi-channel system of distributaries in bedrock and alluvium	Rock pool (1), Rapid (1), Alluvial pool (1), Bedrock core bar (1), Rock distributary (1), Alluvial distributary (1), Cataract (2), Waterfall (2), Boulder bed (2), Armoured area (2), Lee bar (2), Rock backwater (2), Alluvial backwater (2) alluvial bars (2).
Bedrock anastomosing	Multi-channel system of permanent bedrock distributaries. Sediment may accumulate on topographic highs.	Rock pool (1), Rapid (1), Bedrock core bar (1), Cataract (1), Waterfall (1), Rock distributary (1), Boulder bed (2), Armoured area (2), Lee bar (2), Rock backwater (2).
Mixed pool-rapid	System of shallow faster steeper bedrock dominated rapids and associated upstream backwater pools.	Rock pool (1), Rapid (1), Bedrock core bar (2), Lateral bar (2), Lee bar (2), Cataract (2), Boulder bed (2), Armoured area (2), Floodplain (2), Rock distributary (2), Terrace (2), Rock backwater (2), Braid bar (3), Pool (3), Riffle (3) Alluvial distributary (3),.
(1) = Definite occurrence, (2) = Probable occurrence, (3) = Rare occurrence		

3.1.1.3 Reaches of the Sabie River

At the next level in the geomorphological hierarchy (figure 5) are associations of channel types known as reaches. Reaches (Figure 12) are classified based on functional relationships between channel types where one channel type can affect the type of channel occurring up or downstream from it due to its influence on the local flow and sediment dynamics. For example, braided and bedrock anastomosing sections are seen to alternate as sediment builds up behind the bedrock barriers. Such relationships have also been described for bedrock influenced rivers by (Howard, 1987). The reaches may be straight or sinuous, depending on the macro-channel plan-form. Twenty two reaches have been identified on the Sabie River in the Lowveld (van Niekerk and Heritage, 1993).

Straight reaches of the incised macro-channel of the Sabie River are common and can be longitudinally extensive (up to 10km). Large scale lateral bars covering up to half of the macro-channel are common. Braided, pool-rapid, single thread and bedrock anastomosing channel types may be present. Straight reaches follow major lineaments in the bedrock. Most sinuous macro-channel reaches along the Sabie River appear to be controlled by the bedrock lithology and structure rather than being antecedent meanders. Notable exceptions are the reaches downstream of Lower Sabie in which large scale, regular bends appear to be the result of river incision along an ancient meander pattern. Both sinuous and straight reaches have been observed to contain both sinuous and straight channels of all types. This results from the development of large scale macro-channel depositional features whose formation and development are a function of high magnitude flows.

3.1.1.4 Macro-reaches and zones of the Sabie River

A macro-reach (Figure 13) may consist of one or more reaches. Nine macro-reaches have been identified on the Sabie River in the Lowveld (van Niekerk and Heritage, 1993) based on the geomorphology, geology, hydrology, macro-channel gradient and width, and vegetation. Macro-reaches in this classification correspond to the reaches defined by (Wadeson and Rountree, 1995). The definition of zones was based on relief and geology. The delineation of different zones from a process point of view could be enhanced through more precise definition of their boundaries by the incorporation of the (Wadeson and Rountree, 1995) concept of zones which are homogeneous with respect of flood runoff and sediment production. Such an exercise was not attempted here, as the need for improvement on the delineation of the hierarchy at this level was not justifiable given that the scales of representative reach characterisation and prediction of geomorphological change were at finer levels. Full reach and macro-reach descriptions for the Sabie River in the Lowveld are given in (van Niekerk and Heritage, 1993).

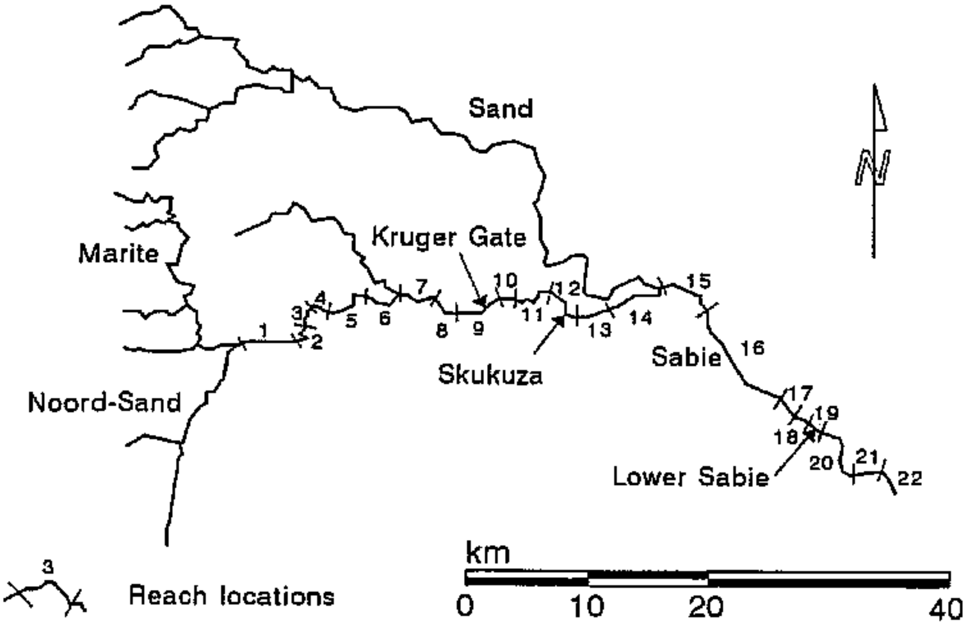

Figure 12. Reaches identified for the Sabie River in the Kruger National Park.

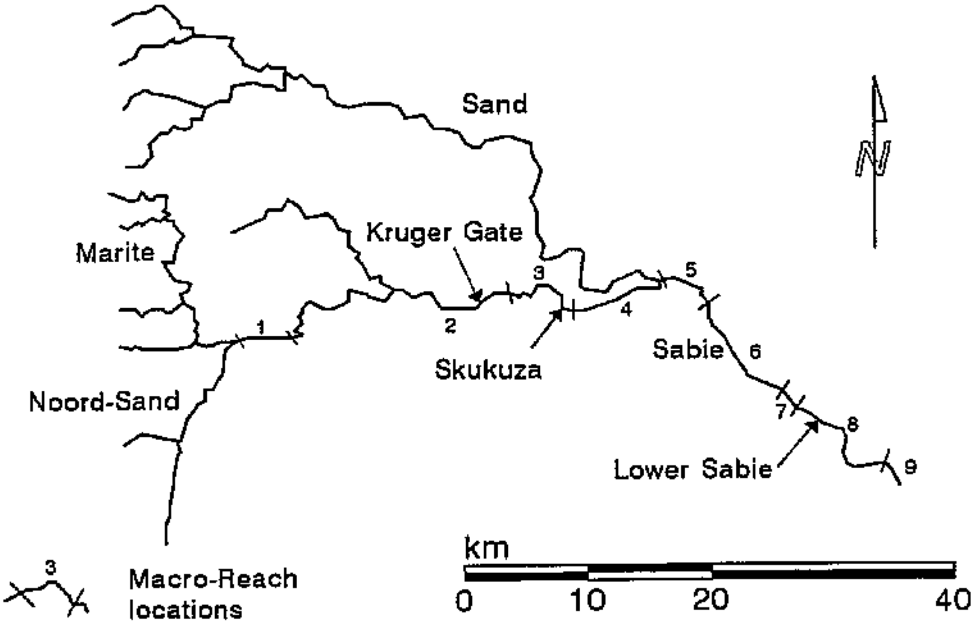

Figure 13. Macro-reaches identified for the Sabie River in the Kruger National Park.

3.1.2 Comparison of the proposed representative reach classification and a statistical analysis of the Sabie River geomorphology.

Cluster analysis was used to determine the robustness of the 10 unit channel type breakdown and the 5 unit representative reach categorisation proposed for the Sabie River was tested on a data set derived from the geomorphological mapping of 25km of the river in the Lowveld (5km bedrock anastomosing, 6.5km pool-rapid, 8km mixed anastomosing, 1km single-thread and 4.5km braided). Aerial photographs of the Sabie in, 1986 (0.75m^2 plates at 1:10,000 scale) were digitised, mapping the aerial extent of features at the level of morphologic unit. The following units were identified:

i. Alluvial backwater
ii. Bedrock backwater
iii. Alluvial pool
iv. Bedrock pool
v. Mixed pool
vi. Braid bar
vii. Active channel lateral bar
viii. Active channel point bar
ix. Active channel lee bar
x. Bedrock core bar
xi. Bedrock pavement
xii. Erosional bench
xiii. Island
xiv. Macro-channel lateral bar
xv. Macro-channel point bar
xvi. Macro-channel lee bar
xvii. Rapid
xviii. Alluvial distributary
xix. Bedrock distributary
xx. Mixed distributary
xxi. Terrestrial rock outcrop
xxii. Levee
xxiii. Rip-channel
xxiv. Other consolidated macro-channel deposits

The mapped data were divided into 250m long sub-reaches and given a channel type classification based on the representative reach characteristics detailed in Table 6. A k-means cluster analysis was conducted on the data, followed by a discriminant analysis to determine the strength of the clustering. Twelve robust clusters emerged (Table 7).

