REFINEMENT OF GEOMORPHOLOGICAL TOOLS FOR THE SUSTAINABLE MANAGEMENT OF THE RIVER ENVIRONMENT

Report to the Water Research Commission

by

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Report No: 1181/1/04
ISBN No: 1-77005-284-4

MARCH 2005

EXECUTIVE SUMMARY

Specifying flows to provide a range of suitable habitat for instream organisms is one of the key activities in assessing water quantity requirements for the Ecological Reserve (the Ecological Water Requirement - EWR). Specialists are asked to agree on a suite of discharges that will provide habitat specifically for invertebrate and fish species found in the river reach. Habitats patches are described in terms of depth, velocity and the underlying substrate as well as the connectivity between patches, important for example for fish passage.

Conventional techniques used in South Africa base the assessment of discharge related habitat changes on the average depth and velocity estimated for one or two transects across the study site. There is a recognised need for an effective technique to map habitat within the context of the Ecological Reserve. Two dimensional models that can create velocity and depth distributions within a channel section are available, but the soft ware is expensive, requires intensive field data collection and, more importantly, the problems of modelling low flows in hydraulically complex channels are compounded as one moves from a one-dimensional to two-dimensional model. An alternative approach is to couple field mapping of hydraulic habitats with data manipulation using GIS. This is the approach developed in the project reported on here.

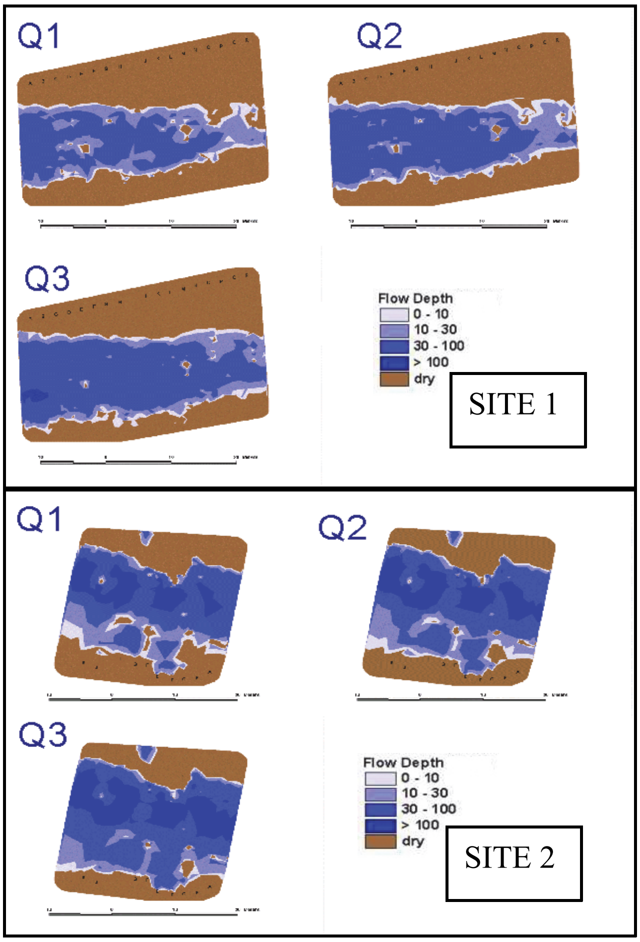
Field mapping of hydraulic habitat was based on the concept of hydraulic biotopes as defined by Wadeson (1994). These have the advantage that they can be recognised through the flow type - the surface expression of the underlying flow hydraulics. The hydraulic validity of the flow type classification is supported by research by Rowntree and Wadeson (1998), Padmore (1998) and Birkholz (2003), while their ecological significance has been tested by King and Schael (2001) and Birkholz (2003) for Western Cape and Drakensberg streams respectively.

The aims of the present project were as follows:

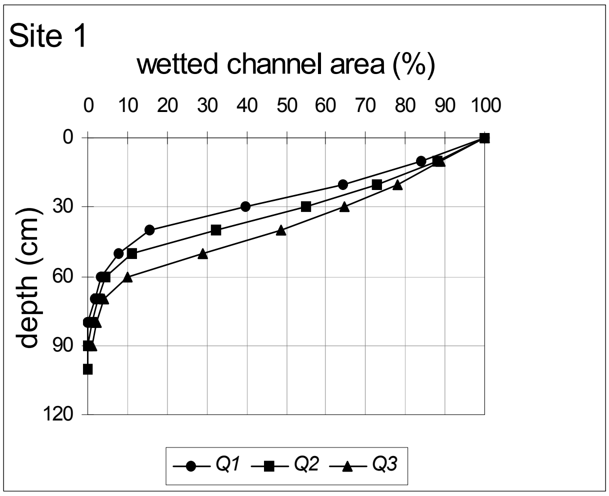
- Develop a geomorphological tool to describe discharge related changes in instream habitat using hydraulic biotope mapping
- To apply hydraulic biotope mapping to assessment of the Ecological Reserve

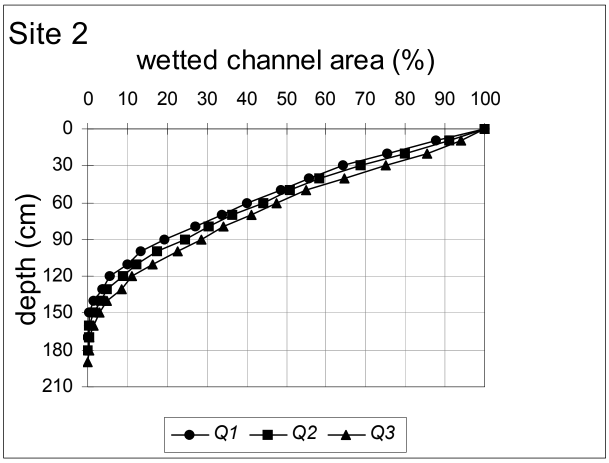
Four sites were selected in the upper Sabie River (Mpumalanga) and the Kat River (Eastern Cape). These four sites represented a range of channel morphology and discharge regimes. A detailed survey of the channel morphology was carried out using multiple cross sections; a minimum of ten sections at each site was used. Flow type and substrate were mapped along each transect. Vegetation was also surveyed. Flow type mapping was repeated at each site at three discharges.

The topographic survey data was manipulated using the Geographical Information System software ARCVIEW to create a Digital Terrain Model (DTM) of each site. Maps of the substrate, vegetation and flow type were created by interpolation between transects. Three

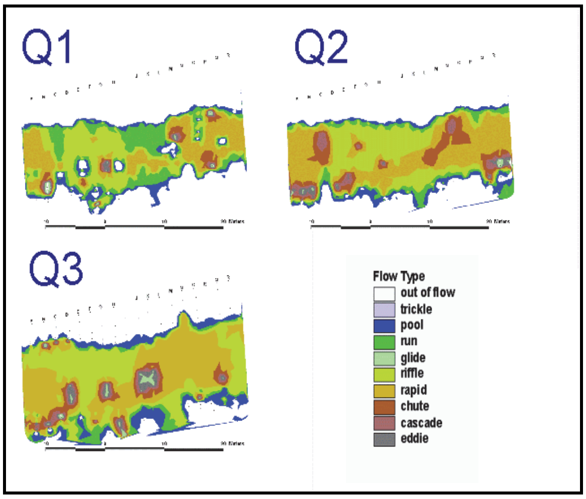


GIS was used t o create maps of water depth at each site for the three discharges observed in the field. These maps show water depth at the two sites on the Sabie River. The patchy depth distribution at Site 2 contrasts with the more uniform distribution of Site 1.



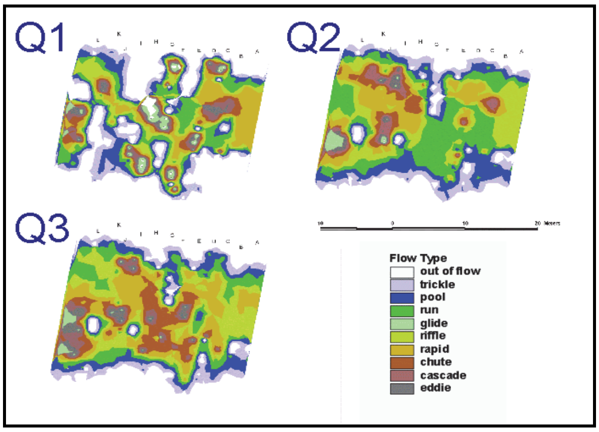


These graphs were derived form the maps of water depth. They show the distribution of depth at the different discharges and can be used to estimate the area of the channel that is greater than a given depth. For example 30 cm is often identified as a critical depth for fish passage. Site 2 clearly has a greater extent of deep water at all discharges, but its patchy distribution was evident from the water depth maps.

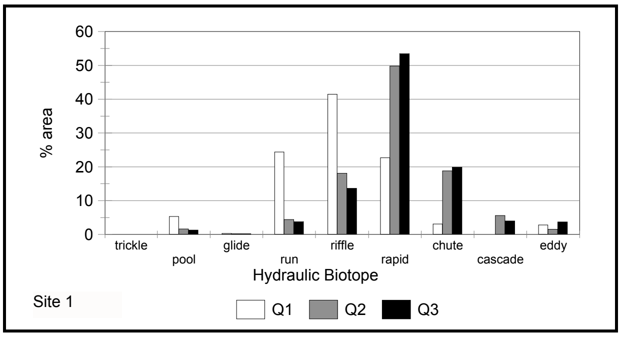


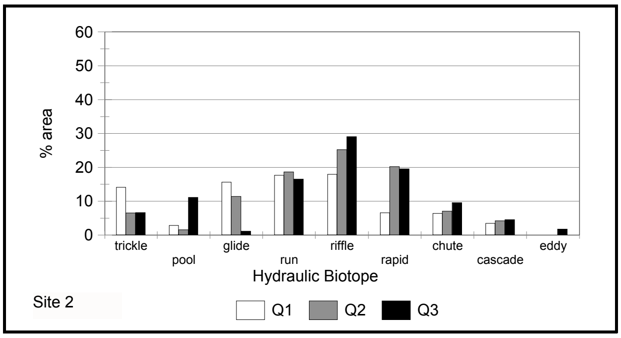
SITE 1

SITE 2



Hydraulic biotopes at the study sites were mapped in the field using line transects. A GIS was used to create the maps seen here for the Sabie River. The maps are useful in showing the distribution of hydraulic biotopes and, in particular, the degree of connectivity or, conversely, patchiness





These graphs were derived from the hydraulic biotope maps. They give a clear picture of how the proportions of hydraulic biotopes change with discharge. The two sites on the Sabie differ in their distribution of hydraulic biotopes, and the way that these respond to increasing discharge.

flowtype maps were created for each site, at each of the three discharges. Flow depth maps were created by combining the measured water stage with the topographic map.

Overlay techniques in ARCVIEW allowed the aerial extent of the different habitat combinations in terms of hydraulic biotope (flow type) and water depth to be explored.

The mapping technique proved to be an effective way of producing information on the spatial distribution of habitats that can be used in an environmental flow requirement (EWR) workshop. Its application in the Thukela workshop is given by way of an example. Ecologists found the maps easy to follow and greatly increased their confidence in recommending flows. Habitat mapping is now recognised as an important component of an EWR determination.

The results showed that the habitat-discharge relationship varies with channel morphology. We are not yet in a position to predict this relationship from the morphological characteristics of the stream, but with wider application to different sites this might become possible.

In comparison to 2-D hydraulic models, the field data requirements are similar. The output from this method depends on simple GIS modeling and field observation. It does not require complex hydraulic modelling. For observed flows this should give an accurate representation of habitat distributions. For flows intermediate to and outside the range of those observed, depth can be predicted but the hydraulic biotopes, and hence the velocity class, must be interpolated or extrapolated subjectively. This is not easy given the type of data used in the process. Accuracy depends on the number of field visits and the range of discharge. Data collection is moderately time consuming in complex channels. In comparison, 2-D models are based on a one-off field visit for the topographic survey, plus repeated stage-discharge readings for the purpose of model calibration. Once calibrated it is possible to produce model output for a wide range of discharges, but the accuracy is uncertain because there is no field verification. There are inevitable problems of modelling the hydraulically complex channels that are often selected for EWR determinations. These conclusions point to a possible way forward in which the two approaches are combined.

ACKNOWLEDGMENTS

This research project was funded by the Water Research Commission, whose contributions and support are acknowledged. Field data collection was carried out by the authors with the assistance of Ms D Trautman (Sabie River) and students from the Geography 3 class (Kat River). The support of Rhodes University and the Geography Department in providing field equipment and administrative backup is gratefully acknowledged.

ACRONYMS

DTM	Digital Terrain Model
EWR	Environmental Water Requirement
GIS	Geographic Information System

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1. INTRODUCTION

River channels are geomorphological features which are formed by the water and sediment that they transport. It is not surprising, therefore, that fluvial geomorphology has become an important component of many river management initiatives (Rowntree and Wadeson, 1999; Rowntree et al., 2002; Newson & Newson, 2000; Thomas and Sheldon, 2002). The geomorphological processes determine the morphology of the channel which in turn provides the physical framework, or physical habitat, within which the stream biota live (Huryn, 1987; Ward, 1988; Rempel et al., 2000; Gjerløv et al., 2003; Roy et al., 2003). Geomorphology, therefore, has become an important consideration in the assessment and maintenance of river health.

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

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

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

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

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

Habitat is comprised of a number of components. Instream habitat, for example, depends on the flow hydraulics, substrate conditions, overhead cover, water temperature and water chemistry. The first two of these components can be related directly to the channel geomorphology and can be termed hydraulic habitat. Available hydraulic habitat can be described in terms of the wetted perimeter (the total availability of habitat), the flow depth and flow velocity, coupled to the material on the channel bed which forms the habitat substrate. The ecological importance of these habitat variables has been recognised by a number of stream ecologists including Statzner et al. (1988), Hildrew and Giller (1994), Gjerløv et al. (2003) and Roy et al. (2003).

Hydraulic habitat varies across the channel cross-section, forming distinct patches that can be related to the channel form and bed conditions. A number of stream ecologists (Statzner et al. 1988; Hildrew and Giller, 1994; Rempel et al. 2000) have recognised patchiness as animportant descriptor of instream habitat. Hildrew and Giller (1994) have related macro-invertebrate distribution to patches described in terms of depth, substrate and discharge. Patch mosaics are seen by these authors has providing refugia from stress and disturbance at higher flows.

Wadeson (1994) recognised the importance of patches determined by the spatially and temporarily variable flow hydraulics. He termed these patches hydraulic biotopes, defined as *a spatially distinct in-stream flow environment characterised by specific substratum and hydraulic attributes*. Hydraulic habitat changes with bed morphology (Birkholz, 2003) and also with discharge (Rowntree and Wadeson, 1996); wetted perimeter, depth and velocity all increase with discharge so that both the total available habitat and the quality of that habitat (the hydraulic biotopes) change. The nature of this relationship depends on the geomorphology characteristics of the channel at any given site, as has been demonstrated by Rowntree & Wadeson (1996), Padmore (1998) and Newson & Newson (2000).

Habitat assessments in South African ecological reserve (Environmental Water Requirement - EWR) workshops have, in the past, been based on hydraulic analyses applied to one or two line transects across representative morphological units at representative sites (Rowntree and Wadeson, 1998). An hydraulic analysis is applied to each transect to derive the discharge related changes in wetted perimeter, maximum depth, the depth distribution across the profile, and mean velocity. The distribution of substrate size across the section can also be provided. The quantitative description of habitat at any one point on the transect is therefore limited to substrate and flow depth; estimates of point velocities are unavailable. In effect, the transect is treated as a lumped system, characterised by average values. This is a major limitation of the method as used at present. A second, possibly more serious limitation is that quantitative assessments are restricted to a single line transect for each representative morphological unit. There is a clear need for a technique that can assess spatial changes in habitat across the unit as a whole and can incorporate discharge related spatial changes in habitat as an integral part of reserve assessments. Hydraulic biotope mapping is suggested as a means of achieving this.