Table 7. Summary of the sub-area cluster analysis results for the Sabie River, (figures indicate the number of sub-reaches in each cluster belonging to each channel type).

cluster	Bed An	Pool-rap	Mix An	Braided	Single thread	Intermediate	Total
1	4	20	9	2			35
2	1		7				8
3	3						3
4	10	2					12
5	3						3
6	1	9	6	1		1	18
7		3					3
8	4						4
9	5						5
10						1	1
11						1	1
12	1	9		31	3	4	47

The results of the cluster analysis does show that each cluster is dominated by a certain channel type, they can be characterised as follows:

Cluster 1:
Characterised by the presence of major bedrock dominated features especially distributary channels, the majority of the cluster (15 of 35 250m sub-reaches) is of examples of pool-rapid channel type with bedrock anastomosing examples occurring on the periphery of the cluster. Two braided channel types are included, these have unusually high areas of exposed bedrock and can possibly be reclassified as transitional.

Overall: Pool-rapid.

Cluster 2:
Characterised by dry alluvial distributaries, this cluster consists entirely of examples of the mixed anastomosing channel type.

Overall: Mixed Anastomosing.

Cluster 3:
Characterised by bedrock anastomosing distributary channels, all 3 members of this cluster were classified as bedrock anastomosing.

Overall: Bedrock anastomosing.

Cluster 4:
This cluster is characterised by considerable deposits of macro-channel sediment and multiple distributary channels. Ten of the 12 members of the cluster are bedrock anastomosing channels with two pool-rapid examples.

Overall: Bedrock Anastomosing.

Cluster 5:
This small cluster (3 members) consists entirely of bedrock anastomosing channel types and is characterised by a preponderance of bedrock pools.

Overall: Bedrock Anastomosing.

Cluster 6:
This 17 member cluster largely comprise pool-rapid channel types and is characterised by the presence of erosional benches.

Overall: Pool-rapid.

Cluster 7:
A small (3 member) cluster with no distinct channel type.

Overall: Pool-rapid.

Cluster 8:
Bedrock dominated cluster of 4 members characterised by bedrock distributaries and bedrock pavement.

Overall: Bedrock Anastomosing.

Cluster 9:
Bedrock dominated cluster of 5 members characterised by bedrock pavement.

Overall: Bedrock Anastomosing.

Clusters 10 and 11:
Single member clusters probably influenced in the analysis by the dominance of an island in each 250m sub-reach. As no overall channel type could be attributed to these clusters.

Cluster 12:
Large cluster (47 members) characterised by unconsolidated bar deposits (point bars, lateral bars, braided bars). This cluster contains the majority of the alluvial channel types, particularly the braided areas, the single thread channels associated closely towards the centre of this cluster. Occasional pool-rapid channels are present (8 of 47 members) which have larger than normal quantities of deposited sediment and may be transitional.

Overall: Braided single-thread.

Each cluster was investigated at the level of morphological unit in order to determine the features that generated association between sub-units. A significant positive difference between the mean significance value for each morphological unit in each of the clusters with the whole river mean significance value indicates the importance of a morphological feature in determining the sub-unit clusters (Table 8). The following features were significant:

Cluster 1: **Pool-rapid**
Consolidated macro-channel alluvial deposits and macro-channel distributary channels were significant in causing these 35 sub-units to cluster.

Cluster 2: **Mixed anastomosing**
Bedrock backwaters, bedrock pavement, bedrock pools, terrestrial rock outcrops, bedrock distributaries and macro-channel alluvial deposits characterised this assemblage of alluviated anastomosing channel types.

Cluster 3: **Bedrock anastomosing**
Bedrock core bars, macro-channel lateral bars and significant mid-channel islands were important in the characterisation of this cluster.

Cluster 4: **Bedrock anastomosing**
Macro-channel alluvial deposits, particularly lee bars behind bedrock obstructions and distributary channels characterise this cluster.

Cluster 5: **Bedrock anastomosing**
Bedrock distributaries and associated bedrock pools and rapids were the most significant morphological variables in this cluster, with bedrock core bars, macro-channel alluvial deposits and islands also having some influence.

Cluster 6: **Pool-rapid**
This cluster was characterised by the presence of an erosional bench and unconsolidated lee bar deposits.

Cluster 7: **Pool-rapid**
This more alluvial cluster is characterised by unconsolidated sediment in the form of active channel braid bars, alluvial pools, macro-channel point bars and overbank levee deposits.

Cluster 8: **Bedrock anastomosing**
This cluster is characterised by bedrock distributaries and bedrock core bar deposits.

Cluster 9: **Bedrock anastomosing**
This cluster is characterised by bedrock pavement.

Cluster 10 and 11: **No overall channel type**
The presence of a large island significantly influenced these clusters and precluded sensible definition of the overall channel type.

Cluster 12: **Braided single-thread**
This final cluster is characterised by unconsolidated braid bars, lateral bars, point bars and associated rip channels, alluvial distributaries and alluvial pools.

From this data a comparison can be made with the morphological assemblage of the representative reach channel types as determined through observation (Table 6). Often the significant morphologic variables coincide (Table 9) indicating that the observational technique can be used with confidence when categorising a river system.

Table 8. Significant morphologic variables determining cluster patterns for the Sabie River. Values represent the division of the cluster mean by the overall mean for each morphologic unit, (shading indicates important variable, bold indicates very important variable).

Morphologic unit	SAS clusters											
	cluster 1 n= 10	cluster 2	cluster 3	cluster 4	cluster 5	cluster 6	cluster 7	cluster 8	cluster 9	cluster 10	cluster 11	cluster 12
Alluvial Backwater	0.93	10.99	0.77	8.76	-7.30	-2.14	-4.39	-2.35	-0.72	7.30	**83.70**	-4.84
Alluvial Pool	-44.03	-132.64	-170.51	-181.76	-352.51	-263.68	**116.49**	-321.94	-176.27	-352.51	-284.31	**282.40**
Braid Bar	-50.07	-74.86	-62.77	-64.03	-77.35	-35.87	**174.90**	-74.72	-48.85	-73.38	-51.64	90.19
Bedrock Backwater	-44.12	**144.75**	-27.88	-19.23	-8.58	-6.61	-51.08	-8.07	-51.08	-37.28	-51.08	28.64
Bedrock Core Bar	-323.87	87.53	**4940.61**	1772.03	1293.94	-266.78	-600.70	2082.28	516.88	-395.72	19.28	-693.04
Bedrock Pavement	-21.08	**244.50**	-30.27	-11.86	74.86	-25.33	-30.27	71.33	113.13	-30.27	-30.27	-30.27
Bedrock Pool	-11.04	**71.20**	-18.37	-12.49	**78.43**	23.91	-18.37	19.58	47.45	-4.47	-18.37	-18.37
Erosional Bench	-6.37	-15.31	-15.31	-15.31	-15.31	**66.35**	-15.31	-15.31	-15.31	-15.31	-15.31	-7.48
Island	-214.62	-519.32	2101.22	1556.05	2262.55	-375.78	-559.35	1395.05	647.35	2272.55	**2902.55**	-534.32
Lateral Bar	-40.21	-121.60	15.23	-80.10	-86.60	3.34	3.40	-120.79	-75.79	10.40	**208.40**	86.01
Active Channel Lee bar	-0.22	-2.12	-2.12	-0.94	-2.12	**4.53**	-2.12	-1.40	-2.12	-2.12	-2.12	-0.13
Macro Channel Bank	-32.23	255.84	-134.58	-11.83	1938.75	410.59	105.42	592.09	-147.91	-447.91	952.09	-348.94
Macro Channel Lateral Bar	-202.57	-259.73	**3499.44**	-84.56	-820.90	932.49	-736.23	1037.77	693.17	**3722.77**	1452.77	-525.45
Macro Channel Point Bar	24.54	-232.70	-232.70	-227.49	-232.70	136.52	**407.30**	-232.70	-173.50	-232.70	-232.70	77.36
Active Channel Point Bar	-19.33	-19.33	-19.33	-19.33	-19.33	-18.81	-19.33	-19.33	-19.16	-19.33	-19.33	37.24
Water Area of Rapids	12.03	-10.49	38.73	13.57	**215.40**	14.30	14.23	38.64	-2.52	25.16	**194.06**	-40.08
Terrestrial Rock Outcrop	-97.32	**2761.83**	-236.59	-41.32	**2337.04**	-254.39	-367.49	2. 83	53.18	-11.42	-413.42	-388.85

Table 8 (cont.). Significant morphologic variables determining cluster patterns for the Sabie River. Values represent the division of the cluster mean by the overall mean for each morphologic unit, (shading indicates important variable, bold indicates very important variable).