Habitat mapping and recognition that the distribution and assemblages of hydraulic habitats change with discharge has been recognised as an important component of the assessment of Environmental Water Requirements. A number of approaches to habitat mapping have been developed. Two dimensional modelling is a relatively sophisticated approach that can produce detailed maps of velocity and depth vectors from a survey of channel topography (Addley and Hardy, 2002; Hardy and Addley, 2002). Although effective at producing modelled distributions at any selected discharge, such an approach is data intensive, expensive and becomes more difficult to apply as the complexity and roughness of a channel increases. An alternative approach is to map the visual expression of the hydraulic characteristics of the flow as can be discerned from the "flow type" as seen at the surface (see Table 1 for definitions). These flow types have been recognised by a number of researchers and have been shown to have consistent characteristics in terms of hydraulic indices such as Froude number and shear velocity (Padmore, 1998; Wadeson & Rowntree, 1998; Newson & Newson 2000; King & Schael, 2001; Birkholz, 2003). These researchers have developed and applied a classification of hydraulic habitat based primarily on flow type which is termed the physical biotope (Padmore, 1998) or hydraulic biotope (Wadeson & Rowntree, 1998) (Table 2). King and Schael (2001) working in the Western cape of South Africa and Bikholz (2003) working in the KwaZulu-Natal Drakensberg, have confirmed the ecological validity of hydraulic biotopes at least with respect to invertebrate fauna.

Habitat mapping of hydraulic biotopes has been proposed by Wadeson & Rowntree (2001) Newson et al. (2002), Maddock & Lander (2002), Pollard (2002), among others, as a practical means of capturing habitat distribution and change for a range of discharges. As the flow type is a visual manifestation of the flow hydraulics, it is a variable that is relatively straightforward to map. Hydraulic biotopes, however, tend to be distributed in a complex of small patches, especially in morphological units such as riffles and rapids, the area of focus in most reserve workshops. This makes mapping a time consuming process if conventional methods of surveying are used (King & Schael, 2001). Practical mapping methods that can be applied to the EWR assessments need to be developed.

Table 1.1: Definitions of flow types (after Rowntree and Wadeson, 1999)

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

Table 1.2: Definitions of hydraulic biotopes in terms of flow types. Further subdivision can be made in terms of substrate (modified from Rowntree and Wadeson, 1999).

Hydraulic Biotopes	Definition
Trickle:	Very small volumes of flow trickling through cobbles or over bedrock. Trickles are characterised by barely perceptible flow.
Pool:	A pool is in direct hydraulic contact with upstream and downstream water but has no perceptible flow.
Glide:	A glide exhibits smooth uniform flow. A glide may occur over any substrate as long as the depth is sufficient to minimise relative roughness. Glides exhibit no significant convergence or divergence.
Run:	A run can occur over any substrate apart from silt. Runs often form the transition between riffles and the downstream pool. A run may be characterised by a rippled or surging flow type.
Riffle:	Riffles occur over potentially mobile, coarse alluvial substrates from gravel to cobble. A riffle may be characterised as having undular standing waves (or breaking standing waves).
Rapid:	Rapids occur over a fixed substrate such as boulder or bedrock. Rapids are characterised by having breaking standing waves, chutes or limited free falling flow.
Chute:	A chute is characterised by a convergance of fast flowing water (relative to surrounding flow) between obstructions in the channel.
Cascade:	A cascade occurs where water falls over an obstruction, usually less than 1 metre in height.
Eddy:	An eddy is characterised by water flowing upstream against the current.

Methods for mapping hydraulic biotopes have been developed and tested in the context of South African EWR assessments by Wadeson (2003). Wadeson (2003) discusses two approaches to the habitat mapping problem. The first utilises digital photography which is manipulated using Geographical Information System software (GIS). Although this first approach is relatively quick and cost effective, there are a number of limitations:

- The procedure requires expensive technology (digital camera, notebook computer etc); some specialised training is required.
- Only a limited area can be mapped at any one time (dependent on the focal range of the camera and the height of the photograph above the site).

- The standardisation for repeat photographs is extremely difficult, i.e position of photographer, angle, height, scale etc.
- The technique is not suitable for high-flow mapping as one cannot enter the channel for classification and field verification.
- Clearly recognisable landmarks (above the flood line) must be visible within each photograph so that repeat photographs can be taken for different discharges.
- It is a two dimensional technique that is not easily coupled to the present Instream Flow Requirement procedure.

The second approach requires a detailed survey of the area of interest. This data set is also manipulated using GIS software to create a three dimensional digital terrain model (DTM). Initial research (Wadeson, 2003) has indicated that this second technique may have considerable potential for development as a management tool and for integration within the present procedure for assessing Environmental Water Requirements (EWR) as required as part of the ecological reserve procedure. For this reason the present Water Research Commission funded project was undertaken to try to develop the procedure further. The specific aims of this project were to:

- Develop a geomorphological tool to describe discharge related changes in instream habitat using hydraulic biotope mapping
- To apply hydraulic biotope mapping to assessment of the Ecological Reserve

2 METHODS

2.1 The Research Area and Study Sites

Two river systems were selected for this research, the first being the Sabie River (Mpumalanga) and the second the Kat River (Eastern Cape), a tributary of the Great Fish River (Figure 2.1). These two rivers demonstrate different channel morphology, different catchment condition and different levels of anthropogenic disturbance. Two research sites were selected in each river.

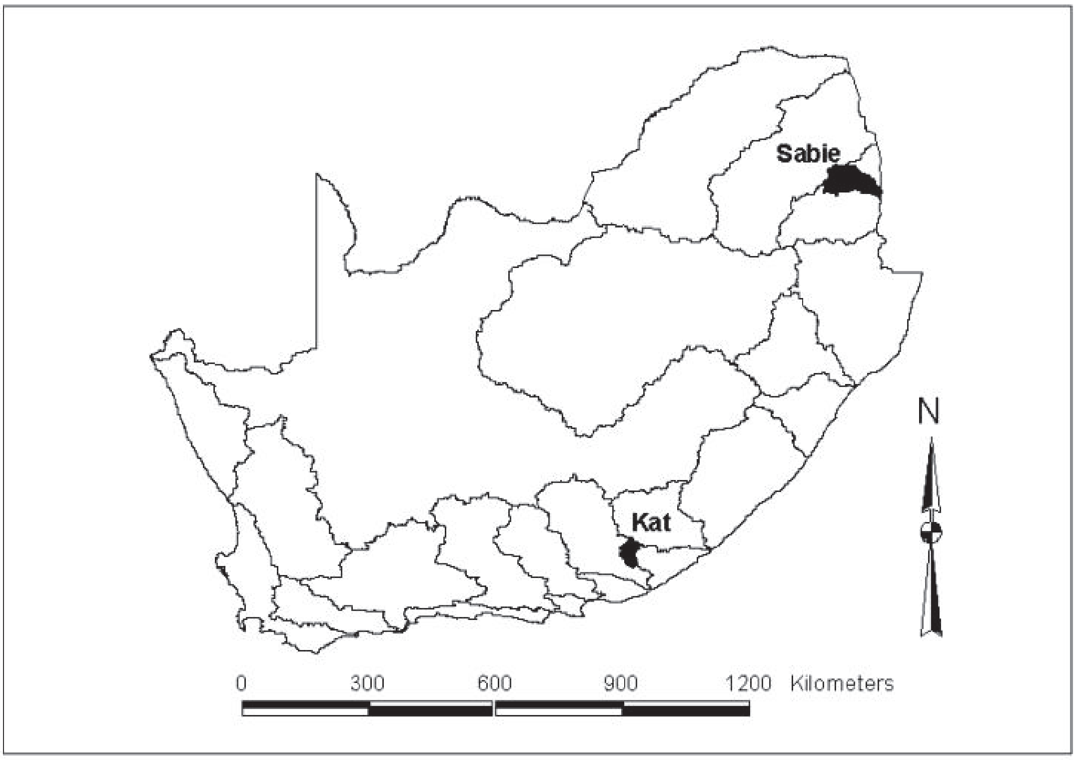


Figure 2.1 Location of the Sabie and Kat catchments within South African primary drainage regions

2.1 . 1

The Sabie River

Two sites were selected in the upper reaches of the Sabie River (Mpumalanga)(Figure 2.2) . The research area was situated between the towns of Sabie and Hazyview at an altitude of approximately 900m amsl. The Sabie River rises on the eastern slopes of the Mauch Berg in the Transvaal Drakensberg at an altitude of about 2200 m and flows eastwards for some 210 km to its confluence with the Incomati River in Mozambique. The catchment area is about 7096 km^2. The Sabie River has ecological importance as the only perennial river flowing through the Kruger National Park.

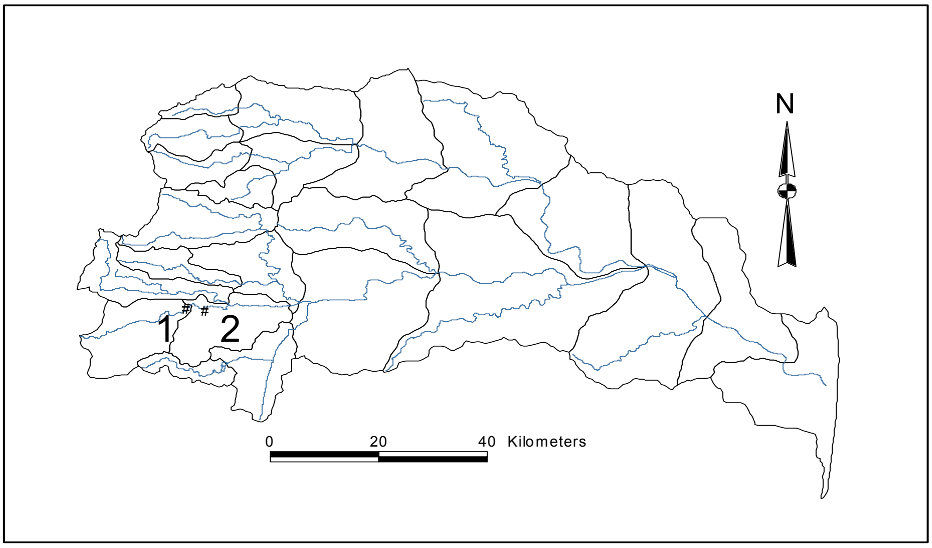


Figure 2.2 Location of study sites on the Sabie River

The two sites were in close proximity to each other and were located within the same reach as determined by channel gradient. The catchment area above the two sites was approximately 180 km^2 with a mean annual precipitaion of 1241 mm and a mean annual runoff of 453 mm (Midgley et al. 1994). The river reach can be described as "upper foothill" with an average gradient of 0.015 (Rowntree *et al.* 2000). Characteristic morphology for this type of reach is a moderately steep, cobble bed or mixed bedrock-cobble bed channel with plane bed, pool-riffle or pool-rapid reach types. Lengths of pools and riffles/rapids are usually similar. A narrow flood plain of sand or gravel or cobble is present.

Site 1 in the Sabie River (Plate 1) is situated within the Frankfort forest and consists of a riffle/pool morphology over coarse substrate. Bed material consists of boulders and large cobbles interspersed with bedrock. Site 2 (Plate 2) consists of a more complex pool/rapid morphology dominated by large boulders and bedrock.

Plate 1 Sabie River, Site 1

Plate 2 Sabie River, Site 2

2.1.2 The Kat River

Two sites were selected in the Kat River (Eastern Cape). The Kat River rises at an altitude of about 2200 m and flows for some 177 km to its confluence with the Great Fish River. The catchment area is about 1700 km^2.

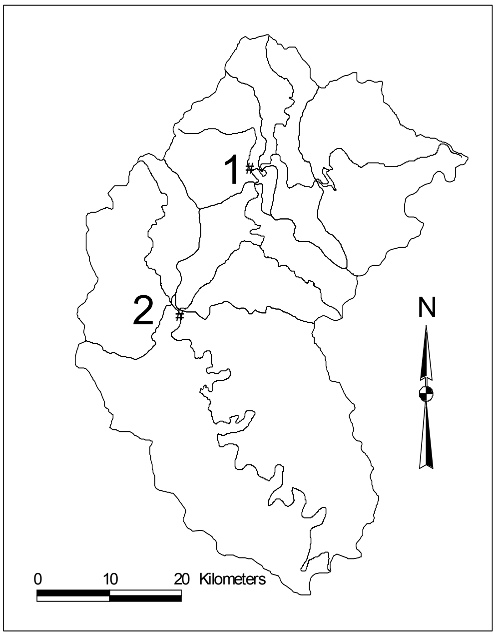


Figure 2.3 Location of study sites on the Kat River

The location of the research sites in the Kat catchment are shown in Figure 2.3. Site 1 was located on the Balfour River, a perennial tributary of the Kat. The catchment area above the site is approximately 134 km^2, with a mean annual precipitation of 768 mm and a mean annual runoff of 91 mm (Midgley et al. 1994). The altitude of Site 1 is close to 580 m amsl. The gradient of the channel reach in which this site was located was estimated to be 0.0175. Site 1 (Plate 3) was characterised by a pool/rapid morphology over coarse substrate. Bed material consists of boulders and large cobbles interspersed with bedrock

Site 2 was located on the Kat River itself at an altitude close to 460 m amsl. The catchment area above the site is approximately 970 km^2, with a mean annual precipitation of 704 mm and

Plate 3 Kat River Site 1 (on the Balfour)

Plate 4 Kat River Site 2

a mean annual runoff of 65 mm (Midgley et al. 1994). Flow releases from the Kat Dam supply downstream citrus farmers with irrigation water. The gradient of the river reach was estimated as 0.00437. Site 2 (Plate 4) consisted of a pool/riffle morphology dominated by boulders and large cobble interspersed with gravel. A tributary immediately upstream of the site delivered gravel and sand to the channel from an eroded area of the catchment.

2.2 Data Collection

2.2.1 Selection of morphological units

Habitat surveys were confined to the morphological units acting as hydraulic controls in the two sites: the riffle in Sabie site 1 and the rapid in Sabie site 2, the rapid in Kat site 1 and the riffle in Kat site 2. These morphological units are acknowledged by ecologists as being the areas of greatest biological diversity and are the most susceptible to loss of critical habitat at low flows (O'Keeffe, pers comm.). Pools tend to maintain flow depth even at very low flows and are recognised as important refuge areas for stream fauna.

2.2.2 Base line topographic survey

The channel topography was surveyed using a total station to create a 3D-template on which habitat components could be overlaid. The objective of this survey was to capture, as accurately as possible, the change in bed topography. A grid pattern for data collection was used by laying out two lines (ropes) on opposite banks of the river. A third rope was fixed perpendicular to the flow between these two lines to mark the first survey transect and guide the prism holder. This rope was moved after the completion of each transect. The number of transects at each site was determined by the physical complexity and time constraints. As a standard procedure, two metre intervals were used between transects and approximately 15 - 20 transects surveyed at each site. The complexity of the river bed in these surveys required approximately 20 - 30 points to be captured along each transect. Each point was numbered and a record made of the bed material sediment size (Table 2.1), presence or absence of vegetation and a classification of the hydraulic biotype based on flow type (Table1.1). The detailed topographic survey was a once off procedure which provided a 3-dimensional topographical template upon which other data could be overlain.