	SAS clusters											
Morphologic unit	cluster 1	cluster 2	cluster 3	cluster 4	cluster 5	cluster 6	cluster 7	cluster 8	cluster 9	cluster 10	cluster 11	cluster 12
	n= 10											
Mac Chan Alluv Dep	388.74	**4096.40**	-1179.63	**1395.65**	**1217.07**	-516.36	-1079.93	-830.60	-1201.72	-478.60	-780.60	-835.68
Act Chan Alluv Dep	-0.21	-6.55	-4.22	-6.55	42.11	-6.55	-6.55	-5.10	25.71	**173.45**	-6.55	-2.35
Mixed Pool	0.42	140.00	67.07	160.26	379.40	237.52	-213.23	24.57	57.07	**417.07**	51.07	-185.09
Macro Channel Lee Bar	9.98	-5.85	-5.85	**16.69**	-5.85	-5.85	-5.85	-5.85	-5.85	-5.85	-5.85	-5.85
Alluvial Distributary	-15.12	-27.96	2.96	-10.09	-27.96	-23.27	17.93	-27.96	-3.32	-19.59	-8.69	**30.64**
Bedrock Distributary	-25.38	**111.78**	-20.66	-33.77	**403.25**	-33.77	-33.77	244.15	73.51	113.71	123.92	-33.77
Ephemeral Distributary	-0.82	**96.88**	38.20	**70.59**	5.28	-20.70	-28.82	7.98	-21.16	15.62	9.71	-24.93
Levee	-286.04	-286.66	-286.66	-286.66	-286.66	-286.66	**9713.34**	-281.32	-278.68	-286.66	**9713.34**	-285.63
Macro Channel Distrib	**0.71**	-0.78	-0.78	-0.78	-0.78	-0.78	-0.78	-0.78	-0.78	-0.78	-0.78	0.42
Mixed Distributary	8.16	-45.09	235.48	77.54	-29.06	88.12	-14.77	-51.31	-40.50	**168.24**	-59.35	-56.62
Rip Channel	-0.26	-0.58	-0.58	-0.58	-0.58	-0.58	-0.58	-0.58	-0.58	-0.58	-0.58	**0.89**

SAS Institute (2000), SAS, Cary, NC, USA

Table 9. Comparison of the observational and statistical morphological composition of the primary channel types found on the Sabie River in the Kruger National Park, bracketed values relate to the observational characterisation, bold units indicate agreement between the observational classification and the statistical analysis.

Channel Type	Morphological Units
Alluvial single thread	**Lateral bar** (1), **Pool** (1), River cliff (2), **Apical pool** (2), **Point bar** (2), **Rip channel** (2), Riffle (2), Floodplain (2), Terrace (2).
Alluvial braided	**Braid bar** (1), **Alluvial distributary** (1), **Lateral bar** (1), **Point bar** (2), **Rip channel** (2), Cutoff channel (2), Armoured area (2), Floodplain (2), Terrace (2), Alluvial backwater (3), River cliff (3), Levee (3), **Apical pool** (3).
Mixed anastomosing	Rock pool (1), Rapid (1), Alluvial pool (1), **Bedrock core bar** (1), **Rock distributary** (1), **Alluvial distributary** (1), Cataract (2), Waterfall (2), Boulder bed (2), Armoured area (2), Lee bar (2), Rock backwater (2), Alluvial backwater (2) alluvial bars (2), **island** (2).
Bedrock anastomosing	**Rock pool** (1), **Rapid** (1), **Bedrock core bar** (1), Cataract (1), Waterfall (1), **Rock distributary** (1), Boulder bed (2), Armoured area (2), Lee bar (2), **Rock backwater** (2).
Pool-rapid	Rock pool (1), Rapid (1), Bedrock core bar (2), Lateral bar (2), **Lee bar** (2), Cataract (2), Boulder bed (2), Armoured area (2), Floodplain (2), Rock distributary (2), Terrace (2), Rock backwater (2), **Braid bar** (3), **Pool** (3), Riffle (3) Alluvial distributary (3),.

(1) = Definite occurrence, (2) = Probable occurrence, (3) = Rare occurrence

Overall the clusters reflect the observational bottom up classification and selection of representative reaches proposed earlier. The independent statistical analysis reveals the presence of all five principal channel types, together with evidence of channel types that form the transitional states between each of these to form the continuum of channels that exists on the river.

3.1.3 Representative reach selection on the Sabie River

Given that the 5 unit breakdown of the Sabie River has been shown to be statistically robust, an example of each can be chosen as 'representative' of all of the other similarly classified channel types along the river in the Kruger National Park. Five reaches of the Sabie River were chosen to 'represent' the primary channel types found on the Sabie River within the Kruger National Park boundaries based on their geomorphological composition (Figure 11). The channel types covered were: bedrock anastomosing, braided, single thread, pool-rapid and mixed anastomosing. The locations for these cross-sections within the representative reaches are shown on Figures 14 to, 19.

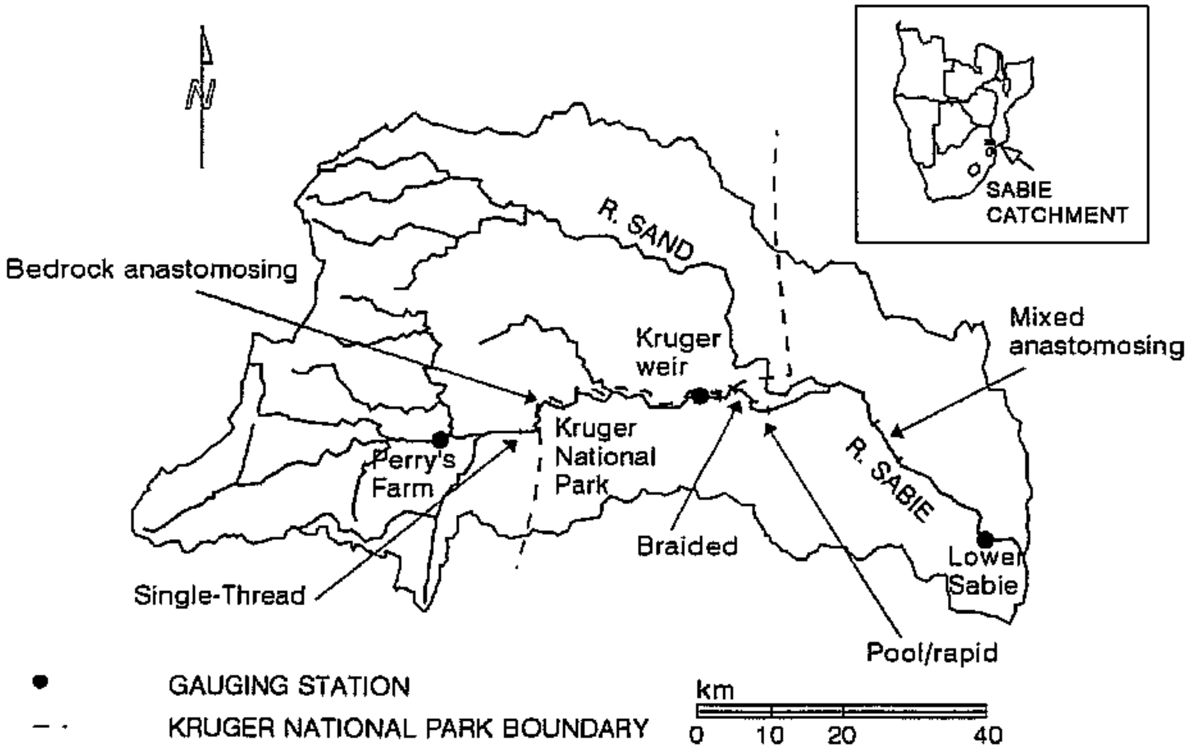

Figure 14. Location of the representative reaches of different channel types on the Sabie River in the Lowveld

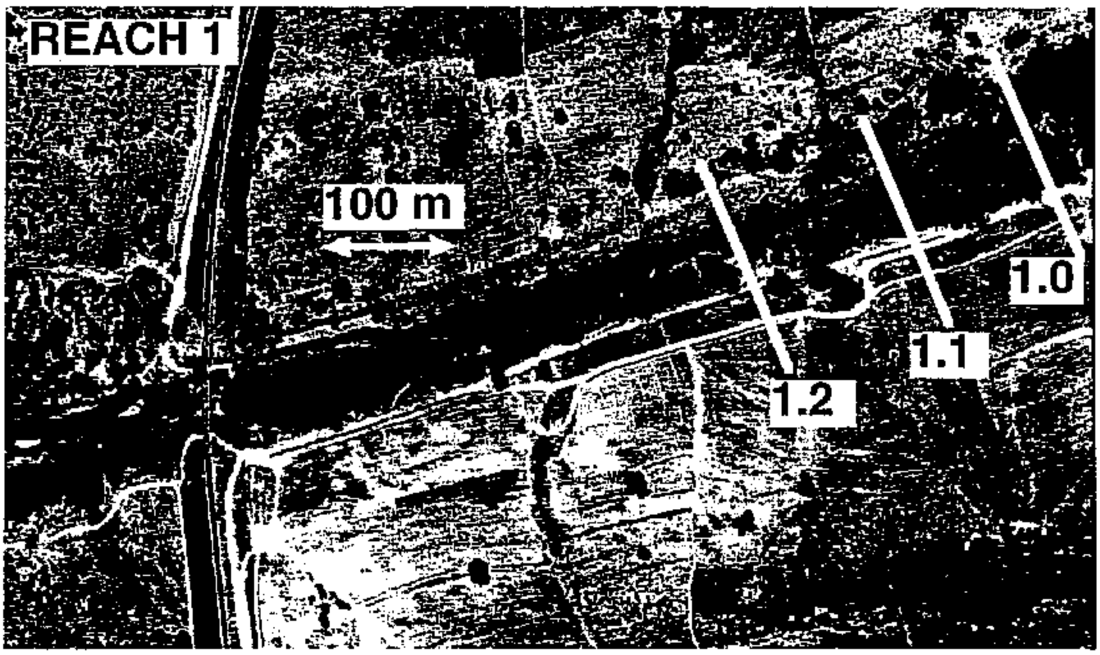

Figure 15. Plan view of reach 1, a single thread channel type, showing cross section locations (numbered). Sections upstream of 1.0 are not represented in the aerial photographic record. The flow direction is from right to left (after Broadhurst *et al.*, 1996).

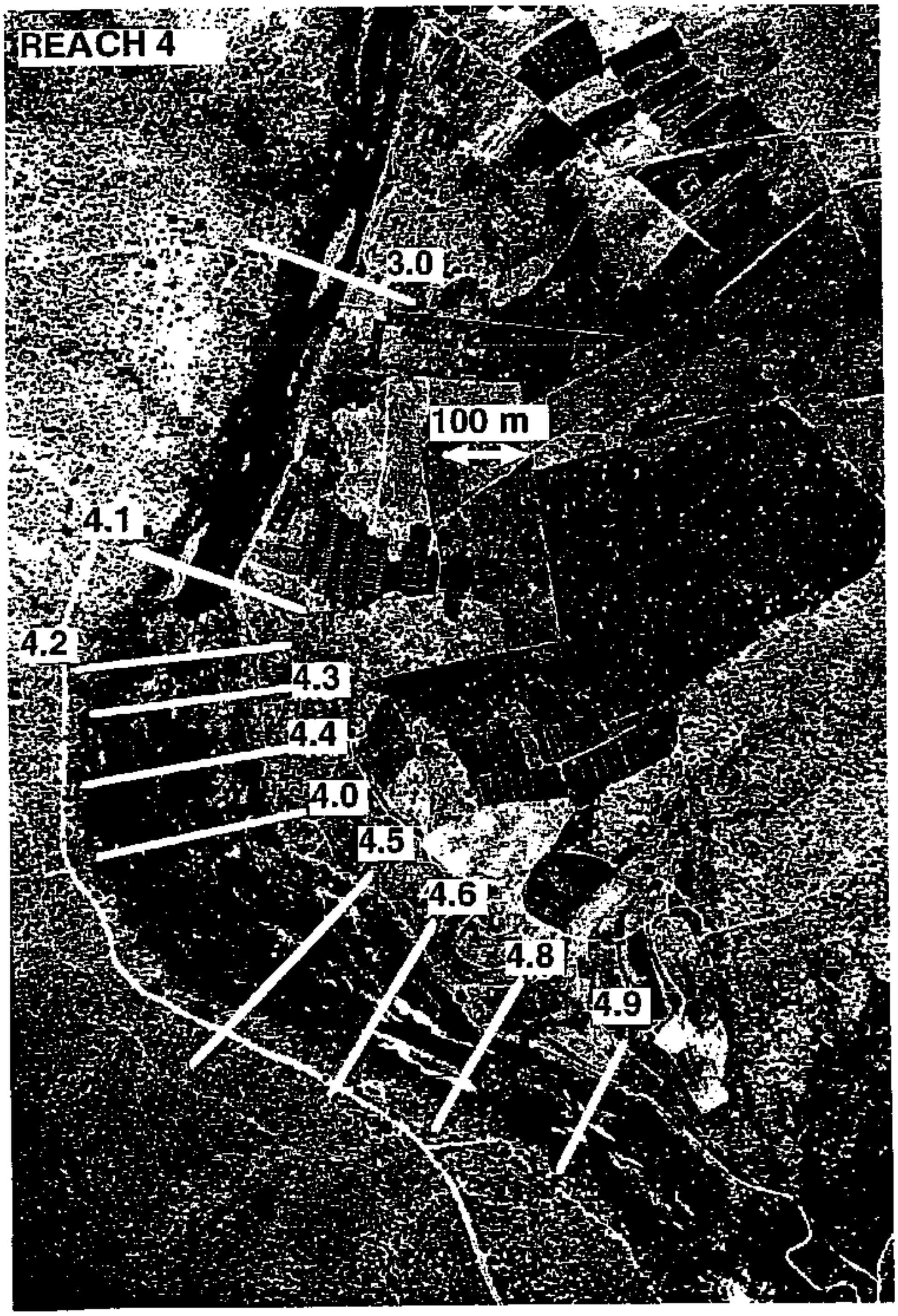

Figure 16. Plan view of reach 4, a bedrock anastomosing channel type, showing cross section locations (numbered). Flow direction is from top to bottom (after Broadhurst *et al.*, 1996).

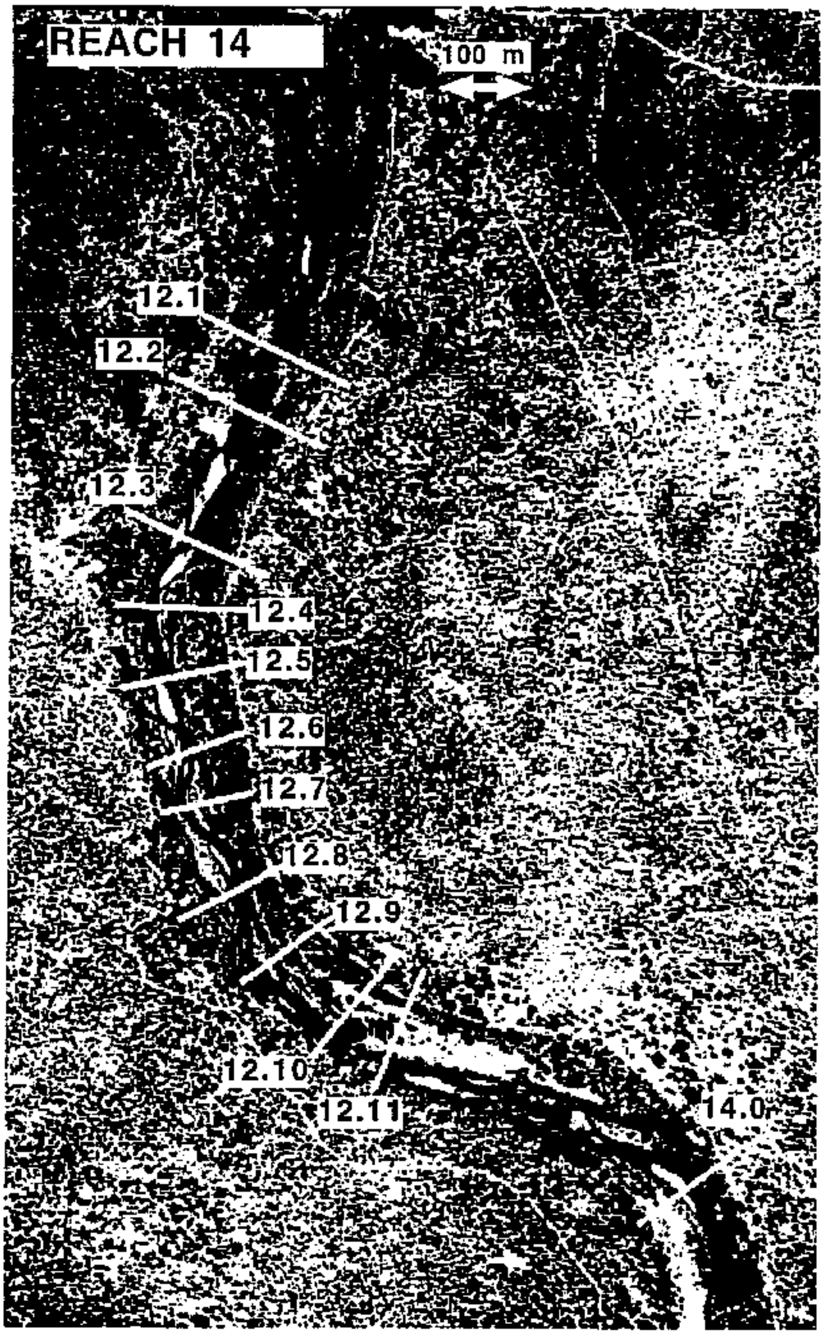

Figure 17. Plan view of reach 14, a braided channel type, showing cross section locations (numbered). Flow direction is from top to bottom (after Broadhurst *et al.*, 1996).