Each point was numbered and a record made of the bed material sediment size, presence or absence of vegetation and the flow type (hydraulic biotype). These data were later manually captured in a spread sheet and linked to the survey data. An example of the linked data sheet is given in Table 2.2.

Table 2.1: Adapted sediment key for field capture

SEDIMENT	SIZE (mm)	ADAPTED KEY
Silt	< 0.06	1
Sand	0.06 - 2	2
Gravel	2 - 16	3
Coarse Gravel	16 - 64	4
Cobble	64 - 128	5
Large Cobble	128 - 256	
Boulder	512 - 1024	6
Large Boulder	> 1024	
Bedrock	not applicable	7

Table 2.2: Example of data sheet for the collection of elevation and sediment data

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

The topographic survey was a once off procedure which provided a 3 dimensional topographical surface upon which other data was overlain.

A stage plate was fixed at each of the four research sites to enable the development of a stage-discharge curve. This stage plate also enabled the field worker to easily determine whether discharge was significantly different from previous data collections. Discharge was measured using the velocity-area method at an appropriate section close to the site. Velocity was measured using an electro-magnetic current meter.

2.2.2 Habitat re-surveys

Hydraulic biotope mapping was repeated at a number of different discharges at each research site. Ranges in discharge varied from wet season base flow to wet season spate. Discharges for the four sites in the two rivers are given in Table 3. The procedure entailed the laying out of a tape measure or marked rope across the channel at each transect line as in the base line survey. The extent of each hydraulic biotope boundary on the transect was recorded on a data sheet. The recorded data was combined with the base line survey data to re-draw hydraulic biotope distribution on the topographic template for the different stages of flow.

Unfortunately the hydraulic biotope data for the Kat River site 2 was corrupted so no accurate hydraulic biotope maps could be constructed.

Table 2.3: Discharge at the time of survey (m^3 s^{-1})

	SABIE RIVER		KAT RIVER	
	SITE 1	SITE 2	SITE 1	SITE 2
Q1	2.83	3.04	n.a.	0.17
Q2	5	5.37	n.a	0.216
Q3	7.9	6.01	n.a	2.096

2.3 Data presentation and analysis

2.3.1 ArcView GIS

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

At each site, three base maps were produced: a topographic map, sediment map and vegetation map. A number of other associated maps were produced to demonstrate the influence of changing discharge on hydraulic biotope distribution. Hydraulic biotope maps were produced for each of the three discharges. The 3-dimensional topography was also used to model the distribution of water depth at each discharge. These maps provide a good visual display of the degree of connectivity of areas of similar depth. Water depth has been identified as an important component of instream habitat in South Africa.

2.3.2 Data analysis

The GIS data base was used to derive histograms and cumulative frequency curves of the habitat distribution and depth distribution respectively. Some simple statistical analyses were carried out to demonstrate changes in "habitat patchiness" in response to changing discharge.

The two sites on the Sabie were used to develop the analytical procedures for describing discharge related habitat characteristics. Full details of these analyses are presented. To avoid duplication these analyses are not presented for the Kat. Selected data from the Kat are presented to demonstrate how different channel morphologies influence the habitat-discharge relationship.

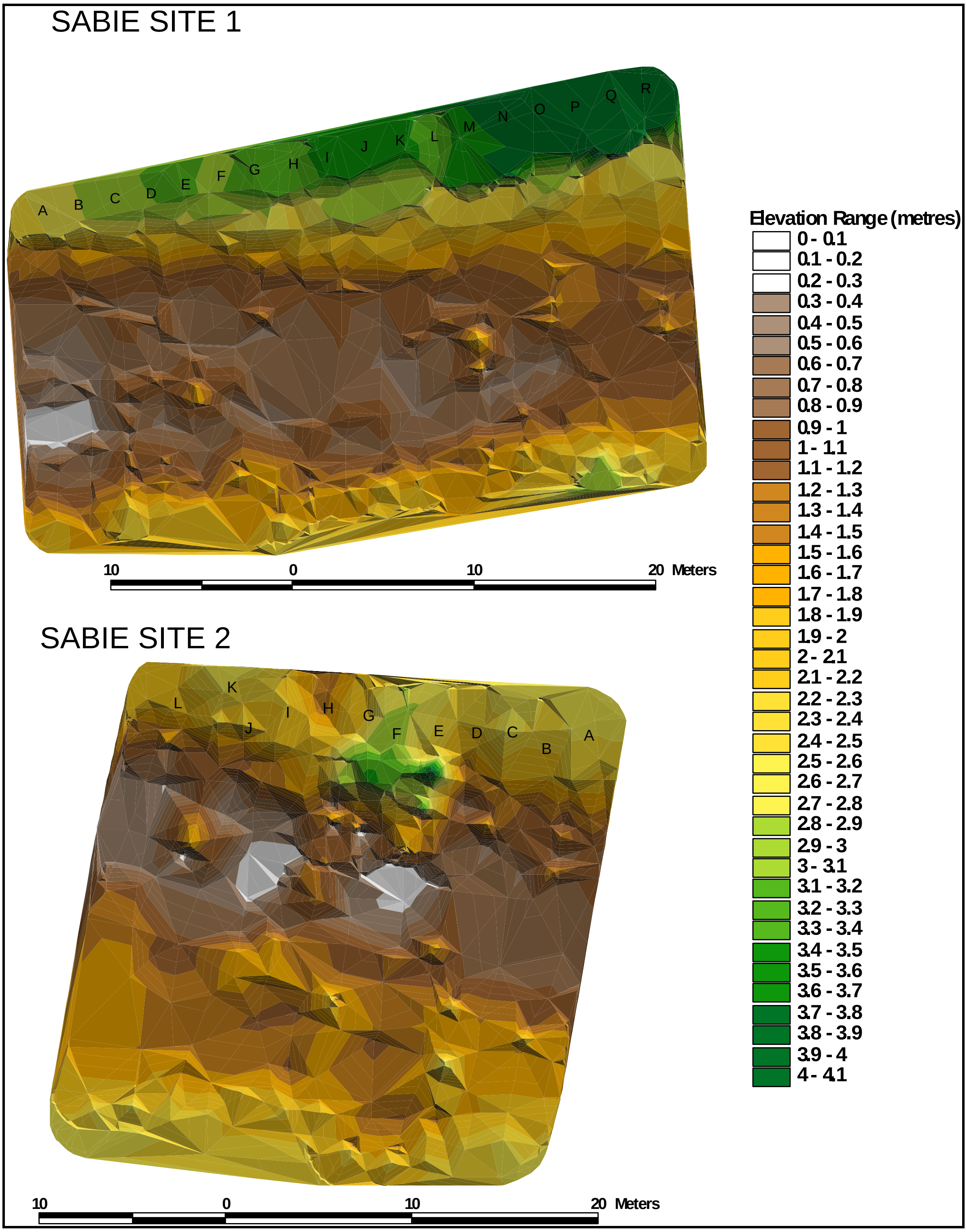


Figure 3.1 Sabie River - Topographic maps of survey sites

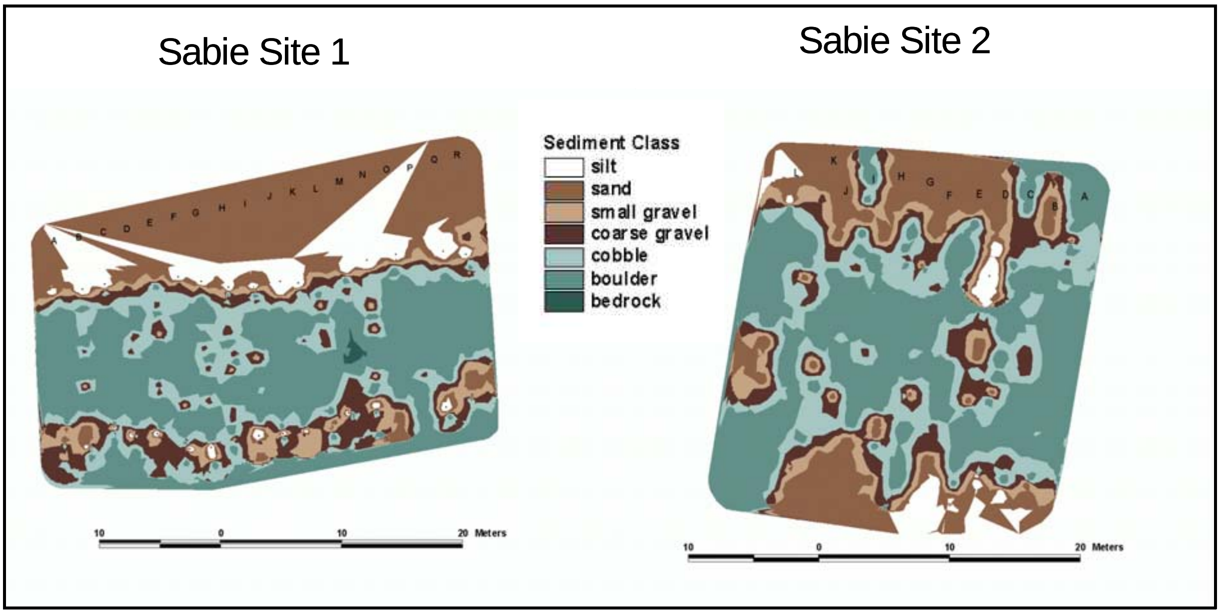


Figure 3.2 Sabie sites - Sediment distribution

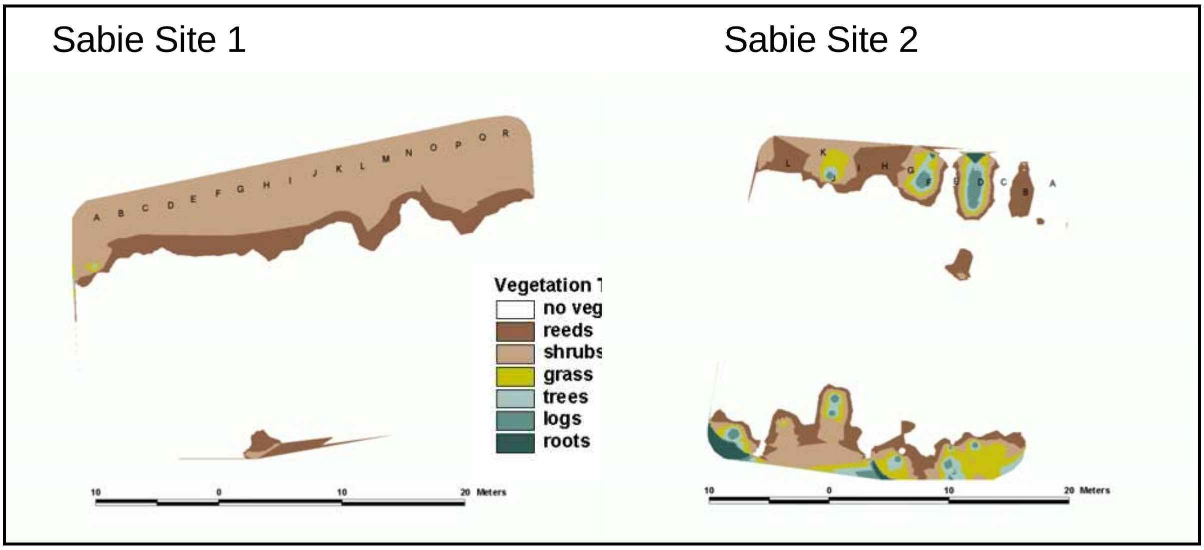


Figure 3.3 Sabie sites - Vegetation distribution

3 RESULTS AND DISCUSSION

3.1 Sabie River

3.1.1 Site topography, sediment characteristics and vegetation

The contrasting topography between the two sites can be seen from Figure 3.1.

Site 1 was confined to a steep riffle section with a number of boulder and bedrock intrusions. The channel bank on the right hand side consisted of sand and was well defined. The left hand side had a steep boulder and bedrock bank. This site was approximately 34 metres in length and 22 metres in width (from bank top to bank top). The water surface slope at the intermediate discharge (Q2) was 0.0137.

At site 2 the topography was relatively complex with numerous bedrock and boulder intrusions on the bed; this created a pool - rapid morphology. The channel banks were well defined with no obvious signs of incision. This site was approximately 26 metres in length and 29 metres in width.

Figure 3.2 compares the sediment distribution at the two sites. Broad similarities can be seen. Cobbles and boulders dominated the active channel at both sites while the presence of sand and gravel on the river bank indicated the position of the active channel boundary. There were pockets of small gravel within the active channels of both sites which were positioned behind coarse material. Bedrock was more abundant at site 2 and the boulders within the active channel were significantly larger.

Figure 3.3 gives the vegetation distribution at the two sites. At site 1 the left hand bank was virtually devoid of vegetation while the right hand bank consists of reeds along the waters edge and shrubs on the banks. At site 2 there was a good diversity and density of riparian vegetation. The channel boundary was dominated by reeds and shrubs.

3.1.2 Water Depth

The distribution of water depth can be considered to be very important for the free and easy movement of fauna within the river channel, particularly fish. For the purpose of mapping water depth, four classes were considered:

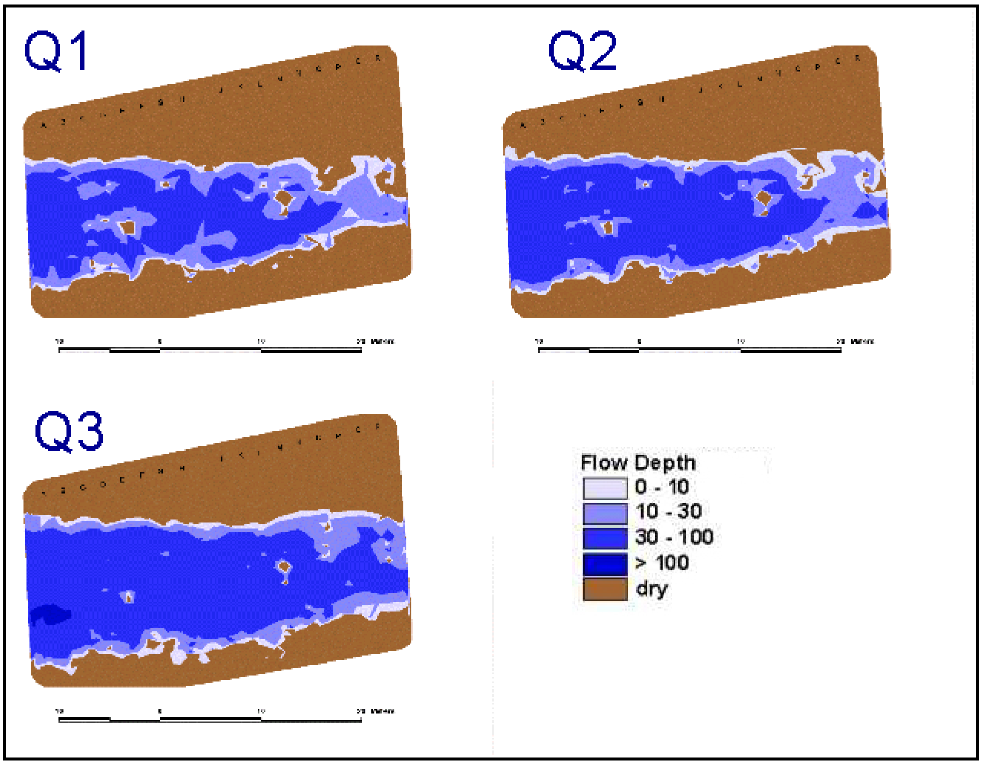


Figure 3.4 Maps of water depth maps at site 1, Sabie River

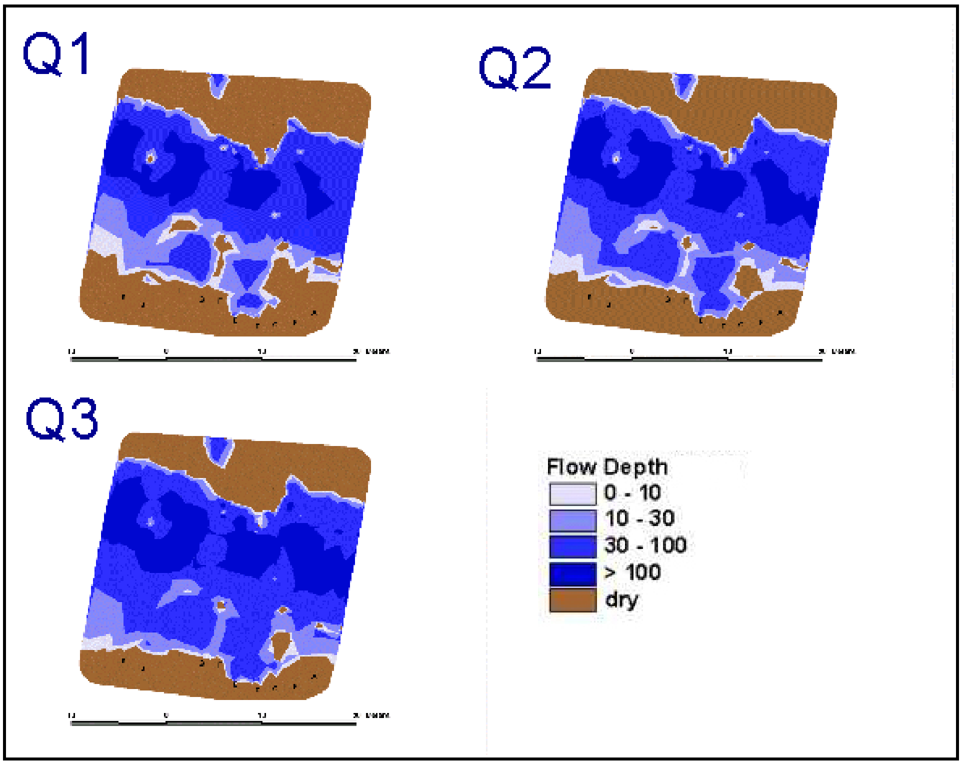
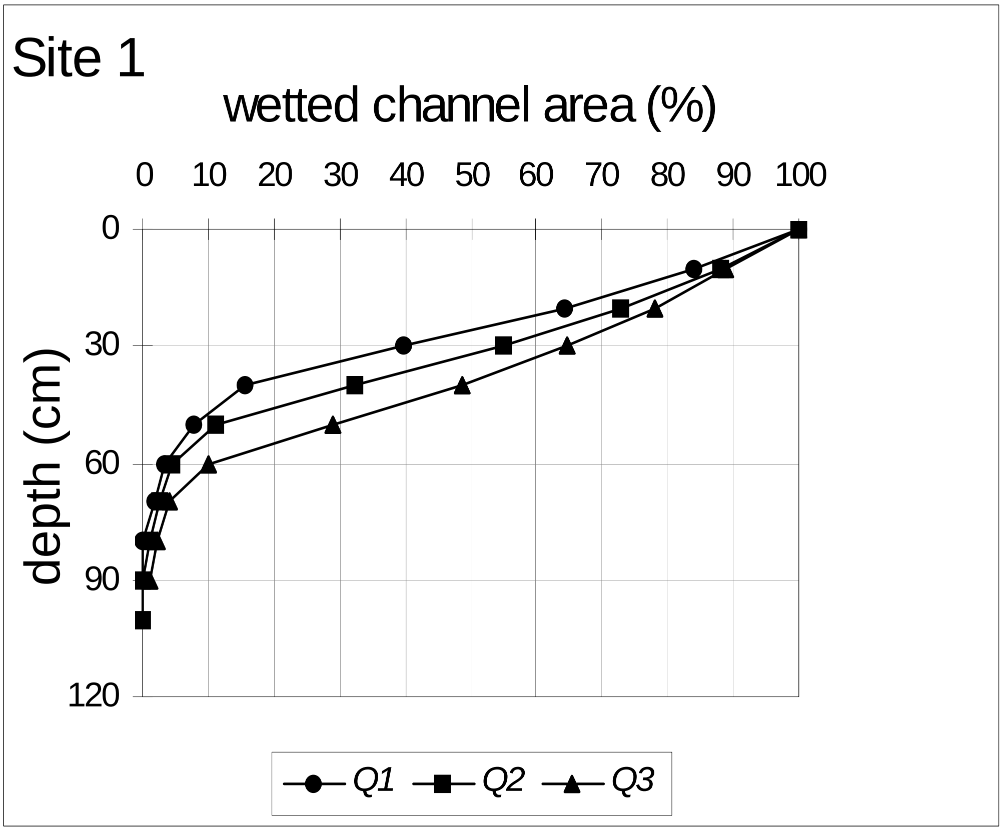


Figure 3.5 Maps of water depth map for site 2, Sabie River



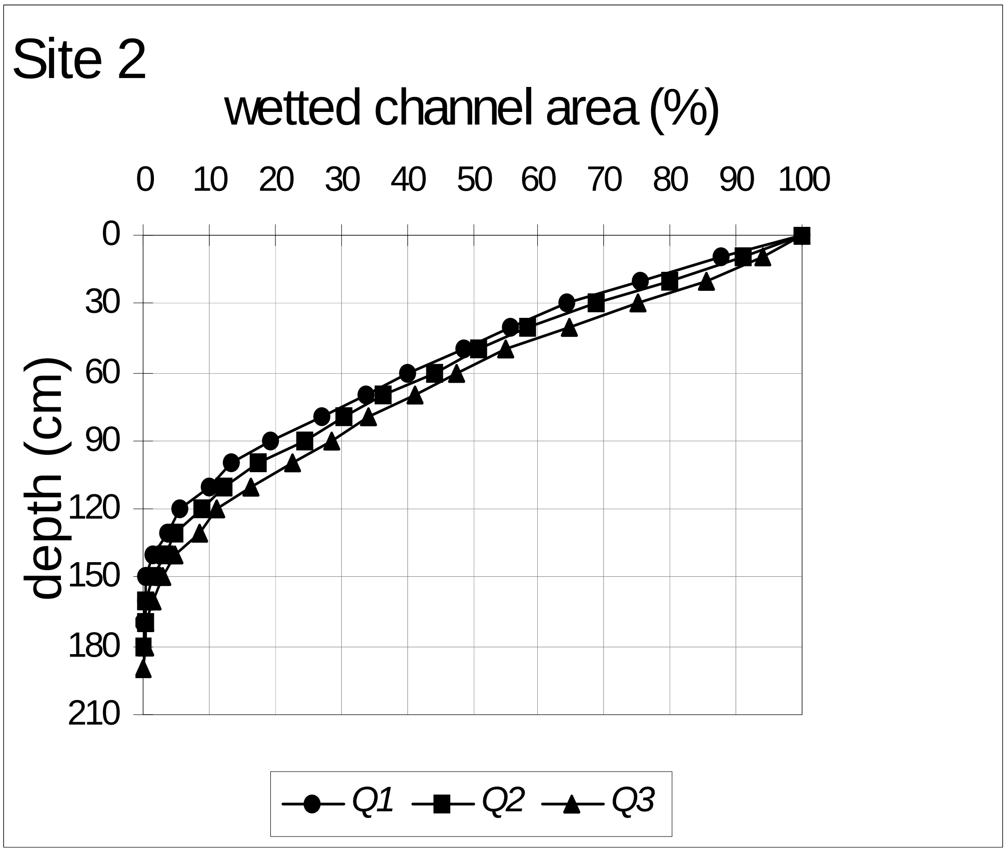


Figure 3.6 Cumulative depth distributions at the two sites on the Sabie River

- Shallow water is considered to be any depth less than 10 cm. This water is generally considered to be too shallow for the free and easy movement of large fish but does provide important habitat for fry and invertebrates.

- Moderate depth is considered to be a flow between and 10 and 30 cm deep. This depth is generally considered to be more suitable for the free and easy movement of fish depending on the species or level of development.

- Deep water is considered to be a depth between 30 and 100 cm. This depth provides good cover for adult fish and allows for free and easy movement.

- Very deep water is considered as any depth over 100 cm.

The following maps (Figures 3.4 & 3.5) demonstrate the change in water depth distribution in response to changing discharge at the two sites

Sabie Site 1

Distribution of water depth at this site illustrates a good continuous cover of the various depth classes. Class 0-10cm was found only on the channel margins at all discharges. It formed a continuous band but was relatively narrow. Depth class 10-30 cm was also represented by a continuous band, predominantly on the channel edge. At the lowest discharge there was a relatively broad cover along the length of the channel, with areas of deeper water (30-100 cm) towards the middle of the channel. As one would expect, the extent of the 10 - 30 cm class was reduced as discharge increased. Depth class 30 - 100 cm was not continuous for the first two discharges because of a break caused by the upstream riffle. At the third discharge a narrow band in this depth class became available to allow an uninterrupted continuation along the length of the site. Depth class > 100 cm was not present at all until the third discharge. At this time it became available as a very small patch at the most downstream end of the site.

If one was to assume that adult fish at this site require a depth of 30 cm or more for free and easy movement, they would be limited in their range at discharge 1 and 2. At discharge 3 they would have access to the full length of the site.

Sabie Site 2

As with site 1, three separate maps of water depth were produced to illustrate changes that occur in response to changing discharge (Figure 3.5). Depth distribution was unlikely to be an issue of concern at this site for the discharges experienced in this study. On the right hand bank there was a narrow continuous band of water 0 - 10 cm deep which was bordered by another narrow band 10 - 30 cm deep. This pattern was not mirrored on the left hand bank where the depth bands were considerably wider. There was a wide continuous band of flow through the center of the river which was 30 - 100 cm deep. This would suggest that there was adequate depth at this lowest measured discharge to provide good cover and free and easy passage for adult fish. On the left hand bank of the river there were isolated areas of water (backwater pools) which were 30 - 100 cm in depth. Fish utilising these areas place themselves at some risk because they have to navigate shallow areas to reach them. The pattern of depth distribution did not change dramatically as discharge increased. Perhaps the most important change was the widening of the class 30 - 100 cm and the fact that the backwater pools joined the mainstream (in this size class). The deepest class of water > 100 cm remained relatively unchanged as discharge increased. Isolated pockets of this depth class get larger until they formed a near continuous cover at discharge 3.

Figure 3.6 provides a means of comparing the distribution of depth at the different discharges. The graphs show the percentage of the wetted area that is greater than a given depth for each discharge. It can be seen that at Q1, 40 % of the area was greater than 30 cm, the critical depth for fish passage (Kleynhans pers. comm.). This increased to 55 % at Q2 and 65 % at Q3. The depths at site 2 were generally much deeper, with 65 % of the area being greater than 30 cm at Q1, increasing to 75 % at Q3.

3.1.3 Hydraulic Biotope Distribution

Sabie River Site 1

Figure 3.7 presents maps of the hydraulic biotopes at the three discharges. Table 3.1 (a-c) tabulates the percentage of each hydraulic biotope by depth class.

Site 1 was characterised by a good diversity of hydraulic biotopes at all discharges. At discharge 1, seven of the possible nine flow types were present, at discharges 2 and 3 eight were present. No trickles were observed at this site, cascades were only present at the higher discharges.

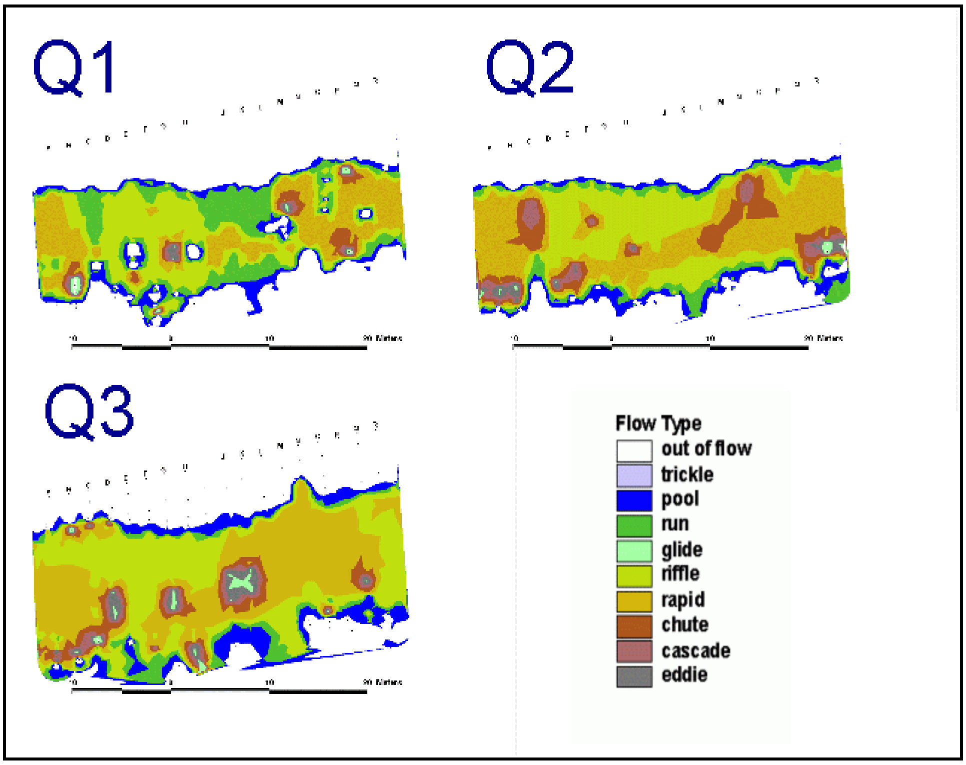


Figure 3.7 Sabie site 1 - Hydraulic biotope distribution

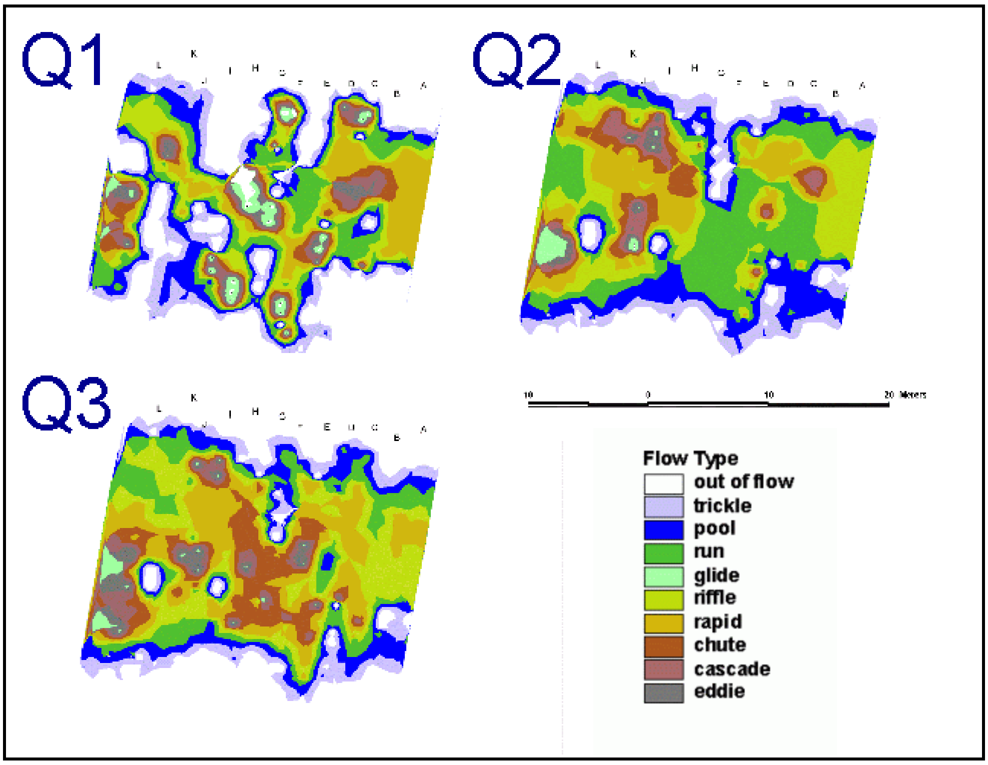


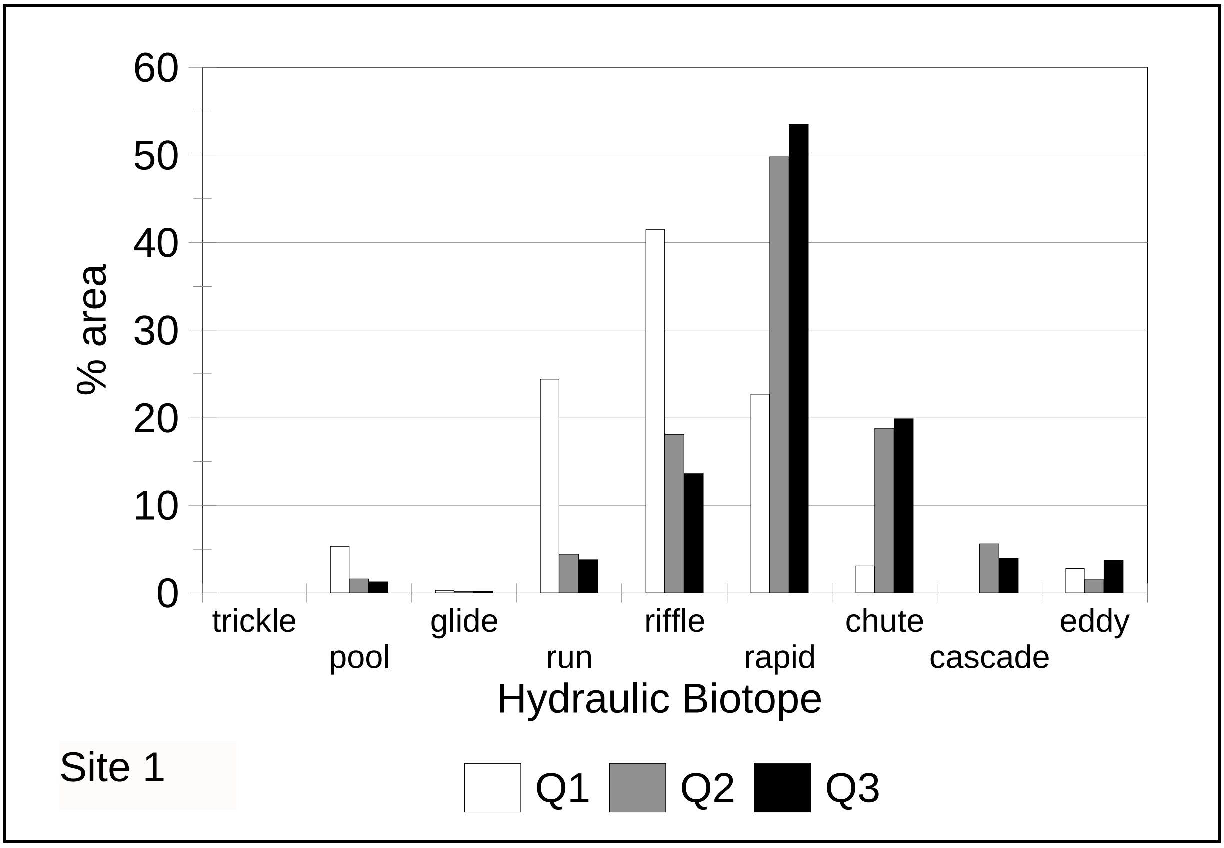
Figure 3.8 Sabie site 2 - Hydraulic biotope distribution

Three of these flow types showed a continuous linkage along the channel margin down the length of the study site (pool, run and riffle) at all discharges. It can be seen that at the lowest discharge the hydraulic biotopes in the main flow area tended to occur as discontinuous patches, but as the flow increased these patches increased in size and started to merge. Thus rapid, which dominates the center of the channel at all discharges, occurred in broken patches at discharge 1 but had become nearly continuous by discharge 3.

Patchiness refers to the number of separate hydraulic biotopes units within a site. Generally it is accepted that a high degree of patchiness is preferable to a more homogenous condition as it promotes ecological diversity. Patchiness does not necessarily provide an indication of habitat diversity. It is quite possible to have a full range of hydraulic biotopes (high habitat diversity) but have a low patchiness. In other words each hydraulic biotope is a single well defined unit which is quite clearly separated from other hydraulic biotopes.

The percentage distribution of habitats at the three discharges is given in Figure 3.9 and Table 3.1. At discharge 1 this site was dominated by riffle (41.5%), run (24.4%) and rapid (22.7%) hydraulic biotopes. Runs were generally less than 30 cm in depth, riffles and rapid less than 40 cm. The high energy biotopes - rapid and chute - made up only 25.8 % of the total area. Although pool was shown to be well distributed throughout this site, it only made up 5.3% of the total area and, as was seen from the maps in Figure 3.7, was confined to the edges of the flow. Only half of the area characterised by pool was over 10 cm in depth. Glide, which can also be considered as a relatively low velocity hydraulic biotope, only constituted 0.3% of the total area.

As discharge increased from discharge 1 to discharge 2 the distribution of hydraulic biotopes shifted towards those characterised by higher energy flows. The percentage of run decreased from 24.4 % to 4.4 % and riffle from 41.5 % to 18.1 %, while rapid increased from 22.7 % to 49.8 % and chute from 3.1 % to 18.8 %. The deepest areas of flow (between 40-50 cm) were dominated by the rapid hydraulic biotope. Cascades also appeared for the first time at this discharge, over a range of depths. Rapid, chute and cascade together made up 74.4 % of the total area. This obviously means a decrease in area of the slower flowing environments.



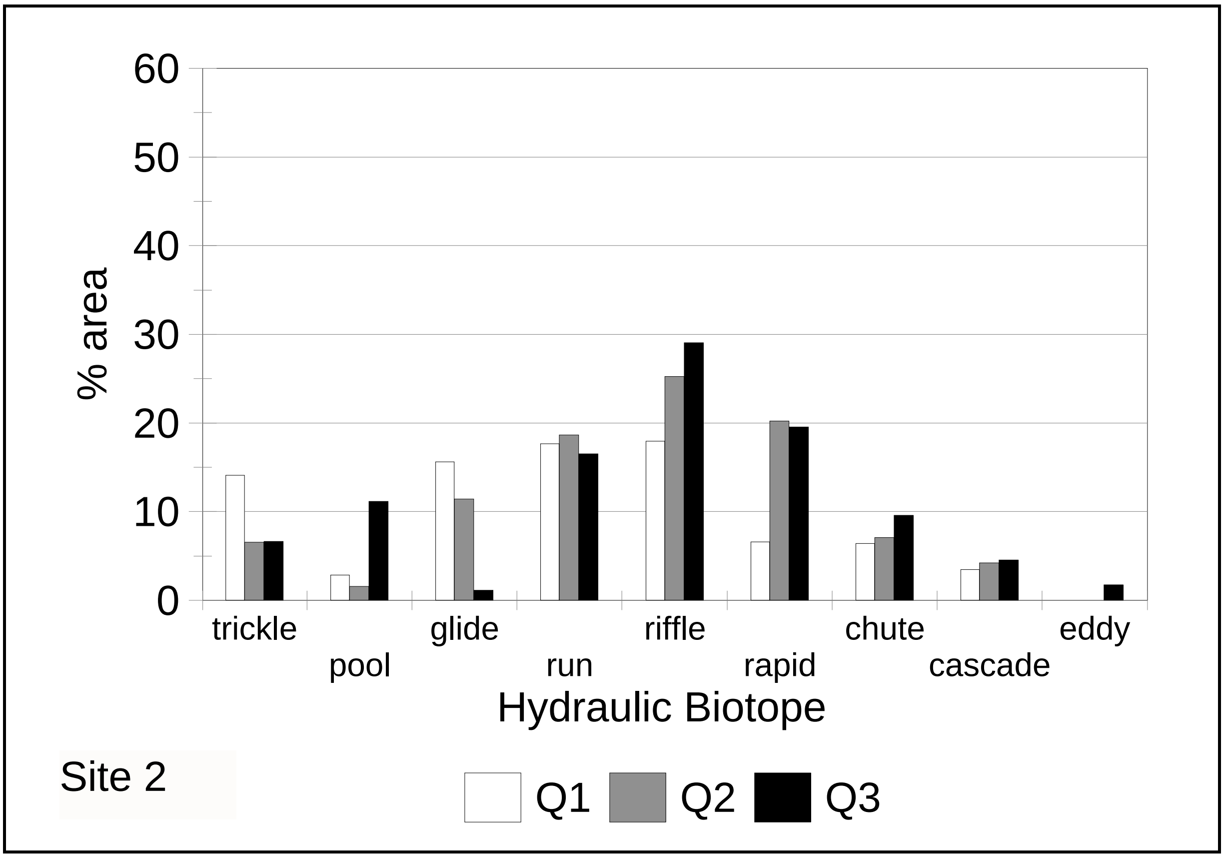


Figure 3.9 Comparison of hydraulic biotopes at Sites 1 and 2, Sabie River

Table 3.1a:Percentage cover for different hydraulic biotopes, Sabie site 1, discharge 1.

DEPTH	pool	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	*2.8*	*0.0*	*4.0*	*4.4*	*4.4*	*0.2*	*0.0*	*0.1*	15.9	15.9
20	*1.6*	*0.0*	*7.8*	*7.5*	*2.5*	*0.3*	*0.0*	*0.1*	19.7	35.6
30	*0.6*	*0.1*	*9.6*	*10.9*	*3.1*	*0.3*	*0.0*	*0.1*	24.8	60.4
40	*0.3*	*0.2*	*2.5*	*13.7*	*6.5*	*0.6*	*0.0*	*0.3*	24.1	84.5
50	*0.0*	*0.0*	*0.2*	*3.4*	*3.4*	*0.6*	*0.0*	*0.0*	7.7	92.1
60	*0.0*	*0.0*	*0.0*	*0.3*	*1.9*	*0.1*	*0.0*	*2.2*	4.4	96.6
70	*0.0*	*0.0*	*0.0*	*0.7*	*0.6*	*0.0*	*0.0*	*0.0*	1.4	98.0
80	*0.0*	*0.0*	*0.2*	*0.6*	*0.3*	*0.9*	*0.0*	*0.0*	2.0	100.0
90	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.0	100.0
%	5.3	0.3	24.4	41.5	22.7	3.1	0.0	2.8	100.0	

Table 3.1b:Percentage cover for different hydraulic biotopes, Sabie site 1, discharge 2.

DEPTH	pool	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	*1.1*	*0.1*	*1.9*	*2.2*	*3.9*	*1.4*	*1.1*	*0.2*	12.0	12.0
20	*0.3*	*0.1*	*1.4*	*2.8*	*6.7*	*3.1*	*0.6*	*0.2*	15.0	27.0
30	*0.2*	*0.0*	*0.8*	*4.3*	*7.3*	*3.9*	*1.3*	*0.3*	18.0	45.0
40	*0.0*	*0.0*	*0.2*	*6.0*	*10.8*	*3.6*	*1.4*	*0.4*	22.4	67.5
50	*0.0*	*0.0*	*0.1*	*2.5*	*14.6*	*3.1*	*0.9*	*0.3*	21.5	89.0
60	*0.0*	*0.0*	*0.0*	*0.3*	*4.2*	*1.8*	*0.3*	*0.1*	6.7	95.7
70	*0.0*	*0.0*	*0.0*	*0.0*	*0.7*	*1.1*	*0.0*	*0.0*	1.9	97.6
80	*0.0*	*0.0*	*0.0*	*0.0*	*0.7*	*0.6*	*0.0*	*0.0*	1.3	98.9
90	*0.0*	*0.0*	*0.0*	*0.0*	*0.8*	*0.3*	*0*	*0*	1.1	100.0
100	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0*	0	100.0
%	1.6	0.2	4.4	18.1	49.8	18.8	5.6	1.5	100	

Table 3.1c:Percentage cover for the different hydraulic biotopes, Sabie site 1, discharge 3.

DEPTH	pool	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	*0.7*	*0.0*	*1.3*	*2.3*	*4.8*	*1.9*	*0.3*	*0.1*	11.3	11.3
20	*0.4*	*0.1*	*0.9*	*1.4*	*5.1*	*2.1*	*0.4*	*0.2*	10.6	22.0
30	*0.0*	*0.0*	*1.0*	*1.6*	*5.8*	*4.0*	*0.6*	*0.3*	13.4	35.3
40	*0.0*	*0.0*	*0.5*	*3.0*	*7.5*	*4.3*	*0.6*	*0.1*	16.0	51.3
50	*0.0*	*0.0*	*0.0*	*3.1*	*10.9*	*4.0*	*0.9*	*1.0*	19.8	71.1
60	*0.0*	*0.0*	*0.0*	*1.9*	*11.3*	*3.1*	*1.2*	*1.4*	19.0	90.1
70	*0.0*	*0.0*	*0.0*	*0.2*	*4.6*	*0.2*	*0.2*	*0.6*	5.9	96.0
80	*0.0*	*0.0*	*0.0*	*0.0*	*1.5*	*0.2*	*0.0*	*0.0*	1.7	97.7
90	*0.0*	*0.0*	*0.0*	*0.0*	*1.1*	*0.0*	*0.0*	*0.0*	1.1	98.8
100	*0.0*	*0.0*	*0.0*	*0.0*	*1.0*	*0.0*	*0.0*	*0.0*	1.0	99.8
110	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.2	100
%	1.3	0.2	3.8	13.6	53.5	19.9	4.0	3.7	100	

The pattern at discharge 3 remained essentially the same as at discharge 2. There was a slight increase in rapid to 53.5 % at the expense of riffle which decreased to 13.6 %. The high energy biotopes (riffle, rapid, chute and cascade) made up 77.4 % of the total area.

Sabie River Site 2

The spatial distribution of hydraulic biotopes at site 2 can be seen from the series of maps in Figure 3.8; Table 3.2 (a-c) tabulates the percentage of each hydraulic biotope by depth class. Eight of the flow types were present at all three discharges, eddies also occurred at discharge 3. In comparison to site 1 (Figure 3.7), the distribution of hydraulic biotopes was far more broken so that patchiness was much greater. The distribution between biotopes was also more uniform (Figure 3.9). As at site 1, pool biotopes, together with trickle, formed a narrow continuous band along the channel margins. By discharge 2, run biotopes had also coalesced towards the channel margins so this biotope also became continuous along the length of the channel. Riffle formed a near continuous band towards the channel margins by discharge 3.