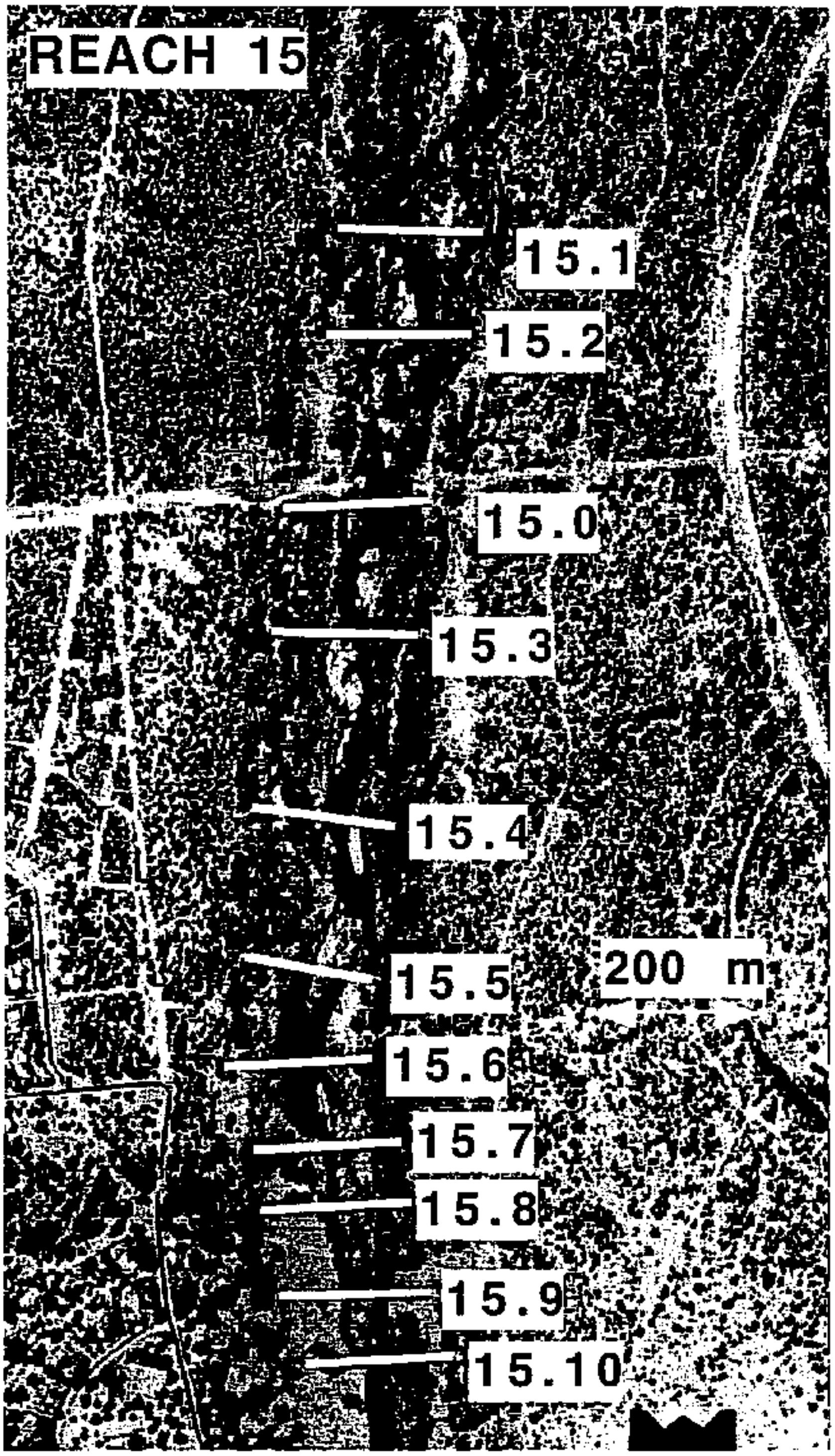

Figure 18. Plan view of reach 15, a pool-rapid channel type, showing cross section locations (numbered). Flow direction is from top to bottom (after Broadhurst *et al.*, 1996).

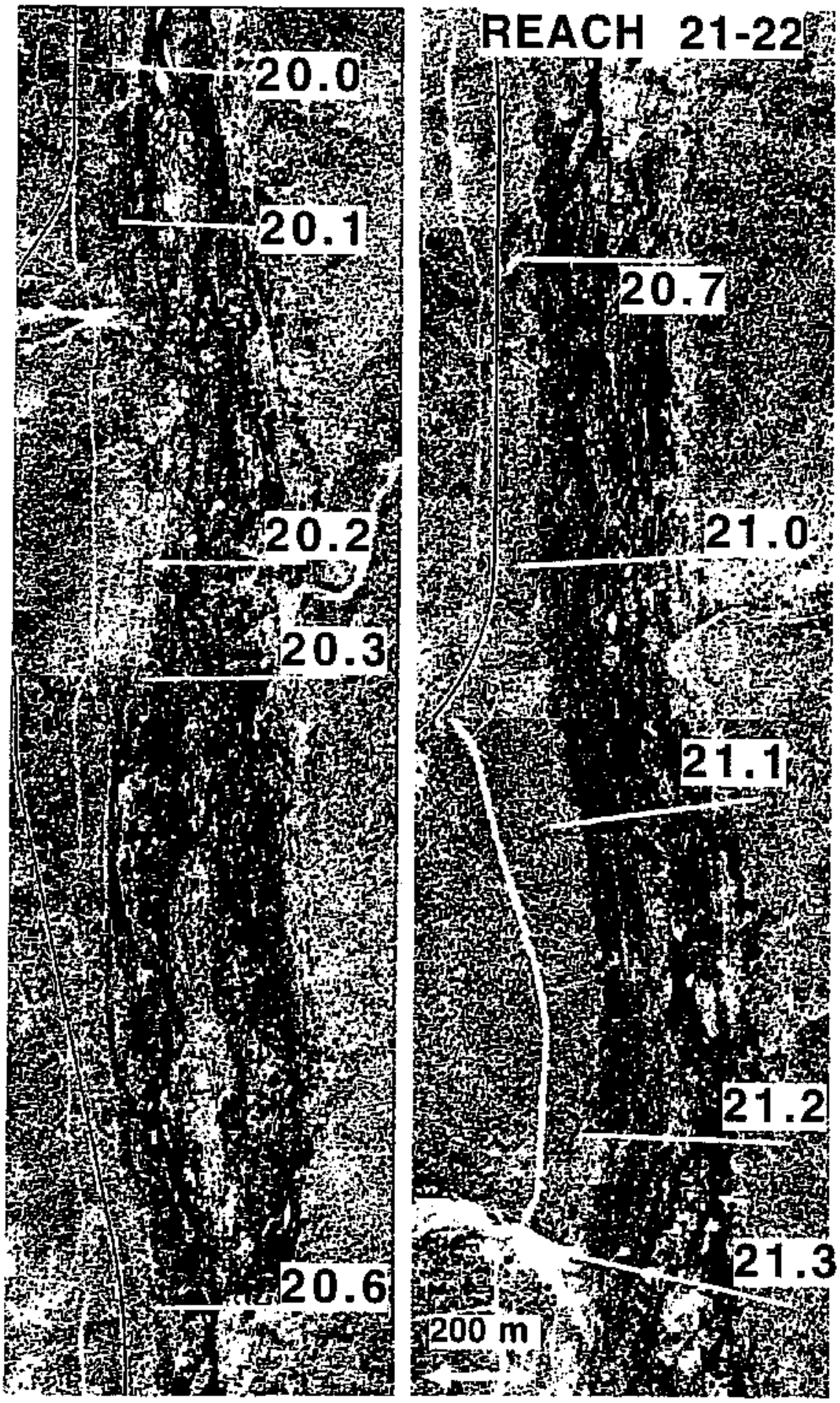

Figure 19. Plan view of reach 21, a mixed anastomosing channel type, showing cross section locations (numbered). Flow direction is from top to bottom (after Broadhurst *et al.*, 1996).

3.2 Characterisation of the processes operating in each of the representative reaches of the Sabie River

It has long been recognised that there is a link between channel form and fluvial process (see Richards, 1982). The form of a channel at any point in space and time is the result of the combined influences of flow hydraulics and sediment dynamics on the underlying geology. It is suggested that similar examples of the same channel type will be influenced by a similar range of controlling processes, in much the same way as a pool-riffle sequence in a temperate alluvial channel is formed and maintained by a set of hydraulic processes that have been well defined (see Sear, 1996, Clifford and Richards, 1992).

3.2.1 Identifying flow resistance components within the study reach

Flow resistance is one of the fundamental governing variables that reflect the hydraulic and sediment transport regime of a section of river (i.e. a channel type cell on the Sabie River). Quantification of the resistance thus allows the hydraulics and sediment transport character to be evaluated.

To identify all the flow resistance components at each channel type and to correlate their occurrence to observed local hydraulic conditions, eight to ten cross sections per channel type were surveyed and flow resistance components were mapped. The longitudinal spacing of the cross sections was designed to incorporate the presence of low flow hydraulic 'controls' that cause energy loss, and thus to define accurately water surface slope along a reach. These 'controls' included bedrock outcrops, major alluvial bars or tributary confluence's and major channel features, such as mid channel braid bars, meander apexes or changes in the vegetation community.

3.2.2 Measurement of local stage

Flow stage for a range of low and medium discharges was recorded at several hydraulically relevant points along each study reach, so as to define the water surface slope along the reach.

Low flow levels were surveyed directly, whereas high flows were recorded using a system of graduated poles known as High Level Flow Recorders. These were covered in water soluble paint and were stepped up the macro channel bank to cover a range of elevated flows. The paint washoff line corresponded to the level of the highest flood stage since resetting the paint and could be correlated to local debris strand lines(see Heritage *et al.*, in press).

These data were then used to characterise the channel geometry and hydraulic behaviour of the representative reaches as the discharge changed.

3.2.3 Discharge estimation

This indirectly recorded stage was related to the peak discharge recorded by the nearest gauging structure: Kruger Weir (reaches 1, 4, 14 and 15) or Lower Sabie Weir (reach 21). It was assumed that the discharge recorded at these weirs was applicable to the study sites, as no major tributaries contribute to the Sabie between the weirs and reaches in question during low and intermediate flows. It is realised that attenuation, resulting from potential losses to groundwater are not accounted for, although in bedrock areas this will not be a problem due to the restricted nature of the phreatic surface in these areas (Birkhead *et al.*, 1995). Instantaneous stage measurement was linked to discharge by lagging the flow record by a flood travel time, T_x, that corresponded to the proportion of the distance of the stage sample site from the total distance between the two weirs used (Figure 20), as equation 11 calculates:

$$T_x = T_1 + \left[(T_2 - T_1) x \frac{(W_1 - S_1)}{(W_1 - W_2)}\right] \qquad \mathbf{21}$$

where T_1 and T_2 are the times at which the flood peak passes weirs 1 and 2 respectively, W_1 and W_2 are the chainages of weirs 1 and 2 respectively and S_1 is the chainage of the study site.

Therefore, stage-discharge relationships were generated for each monitored site using both directly and indirectly measured water level and the corresponding weir derived discharge. Flow levels for flood events, estimated at $650m^3s^{-1}$ and $1700m^3s^{-1}$ (Kruger Weir), and $1000m^3s^{-1}$ and $2300m^3s^{-1}$ (Lower Sabie Weir), were recorded at several sites within and adjacent to the representative reaches. These recorded high flow levels were used to extend the rating curves for the five study reaches, to increase the range of flows to be used to estimate flow resistance.

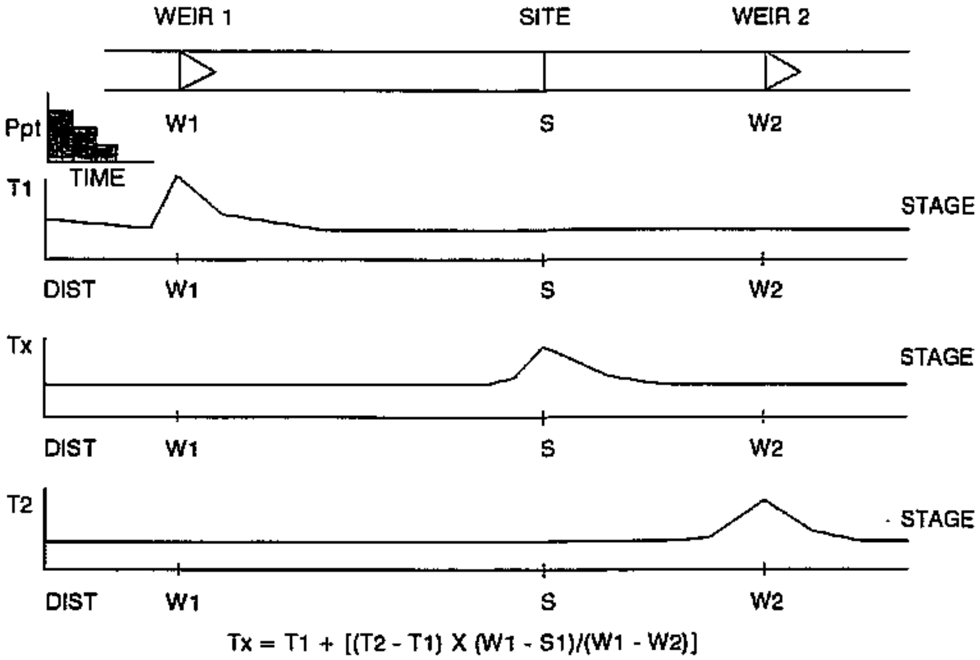

Figure 20. Calculation of stage at a study site, between two gauging weirs, during a flood event.

3.2.4 Sabie River hydraulic character

Given the data from each representative reach it is possible to quantify their flow resistance, hydraulic and sediment transport character. These are reflected in representative frictional coefficients with discharge relationships, changes to the water surface slope with discharge, sediment transport changes with discharge and overall sediment balance for each representative reach.

3.2.4.1 Quantification of channel type flow resistance

Following the (Barnes, 1967) method, and using the hydraulic and channel geometry parameters derived from the cross-section survey, reach flow resistance was quantified for the five channel types (Figure 21). Discrete values of discharge and associated cross section parameters were used to generate these discharge:flow resistance relationships, over the range of flows encountered on the Sabie river during the period of study.

Each representative reach displays a unique flow resistance pattern that characterises it and differentiates it from the other representative reaches on the Sabie River. The bedrock anastomosing channel type has the highest flow resistance, but shows the same trend as all of the channel types, with a decrease in flow resistance from low to medium discharges. The alluvial channel types: braided and single thread have the lowest flow resistance coefficients, with mixed anastomosing and pool-rapid reaches giving intermediate values. The mixed anastomosing and braided reach flow resistance increase marginally from medium to high discharges, as opposed to the bedrock anastomosing reach flow resistance which continues to decline throughout the range of discharges monitored.

Comparison of the representative reach results against other similar channel type cells on the Sabie River was not possible due to the lack of data, however close agreement was found between the results obtained here and values reported in the literature for studies on other similar channel types (Hicks and Mason, 1991, Beven *et al.*, 1979, Whittaker and Jaeggi, 1982, Richards, 1982, Bakry *et al.*, 1992).

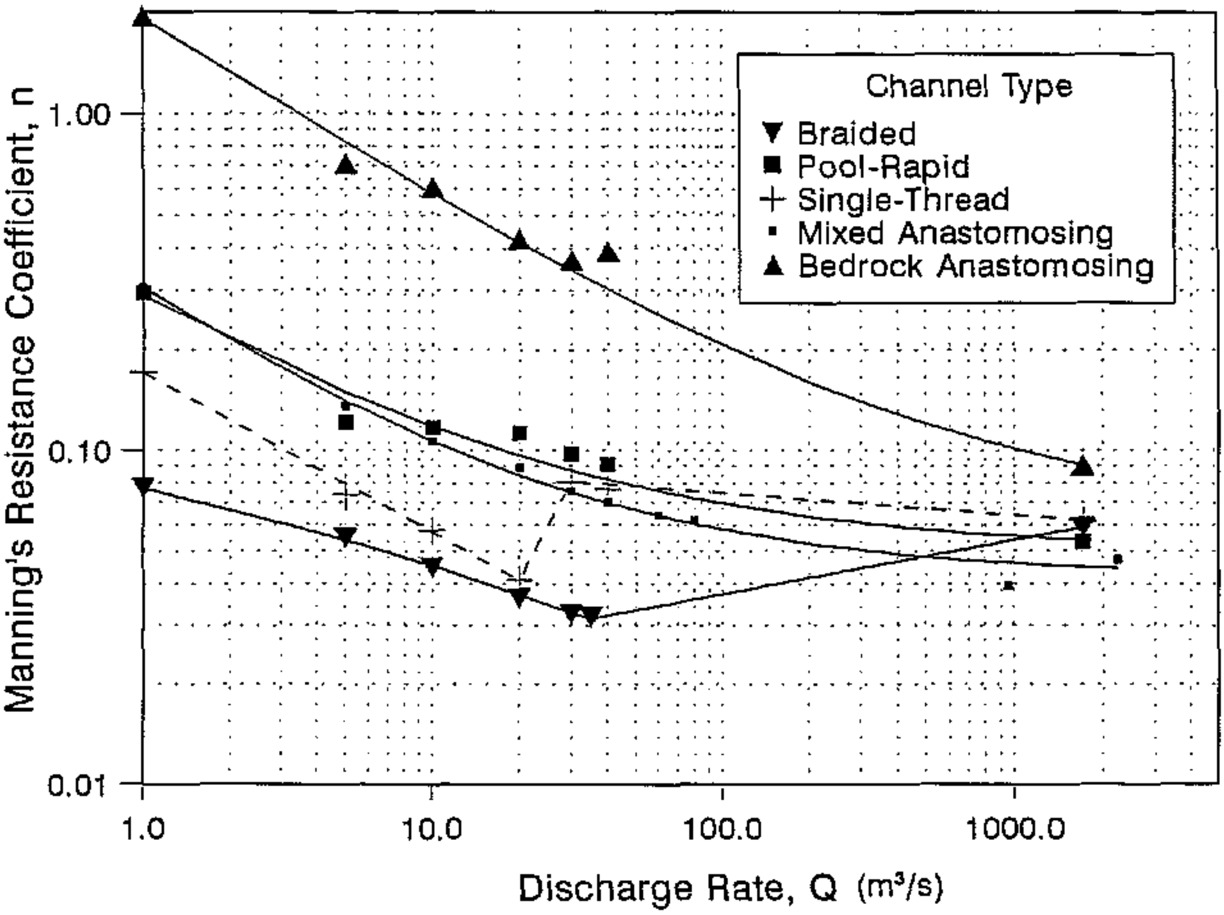

Figure 21. Manning's 'n' quantification over reaches of five different channel types (extended from Broadhurst *et al.* 1996).