Table 3.2a:Percentage cover for the different hydraulic biotopes, Sabie site 2, discharge 1

DEPTH	pool	trickle	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	*3.6*	*3.1*	*0.0*	*2.7*	*1.1*	*0.3*	*0.4*	*0.7*	*0.4*	12.3	12.3
20	*3.4*	*2.6*	*0.0*	*1.8*	*1.5*	*1.4*	*0.7*	*0.5*	*0.2*	12.1	24.4
30	*1.7*	*1.7*	*0.8*	*1.4*	*1.7*	*1.5*	*1.0*	*1.0*	*0.5*	11.3	35.7
40	*1.1*	*0.6*	*0.8*	*1.0*	*1.3*	*1.3*	*0.9*	*0.9*	*0.8*	8.5	44.2
50	*0.9*	*0.5*	*0.5*	*1.2*	*1.3*	*1.1*	*0.6*	*0.4*	*0.8*	7.2	51.4
60	*0.5*	*0.6*	*0.2*	*1.5*	*1.5*	*2.7*	*0.7*	*0.4*	*0.4*	8.4	59.8
70	*0.3*	*0.3*	*0.3*	*0.7*	*1.8*	*2.0*	*0.6*	*0.3*	*0.2*	6.6	66.4
80	*0.2*	*0.5*	*0.0*	*0.5*	*1.3*	*2.3*	*0.7*	*0.9*	*0.1*	6.7	73.0
90	*0.3*	*0.4*	*0.0*	*1.0*	*1.8*	*3.1*	*0.5*	*0.5*	*0.1*	7.7	80.7
100	*0.8*	*0.8*	*0.0*	*1.2*	*1.3*	*0.8*	*0.3*	*0.7*	*0.0*	5.8	86.6
110	*0.4*	*0.6*	*0.1*	*0.4*	*1.0*	*0.5*	*0.1*	*0.3*	*0.1*	3.5	90.0
120	*0.4*	*1.9*	*0.0*	*0.5*	*1.4*	*0.3*	*0.0*	*0.0*	*0.0*	4.5	94.5
130	*0.3*	*0.6*	*0.0*	*0.4*	*0.4*	*0.2*	*0.0*	*0.0*	*0.0*	1.9	96.5
140	*0.2*	*0.5*	*0.0*	*0.8*	*0.2*	*0.2*	*0.0*	*0.0*	*0.0*	2.0	98.4
150	*0.1*	*0.4*	*0.0*	*0.5*	*0.0*	*0.2*	*0.0*	*0.0*	*0.0*	1.3	99.7
160	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.1	99.7
170	*0.0*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.3	100
%	14.1	15.4	2.8	15.6	17.7	17.9	6.6	6.4	3.5	100	

Table 3.2b:
Percentage cover for different hydraulic biotopes, Sabie site 2, discharge 2.

DEPTH	pool	trickle	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	*1.8*	*1.3*	*0.0*	*2.0*	*1.3*	*0.8*	*0.6*	*0.8*	*0.5*	9.1	9.1
20	*1.1*	*1.0*	*0.9*	*1.6*	*1.0*	*1.7*	*1.6*	*0.9*	*1.3*	11.2	20.2
30	*0.9*	*0.7*	*0.4*	*1.4*	*1.3*	*2.7*	*2.4*	*0.8*	*0.4*	11.0	31.2
40	*0.7*	*0.8*	*0.1*	*1.7*	*1.8*	*1.7*	*1.8*	*1.1*	*0.5*	10.3	41.5
50	*0.6*	*0.2*	*0.0*	*1.3*	*1.6*	*1.9*	*1.3*	*0.9*	*0.1*	7.8	49.2
60	*0.3*	*0.2*	*0.0*	*1.2*	*1.7*	*1.1*	*1.7*	*0.4*	*0.1*	6.6	55.9
70	*0.3*	*0.2*	*0.0*	*1.3*	*1.9*	*2.1*	*1.4*	*0.4*	*0.1*	7.6	63.5
80	*0.1*	*0.0*	*0.0*	*0.4*	*1.5*	*2.4*	*1.1*	*0.4*	*0.1*	6.0	69.4
90	*0.1*	*0.0*	*0.1*	*0.2*	*1.0*	*2.2*	*2.0*	*0.2*	*0.3*	6.1	75.5
100	*0.2*	*0.0*	*0.1*	*0.1*	*1.0*	*4.0*	*0.9*	*0.3*	*0.4*	7.0	82.5
110	*0.1*	*0.1*	*0.0*	*0.1*	*1.2*	*2.0*	*0.9*	*0.4*	*0.3*	5.3	87.8
120	*0.1*	*0.0*	*0.1*	*0.1*	*0.8*	*0.9*	*0.8*	*0.2*	*0.2*	3.2	91.0
130	*0.1*	*0.0*	*0.0*	*0.0*	*2.0*	*0.9*	*0.8*	*0.1*	*0.1*	4.1	95.0
140	*0.1*	*0.1*	*0.0*	*0.1*	*0.2*	*0.3*	*0.7*	*0.1*	*0.0*	1.8	96.8
150	*0.1*	*0.1*	*0.0*	*0.1*	*0.1*	*0.3*	*1.0*	*0.2*	*0.0*	1.8	98.6
160	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	*1.0*	*0.0*	*0.0*	1.2	99.7
170	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.0	99.8
180	*0.0*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.2	100
	6.6	5.0	1.6	11.5	18.7	25.3	20.2	7.1	4.2	100	

Table 3.2c:
Percentage cover for different hydraulic biotopes, Sabie site 2, discharge 3.

DEPTH	pool	trickle	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
10	2.3	*1.5*	*0.0*	*1.4*	*0.7*	*0.1*	*0.0*	*0.0*	*0.0*	6	6.0
20	*2.4*	*1.3*	*0.7*	*2.6*	*0.9*	*0.3*	*0.1*	*0.1*	*0.2*	8.5	14.6
30	*1.6*	*0.9*	*0.4*	*2.3*	*1.6*	*1.1*	*1.2*	*0.8*	*0.6*	10.5	25.1
40	*1.3*	*0.7*	*0.0*	*2.0*	*2.9*	*2.3*	*0.9*	*0.3*	*0.0*	10.3	35.4
50	*1.2*	*0.8*	*0.0*	*2.6*	*3.1*	*1.2*	*0.4*	*0.4*	*0.0*	9.7	45.1
60	*0.8*	*0.2*	*0.0*	*2.4*	*2.8*	*0.5*	*0.5*	*0.1*	*0.0*	7.3	52.5
70	*0.3*	*0.1*	*0.0*	*1.1*	*3.1*	*0.8*	*0.5*	*0.2*	*0.0*	6.3	58.7
80	*0.2*	*0.2*	*0*	*0.8*	*2.5*	*2.3*	*0.8*	*0.4*	*0.0*	7.2	65.9
90	*0.1*	*0.0*	*0.0*	*0.4*	*2.1*	*1.9*	*0.7*	*0.4*	*0.0*	5.6	71.5
100	*0.1*	*0.0*	*0.0*	*0.1*	*2.5*	*1.8*	*0.8*	*0.2*	*0.0*	5.7	77.2
110	*0.1*	*0.1*	*0.0*	*0.1*	*2.2*	*3.1*	*0.6*	*0.2*	*0.1*	6.6	83.8
120	*0.1*	*0.1*	*0.0*	*0.1*	*1.7*	*1.2*	*1*	*0.5*	*0.1*	4.9	88.7
130	*0.1*	*0.1*	*0.0*	*0.1*	*0.6*	*0.9*	*0.4*	*0.4*	*0.2*	2.8	91.5
140	*0.1*	*0*	*0.0*	*0.1*	*1.6*	*1.0*	*0.5*	*0.2*	*0.1*	3.8	95.3
150	*0.2*	*0.3*	*0*	*0.2*	*0.1*	*0.4*	*0.2*	*0.2*	*0.2*	1.7	97.0
160	*0.1*	*0.1*	*0.0*	*0.1*	*0.5*	*0.3*	*0.4*	*0.1*	*0.0*	1.6	98.6
170	*0.0*	*0.1*	*0.0*	*0.0*	*0.4*	*0.3*	*0.4*	*0*	*0*	1.1	99.7
180	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0*	0.1	99.8
190	*0*	*0.2*	*0.0*	*0.0*	*0.0*	*0.0*	*0*	*0*	*0*	0.2	100

DEPTH	pool	trickle	glide	run	riffle	rapid	chute	cascade	eddie	%	cum %
	11.2	6.7	1.1	16.5	29.1	19.6	9.6	4.6	1.7	100	

This site was not dominated by any single flow type or flow depth (Table 3.2 and Figure 3.9). At discharge 1 there were 5 hydraulic biotopes which were relatively evenly represented; pool (14.08%), trickle (15.35%), run (15.6%), riffle (17.68%) and rapid (17.94%). This demonstrates a good mix of higher and lower energy hydraulic biotopes. At discharge 2 riffle became the dominant biotope (29.07 %) at the expense of trickle which decreased from 15.3 % to 6.67 %. By discharge 3 there was a shift to the higher energy biotopes - rapid (25.25%) and chute (20.21%), with a reduction of riffle back to (18.65%). The lower energy biotopes (pool, trickle, glide and run) represented slightly less than a quarter of the area (24.6%) at this discharge compared to 47.87 % at discharge 1. It is of interest to note the increase in the pool biotope at the highest discharge. This was due to the flow spreading out into shallow marginal areas.

3.1.4 Patchiness

Patchiness refers to the degree of dis-aggregation of hydraulic biotopes at a site. Generally it is accepted that a high degree of patchiness is preferable to a more homogenous condition as it promotes ecological diversity. Patchiness does not necessarily provide an indication of habitat diversity. It is quite possible to have a full range of hydraulic biotopes (high habitat diversity) but have a low patchiness. In other words each hydraulic biotope is a single well defined unit which is quite clearly separated from other hydraulic biotopes.

Sabie River Site 1

Table 3.3 demonstrates the difference in patchiness for site 1 at three different discharges. Three simple statistical variables have been used; total number of hydraulic biotopes (count), average area (average) and the standard deviation(SD).

Patchiness increased at site 1 in response to an increasing discharge. The number of patches at discharge 3showed a fifty precent increase compared to discharge 1. The average area of each hydraulic biotope remained similar as discharge increased. This was an interesting observation because it suggests that hydraulic biotope diversity and size did not change significantly at this site in response to discharge. Rather the change was in the total habitat area and number of patches. Standard deviation increases slightly from discharge 1 to discharge 2 but remains relatively stable from discharge 2 to discharge 3.

Table 3.3 Patchiness of site 1, for all three discharges

	Q1	Q2	Q3
Number of hydraulic biotopes	8	8	8
Total area (m^2)	434	499	610
Count	145	172	287
Average size (m^2)	2.99	2.9	2.12
SD (m^2)	12.2	15.8	15.4

Sabie River Site 2

Table 3.4 demonstrates the difference in patchiness for site 2 at three different discharges. Patchiness decreased at site 2 in response to an increasing discharge. This pattern was in direct contrast to that found at site 1. The total area of hydraulic biotopes remained constant for the three different discharges. The reason for this was likely to be a result of the topography. Steep, well defined banks mean that as discharge increased the flow depth increased with a limited lateral extension. The average area of each hydraulic biotope increased as discharge increases. This pattern suggests that increasing discharge had the affect of linking the different hydraulic biotopes making each hydraulic biotope larger and producing less patches. The number of patches at discharge 1 was more than double that of discharge 3. The standard deviation increased slightly from discharge 1 through to discharge 3.

Table 3.4 Patchiness of site 2, for all three discharges

	Q1	Q2	Q3
Number of hydraulic biotopes	9	9	9
Total area (m^2)	704	704	704
Count	357	216	168
Average size (m^2)	1.97	3.26	4.19
SD (m^2)	11.66	13.06	15.8

FIGIURE 3.10

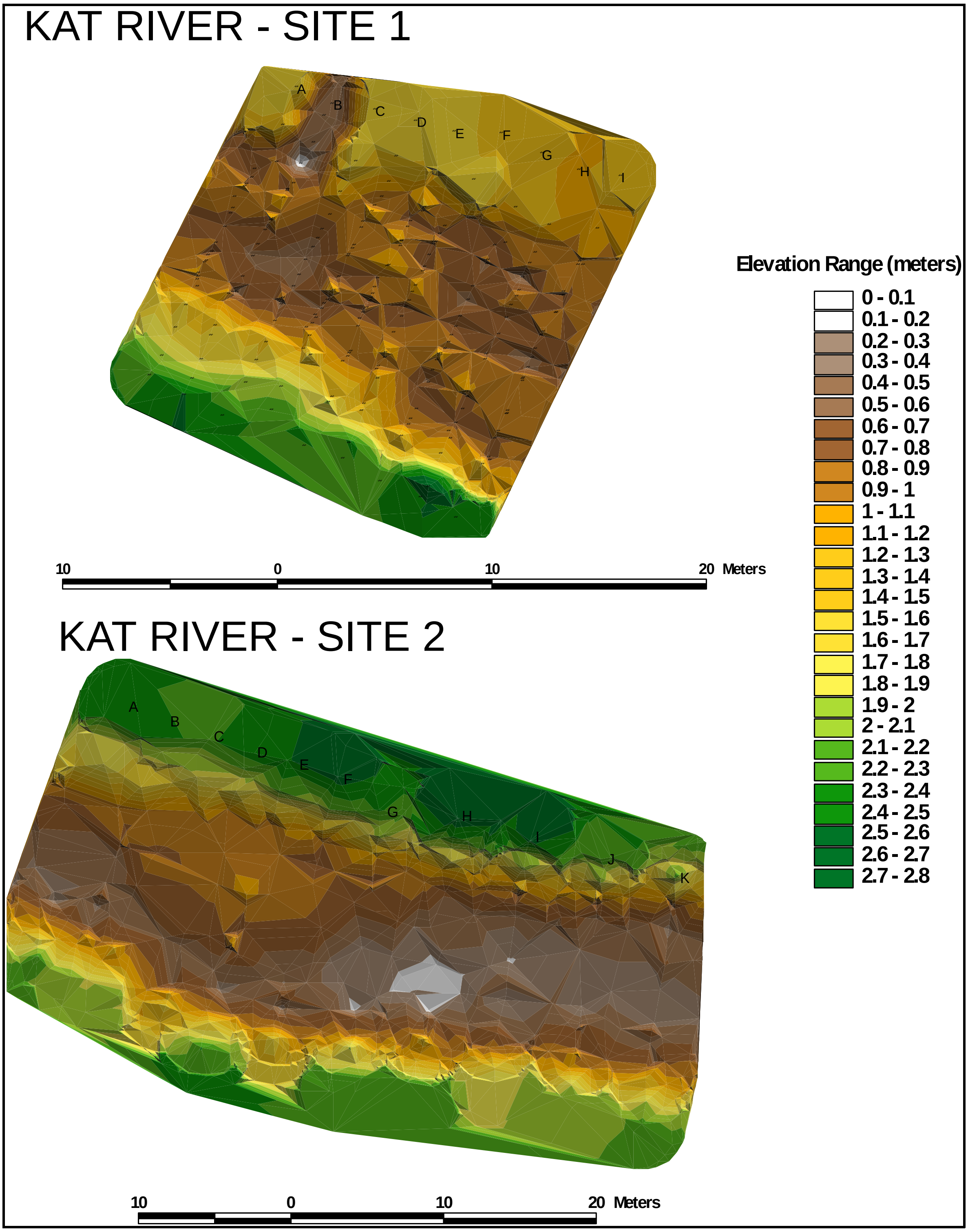


Figure 3.10 Kat River - Topographic maps of survey sites

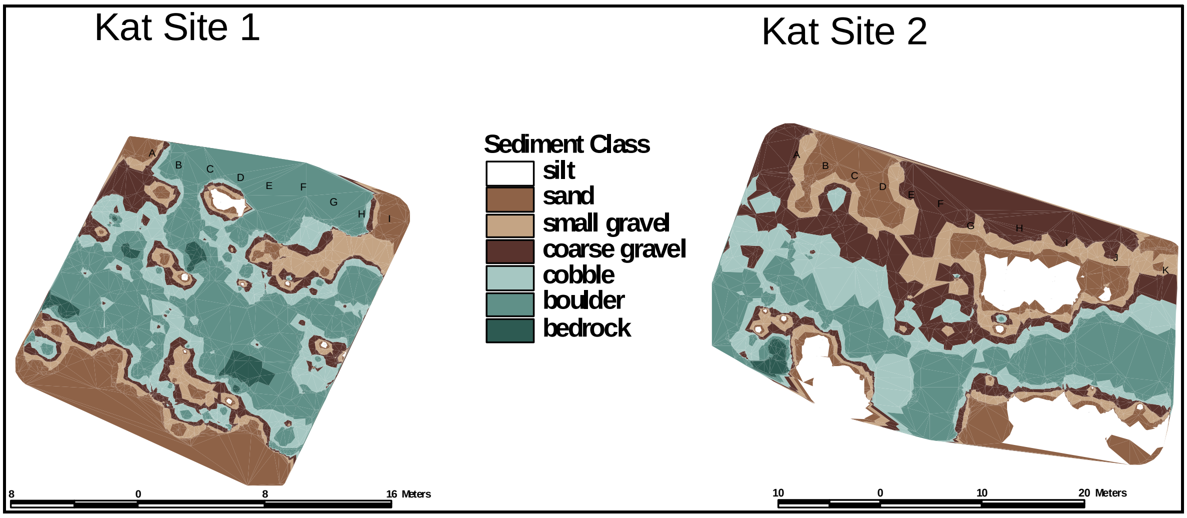


Figure 3.11 Kat sites - Sediment distribution

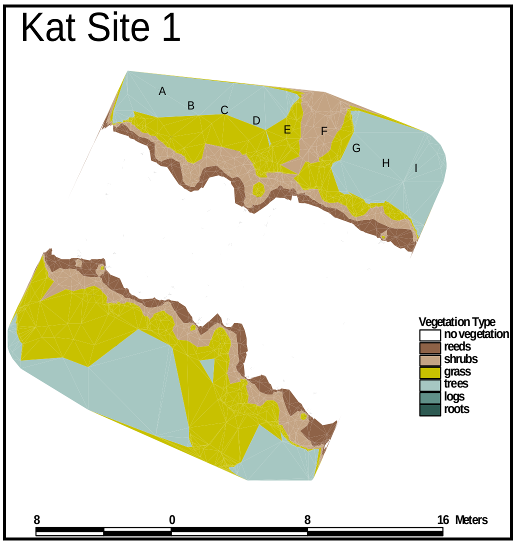


Figure 3.12 Kat sites - Vegetation distribution

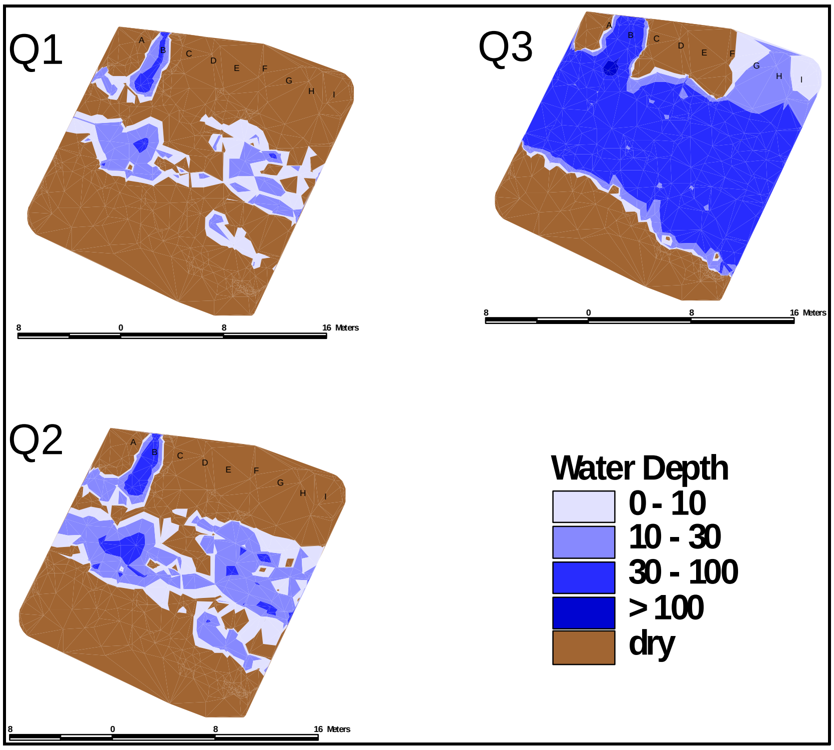


Figure 3.13 Maps of water depth map for site 1, Kat River

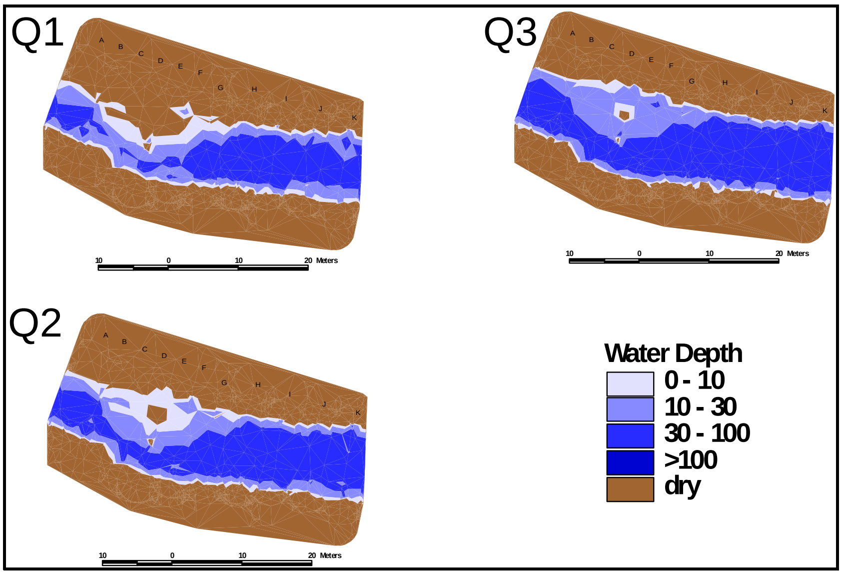
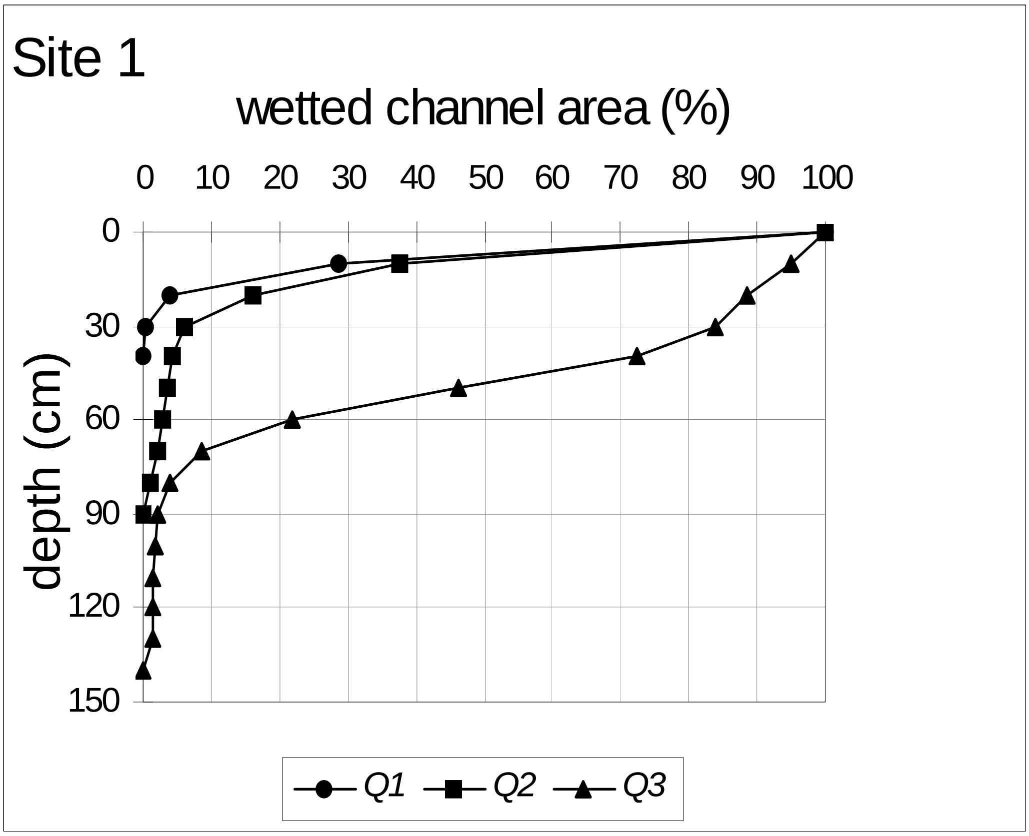


Figure 3.14 Maps of water depth for site 2, Kat River



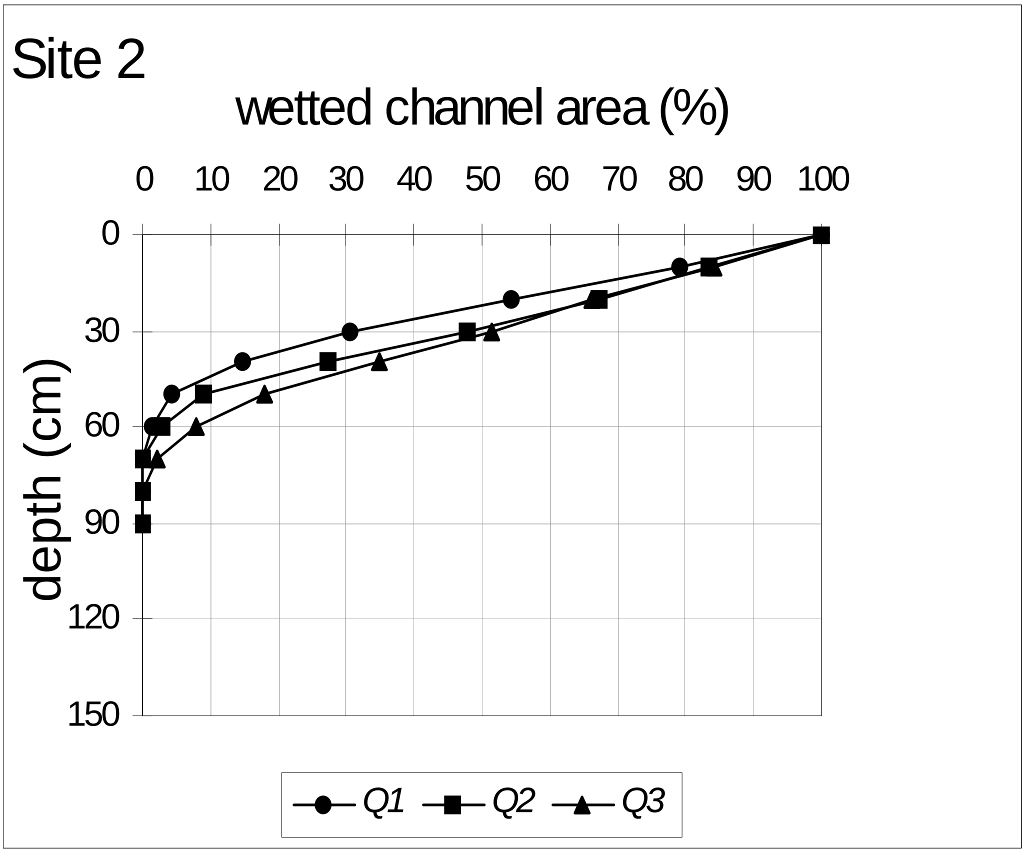


Figure 3.15 Cumulative depth distributions at the two sites on the Kat River

3.2 Kat River

3.2.1 Site topography, sediment characteristics and vegetation

The contrasting topography between the two sites can be seen from Figure 3.10.

Site 1 topography was relatively complex with a number of large boulder and bedrock intrusions which have created a pool-rapid morphology. The channel bank on the right hand side consisted of alluvial sand and was well defined. The left hand bank was not well defined and consisted of coarse gravel and cobble behind a riparian vegetation border. This site was approximately 20 metres in length and 20 metres in width (from bank top to bank top).

At site 2 the topography consisted of a pool - riffle morphology. The channel banks were well defined with no obvious signs of incision. This site was approximately 45 metres in length and 26 metres in width.

Figure 3.11 compares the sediment distribution at the two sites. Cobbles and boulders dominated the active channel at both sites. Pockets of small gravel were present within the active channel of site 1, this material was positioned in the lee of coarse material. Site 2 illustrates the presence of large quantities of coarse gravel as a lateral bar on the left hand bank.

Figure 3.12 illustrates the vegetation distribution at site 1. At the base of both banks was a narrow zone of reeds, as one moves up the banks vegetation changed to shrubs, grasses and finally trees on the bank top.

3.2.2 Water Depth

The maps (Figures 3.13 & 3.14) demonstrate the change in water depth distribution in response to changing discharge at the two sites.

Kat Site 1

Distribution of water depth at this site illustrates a poor cover of the various depth classes until discharge 3. Discharge 1 illustrates a very narrow band of mostly continuous flow in the class 0 -10cm. Discharge 2 illustrates a continuous linkage of flow 0 - 10cm deep and a near continuous linkage of flow 10 - 30cm deep. There were also occasional isolated deeper pockets of water 30 - 100cm deep. At discharge 3 there was a continuous wide band of water 30 - 100 cm deep.

Using the same logic as for the Sabie site, if one was to assume that adult fish at this site require a depth of 30 cm or more for free and easy movement, they would be limited in their range at discharge 1 and 2. At discharge 3 they would have access to the full length of the site.

Kat Site 2

As with site 1, three separate maps of water depth were produced to illustrate changes that occur in response to changing discharge (Figure 3.14). Depth distribution was unlikely to be an issue of concern at this site for the discharges experienced in this study. There was a wide continuous band of flow through the center of the river which was 10 - 30 cm deep at discharge 1. At discharge 2 and 3, a band 30 - 100 cm becomes continuous. This would suggest that there was adequate depth at these discharges to provide good cover and free and easy passage for adult fish. The deepest class of water > 100 cm did not occur at this site for the discharges recorded.

Figure 3.15 compares the distribution of depth at the different discharges and is equivalent to Figure 3.6 for the Sabie. Apart form a local pocket of deep water, the depth at site 1 is quite uniform. There is a greater range of depth at site 2 which is not surprising as both the riffle and pool were included in the survey. At Q1 only 1 % of the wetted area was greater than 30 cm, allowing limited fish passage. The distribution was similar at Q2, with 5 % deeper than 30 cm but increased to 85 % at Q3. For site 2 the percentage of the wetted area greater than 30 cm increased from 30 % at Q1 to just over 50 % at Q3.

Kat Site 1

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Using the same logic as for the Sabie site, if one was to assume that adult fish at this site require a depth of 30 cm or more for free and easy movement, they would be limited in their range at discharge 1 and 2. At discharge 3 they would have access to the full length of the site.

Kat Site 2

As with site 1, three separate maps of water depth were produced to illustrate changes that occur in response to changing discharge (Figure 3.14). Depth distribution was unlikely to be an issue of concern at this site for the discharges experienced in this study. There was a wide continuous band of flow through the center of the river which was 10 - 30 cm deep at discharge 1. At discharge 2 and 3, a band 30 - 100 cm becomes continuous. This would suggest that there was adequate depth at these discharges to provide good cover and free and easy passage for adult fish. The deepest class of water > 100 cm did not occur at this site for the discharges recorded.