3.2.4.2 Differences between discharge and water surface slope for the representative channel types.

A review of the low and high flow water surface slopes similarly indicates that each representative reach may be characterised by a certain range of values that differentiate it from the other representative reaches. Each channel type displays distinct low flow and regional high flow water surface slopes (Figures 22 and 23). Under low flow conditions (Figure 22) the bedrock anastomosing channel type exhibited the steepest slopes (>0.005). Mixed anastomosing channel types were also steep at approximately 0.002, ranging between 0.004 and 0.001. Pool-rapid channel types were slightly less steep averaging around 0.0015, ranging between 0.003 and 0.001. Braided and single thread channels displayed the lowest flow slopes at around 0.0004, ranging between 0.0003 and 0.0006. There was occasional overlap between channel type slope values but in general there was a distinct difference between channel types as follows:

Bedrock anastomosing	Highest slope
Mixed anastomosing	↓
Pool-rapid	
Braided	
Single thread	Lowest slope

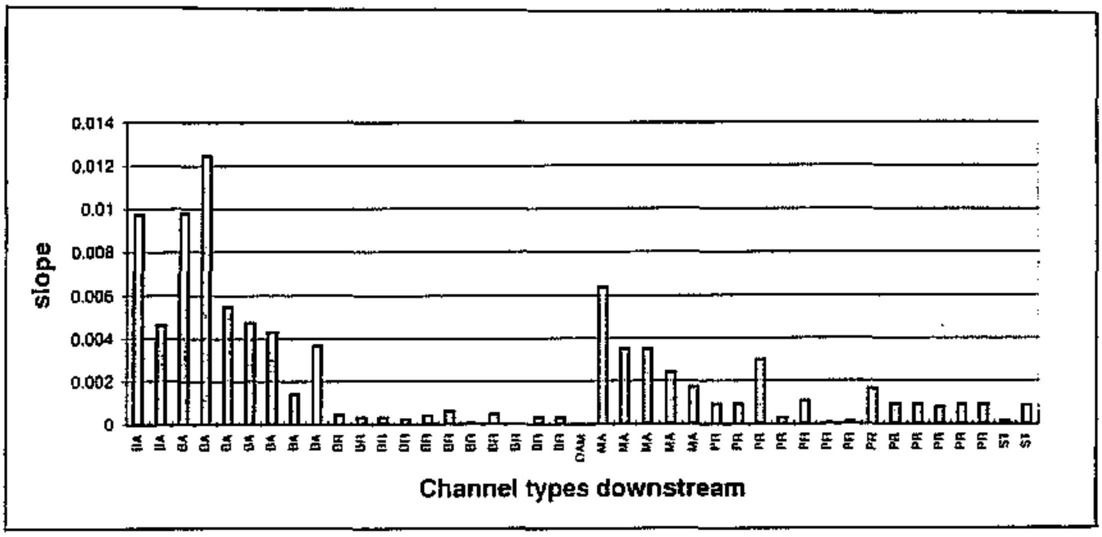

Figure 22. Characteristic low flow water surface slopes for the representative reach channel types of the Sabie River (BA = bedrock anastomosing, BR = braided, ST = single thread, MA = mixed anastomosing and PR = pool-rapid).

At high flows (Figure 23) the water surface slopes become similar as local controls (waterfalls, cataracts, rapids, bar deposits) are drowned out. In general the bedrock anastomosing slopes decline and the mixed anastomosing, pool-rapid, braided and single thread channel types increase to an average on 0.003.

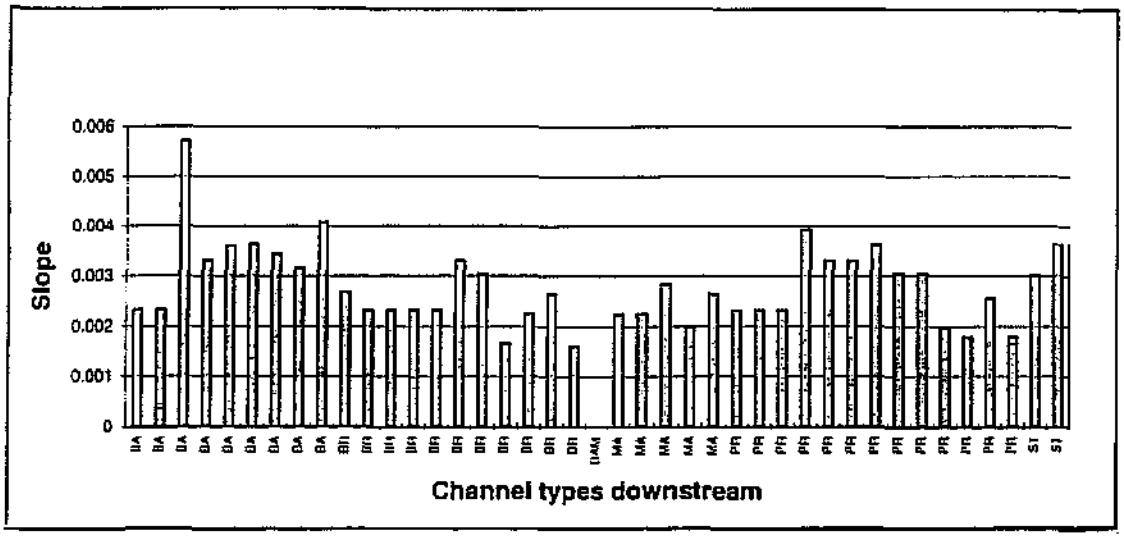

Figure 23. Characteristic high flow water surface slopes for the representative reach channel types of the Sabie River (BA = bedrock anastomosing, BR = braided, ST = single thread, MA = mixed anastomosing and PR = pool-rapid).

3.2.4.3 Differences between discharge and sediment transport for the representative reaches.

The representative reaches on the Sabie river all have distinct potential sediment transport characteristics as determined from the channel flow resistance and flow hydraulics (Figure 24). At low flows the sequence of channel competence is as follows:

Single thread	Highest potential sediment transport
Braided	↓
Mixed anastomosing	
Pool-rapid	
Bedrock anastomosing	Lowest potential sediment transport

At low flows the volumes of sediment moved are small, being of the order of $0.1 kg.s^{-1}$ to $1 kg.s^{-1}$ through the representative reach at $30 m^3.s^{-1}$. This transport behaviour alters at higher flood flows as follows:

Bedrock anastomosing	Highest potential sediment transport
Pool-rapid	↓
Single thread	
Mixed anastomosing	
Braided	Lowest potential sediment transport

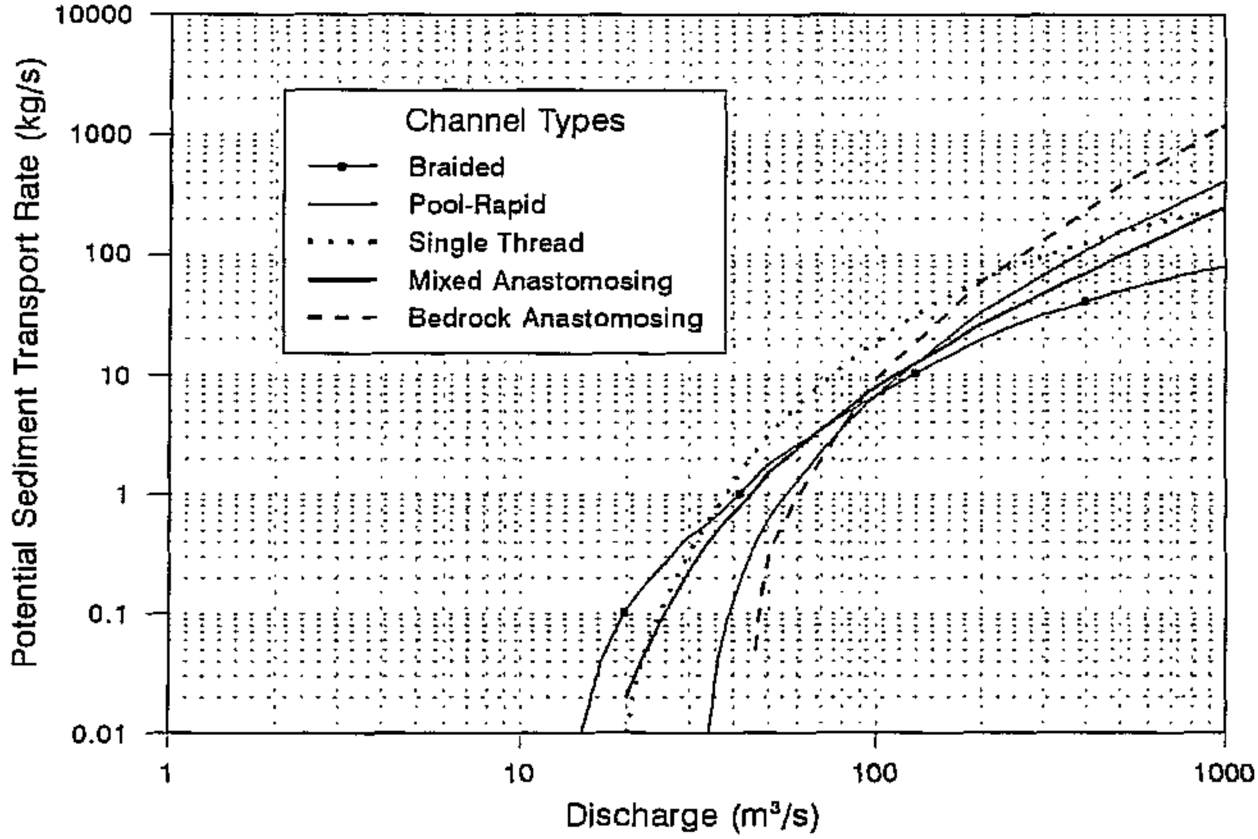

Figure 24. Characteristic potential sediment transport rates for the representative reach channel types of the Sabie River.

This high flow sequence has significance in terms of overall channel character and channel maintenance. Movement of large amounts of sediment (100kg.s^{-1} to 1000kg.s^{-1} through the representative reach at 1000m^3.s^{-1}.) cause the bedrock anastomosing and pool-rapid channel types to remain clear of large amounts of sediment and this is reflected in the dominance of bedrock features in these channels, in contrast the braided and single thread channels are less competent and are prone to sediment accumulation at higher flows.

Slight differences in morphological composition between channel types occur as a result of slight differences in channel water surface slope and sediment transport capacity coupled with local sediment inputs from distributaries. This generates the transition channel types between the principal ones creating the continuum that exists on the Sabie River.

In general it is clear that each representative reach displays significantly different morphological and hydraulic characteristics (Figure 25). For example, the character of a pool-rapid channel can be generalised as being dominated by bedrock , displaying moderate to high transport rates at high flows and lower rates at low flows; the water surface slope remains moderate at all flows, however the width/depth ratio changes from low at low flows to moderate at high flows. This behaviour is characteristic of the pool-rapid channel type and distinguishes it from the behaviour of the other 4 indicating that the channel morphology is a true reflection of the differing influence of these control variables along the river. As such the representative reach approach represents the simplest and most efficient method of classifying and characterising a river channel and generates information based on the intensive study of selected reaches that may be transferred to other unmonitored sections of the river to generate a complete spatial picture of the system functioning.

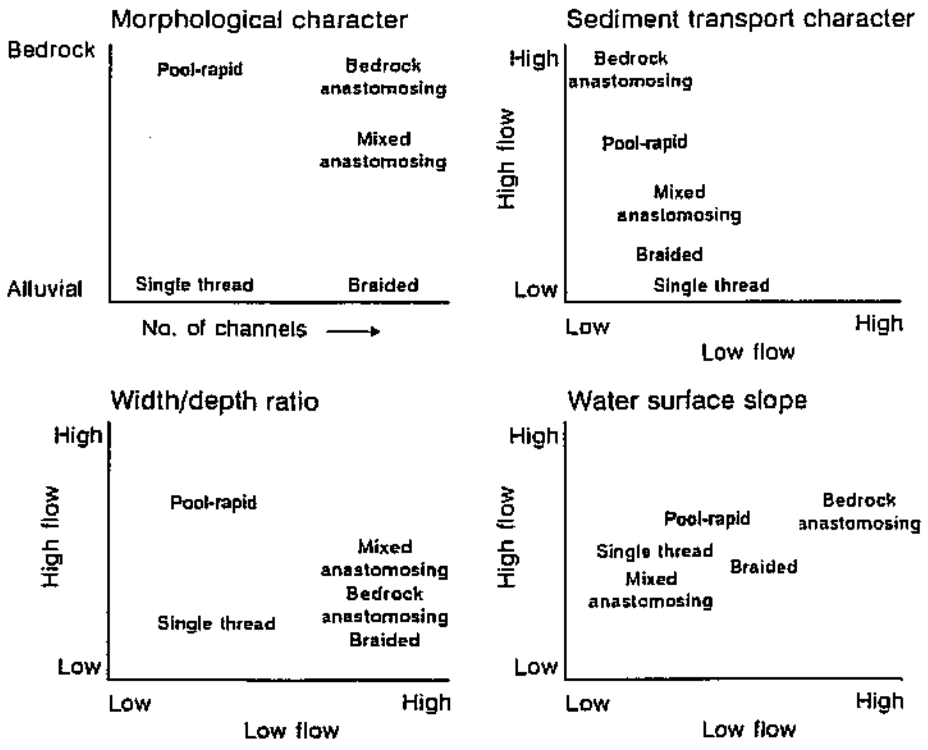

Figure 25. Summary characteristics of representative reaches of different channel types on the Sabie River.

3.3 Examples of the uses of the representative reaches output from the Sabie River study.

The data generated from the application of the representative reaches approach to the Sabie river have been utilised by a number of other research exercises:

i. Establishment of the relationship between vegetation communities, channel type and morphologic unit for the Sabie River (van Coller *et al.*, 1995; van Coller *et al.*, 1997). Significant associations have been established between the distinctive vegetation communities on the river in the Lowveld and the local geomorphology, it is argued that a change in the geomorphology would eventually result in a change in the vegetation distribution along the river,

ii. Selection of representative reaches for the Instream Flow Requirements workshop on the Sabie River, to cover the full range of ecologically significant areas (DWAF, 1997). This selection procedure has highlighted sever al reaches along the river that can be monitored and flow regime changes recommended in order to maintain their geomorphic composition, and through this the overall geomorphological and ecological integrity of the whole river.

iii. Development of a linked bulk sediment routing model to predict channel change on the Sabie River (Heritage *et al.*, in press). The linked channel type breakdown of the Sabie river based on the representative reach concept has allowed a bulk sediment transport model to be constructed to predict changes in the distribution of unconsolidated sediment under different flow and catchment conditions.

iv. Development of a dynamic model of fish and vegetation response to geomorphic change on the Sabie River (Heritage *et al.*, in press). The bulk sediment transport model has been utilised to construct a suite of knowledge based models predicting fish and vegetation response to geomorphological change at the level of morphological unit in each of the representative reach channel types (Jewitt *et al.*, in press).

v. Categorisation of the morphology and stability characteristics related to the Instream Flow requirements workshops on the Letaba, Luvuvhu, Olifants and Mooi rivers (DWAF: 1996a, 1996b, 1997). Video evidence was used to construct a morphological hierarchy of each of these rivers at the level of channel type, this allowed the river composition to be summarised and predictions to be made of the likely channel response to altered flow and sediment regimes.

4.0 Conclusions

The products of this research are:

i. **River rationalisation and zoning methods based on geomorphological criteria.** Qualitative and quantitative techniques are detailed that zone the river based on a bottom-up geomorphic hierarchical classification. The geormorpholgy is used as it is a direct reflection of the variability in catchment controls along and between rivers, hence the catchment variables which are more difficult to quantify need to be considered in the zonation process. The geomorphology was established as the best physical parameter to categorise a river system due to its spatial and temporal response characteristics. It alters as catchment variables alter along the river and over time and is closely linked to ecological change.

ii. **Appropriate methods for establishing a monitoring network (Section 2), enabling hydraulic and channel geomemetry data to be collected at a number of physical scales.** Full descriptions of the data collection network are given together with the example network installed on the Sabie River (section 3).

iii. **Presentations of channel type scale methods to generate channel roughness and hydraulic character.** Methods to process the raw data collected are given in order to generate representative hydraulic and sediment transport characteristics with changing discharge.

iv. **Generation of a large data base of flow resistance coefficients over a range of physical scales and fluvial environments, in addition to hydraulic and channel geometry data.** Quantification of the flow resistance coefficients has aided an assessment of channel dynamics (Heritage *et al.*, in press) allowing biotic change and flow resistance values have been successfully transferred to other reaches (Birkhead *et al.*, in press). These uses of the outputs from this research form integral components of the Kruger National Park Rivers Research Programme and are of use to a variety of river scientists.

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