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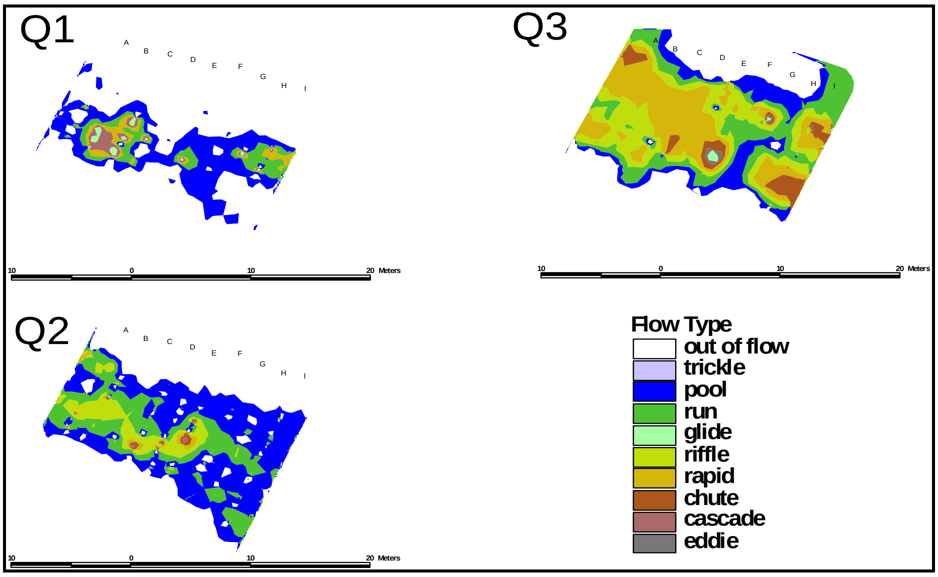
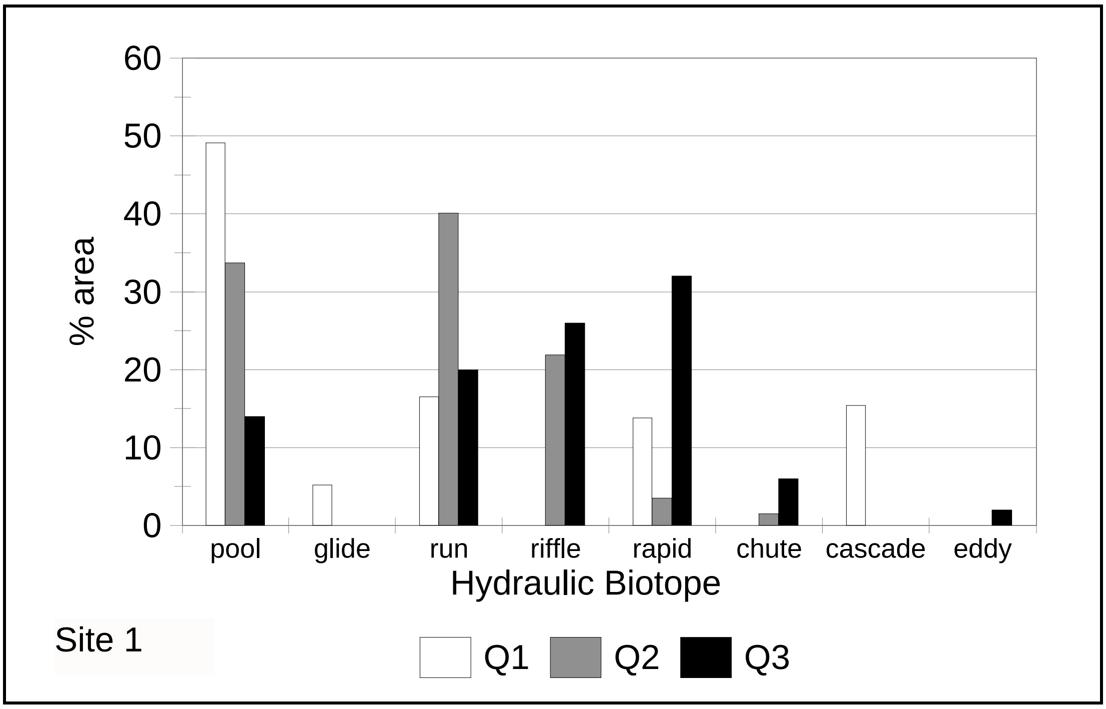


Figure 3.16 Kat River, site 1 - Hydraulic biotope distribution



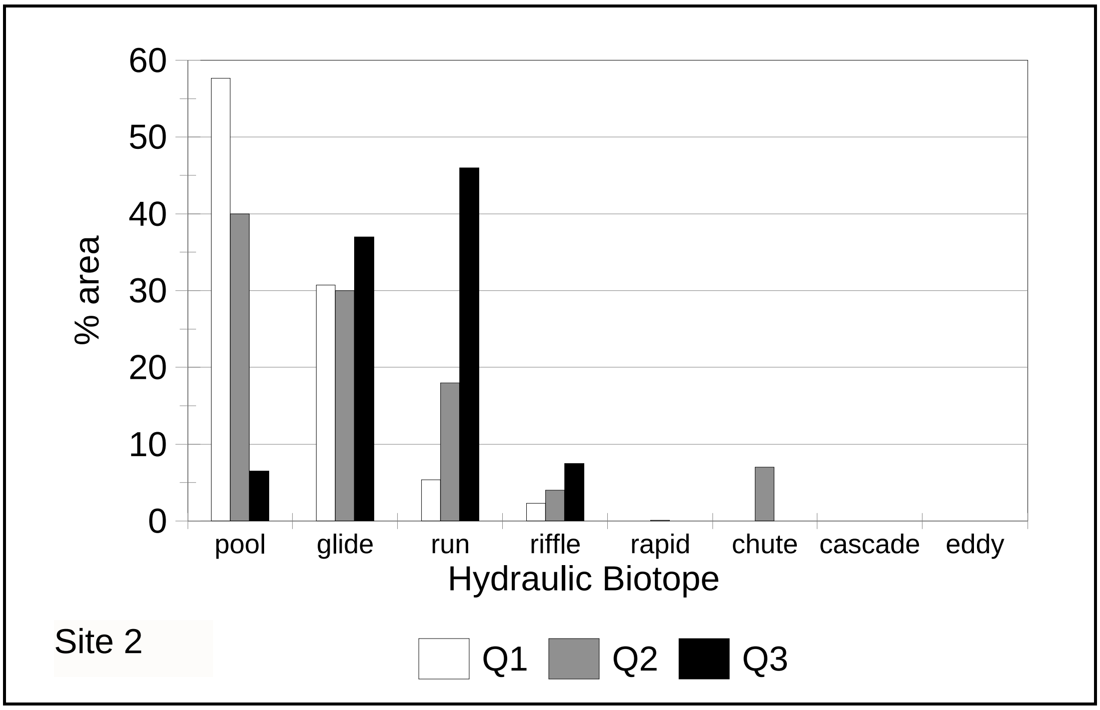


Figure 3.17 Comparison of hydraulic biotopes at Sites 1 and 2, Kat River

3.2.3 Hydraulic Biotope Distribution

Kat River Site 1

Figure 3.16 presents maps of the hydraulic biotopes at the three discharges.

Hydraulic biotope diversity changed in response to discharge at this site. At discharge 1, five of the possible nine flow types were present, at discharges 2 and 3 this figure increases to seven of the possible nine. No trickles were observed at this site, riffles, chutes and eddies were not present at the lower flow but become apparent as flow increased. Cascades were lost as flow increases.

Pool was the only flow type which showed a continuous linkage down the length of the study site at all discharges. This flow type starts as a fairly narrow lateral band around the channel margin but extends across the width of the channel at discharge 2. By discharge 3 the pool and run flow type had become confined to a narrow lateral band; as a consequence glide, riffle, rapid and chute flow types had become nearly continuous.

The percentage distribution of habitats at the three discharges is given in Figure 3.17. At discharge 1 this site was dominated by pool (49.1%), run (16.5%) and cascade (15.4%) hydraulic biotopes. The high energy biotopes - rapid and chute - made up only 13.8 % of the total area. Pool was shown to be well distributed throughout this site, as was seen from the maps in Figure 3.16. Glide, which can also be considered as a relatively low velocity hydraulic biotope, only constituted 5.2% of the total area. As discharge increased from discharge 1 to discharge 2 the distribution of hydraulic biotopes shifted towards those characterised by higher energy flows. The percentage of pool decreased from 49.1% to 33.7% and riffle from 0 % to 21.9 %, while run increased from 16.5 % to 40.1%. Cascades and glides all but disappeared at this discharge. Run and riffle together made up 62 % of the total area. This obviously means a decrease in area of the slower flowing environments.

The pattern at discharge 3 demonstrated another change in hydraulic biotope distribution. As expected, pool and run decreased while riffle, rapid and chute increased. Run, riffle, rapid and chute constitute 83% of the total area.

Patchiness

Patchiness data are presented in Tables 3.5 and 3.6 for the two sites on the Kat. Patchiness at site 2 was estimated form the transects rather than the derived maps. Dimensions are therefore given as lengths rather than areas. For both sites the highest number of patches is at the intermediate discharge. The patches also tend to be smallest at this discharge, with the greatest variability as given by the standard deviation (site 1 only).

Table 3.5 Patchiness of site 1, for all three discharges

	Q1	**Q2**	**Q3**
Number of hydraulic biotopes	5	5	6
Total area (m^2)	434	499	610
Count	157	279	138
Average size (m^2)	2.48	1.4	2.73
SD (m^2)	12.2	15.8	15.4

Table 3.6 Patchiness of site 2, for all three discharges

	Q1	**Q2**	**Q3**
Number of hydraulic biotopes	4	6	4
Total length (m)	81	108	118
Count	40	64	48
Average diameter (m)	2.03	1.69	2.46

3.3 Effect of channel morphology on the relationship between hydraulic biotope pattern and discharge

The four sites were selected to include contrasting channel morphology for the two rivers. Site 1 on the Sabie was a steep riffle section, with cobble and boulder substrate. Site 2 on the Sabie was a more complex site, comprising pool-rapid morphology. Large boulders provided the macro-scale structure of this site; between these boulders cobble and small boulder provided the main substrate. Site 1 on the Kat was also had a pool-rapid morphology, though the scale was smaller and the large boulders were lacking. Site 2 had a pool-riffle morphology with a significant amount of gravel in the substrate. Because of the short length of riffle the pool was included in the habitat survey.

The water depth maps bring out interesting comparisons between the sites. The pool- rapid morphology of site 2 in the Sabie and site 1 in the Kat is associated with a more patchy distribution of depths, whilst the pool-riffle morphology of site 1 in the Sabie and site 2 in the Kat have more continuous depth distributions, with better longitudinal linkage. The patchy distribution in the pool-rapid sites is maintained as discharge increases, whereas it is lost in the riffle. This reflects the cross-section shape of the sites and the degree to which the change in discharge can be taken up by a change in width rather than depth. In the pool-rapid sites the water surface is able to extend laterally as discharge increases, thus creating new areas of shallow water. In the pool-riffle sites the channel width is more constrained, so that increases in discharge are accommodated by an increase in depth, and a decrease in patchiness, rather than a decrease in width.

The hydraulic biotope maps show clear evidence of discharge related changes in the distribution and proportions of the different habitats. At all sites the extent of high energy hydraulic biotopes increased as discharge increased. Clear differences in hydraulic biotope response can be seen between the two different channel types and mirrors the changes noted for depth. The pool-rapid sites in both the Sabie and Kat had patchy hydraulic biotope distributions at all discharges. The geomorphological structure of the channel therefore has a strong bearing on the relationship between habitat availability and discharge.

4. APPLICATION TO ECOLOGICAL FLOW ASSESSMENT

4.1 Habitat mapping and Ecological Water Requirements

Motivation for the research described in this report has been derived from a need by EWR practitioners to extrapolate the results of the hydraulic analysis from a single transect across a morphological unit to the full spatial extent of that unit. Any method developed had to be cost effective and relevant to the ecologists participating in the EWR exercise. It is believed by the authors that the method of habitat mapping presented here meets these needs.

The hydraulic biotope maps differentiate hydraulic habitat in terms of integrated hydraulic variables that manifest themselves in terms of surface flow characteristics - the flow type. Flow type appears to be an expression of the Froude number, which itself integrates velocity and depth (Wadeson and Rowntree, 2001). The hydraulic biotope is thus an expression of the energy state of the flow, but it does not give a direct indication of either velocity or depth, the two variable most often cited by ecologists as determining habitat preference. The depth dimension has been added though the depth maps that were modelled from the channel topography as a simple overlay. If these maps are combined with the habitat maps, an indication of velocity can be obtained by inference. For example a glide between 10 to 30 cm will have a low velocity but a glide with a depth greater than 100 cm will have relatively high flow velocity.

It will be noted that the habitat maps were derived without recourse to velocity measurements. This represents a significant saving of time in the collection of field data. If discharge data can be obtained from a nearby weir it also obviates the need for a flow meter. Hydraulic biotope mapping therefore has clear advantages over the alternative method of detailed sampling of current velocity. It should also be noted that the depth maps are derived without the use of hydraulic modelling. They depend solely on a topographic template over which the water surface is laid. As with all modelling, the result is an approximation of reality, but it is believed that the method gives a quick and effective means of depicting changes in the spatial distribution of depth. Of particular interest is the ability of the maps to portray the linkage between patches of critical flow depth. Only by looking at the maps of depth distribution can we tell, for example, whether conditions are suitable for fish passage along the entire length of the morphological unit.

The template illustrated in Figure 3.6 or Figure 3.15 can be used in association with the maps to determine the discharge that provides optimum depth conditions. It should be noted that Figure 3.6 has been derived from a spreadsheet that allows the changes in depth at different discharges to be modelled interactively in a workshop situation. The maps presented in this report provide an objective assessment of the availability of hydraulic habitat expressed through biotope mapping. The interpretation of these maps in terms of habitat suitability depends on input from specialist ecologists who must consider the information in terms of the specific flow and substrate requirements of selected biota. Habitat maps for selected channel morphologies can be used to give a spatial dimension to the transect based hydraulic variables provided by a hydraulician. These data are presented to the ecologists whose task it is to identify the flow stage that provide the most favourable conditions for the different biotic components - vegetation, fish and invertebrates. Flow stage can then be translated into a discharge through a flow rating curve. These discharges are then integrated to a composite modified flow regime that is agreed amongst the specialist to be the minimum required to provide adequate protection of the water resource. Thus habitat mapping can be seen to be one component of a process that utilises the knowledge of different specialists. An example of habitat mapping as applied to the Thukela Reserve determination id given below.

4.2 Habitat mapping in the Thukela Reserve

A recent comprehensive river reserve to be carried out in South Africa has been that for the Thukela Basin. Following the success of the use of digital terrain mapping (DTM) for the setting of instream flow requirements, it was decided that 5 sites would be selected and mapped in the Thukela basin. Two sites were selected on the main stem of the Thukela River while one site each was selected on the Buffalo, Mooi and Bushmans tributaries.

Many of the ecologists involved in the Thukela EWR had already been exposed to the DTM procedure in the Olifants EWR. For this reason more specific requirements for the collection and presentation of data were voiced by the various specialists in the Thukela study. One particularly important addition was the detailed collection of vegetation data to allow the demarcation of vegetation zones along the river boundary.

The mapping of vegetation within the DTM allowed a fairly accurate assessment of the water level requirements within a river reach to allow for the innundation of roots or stems etc.

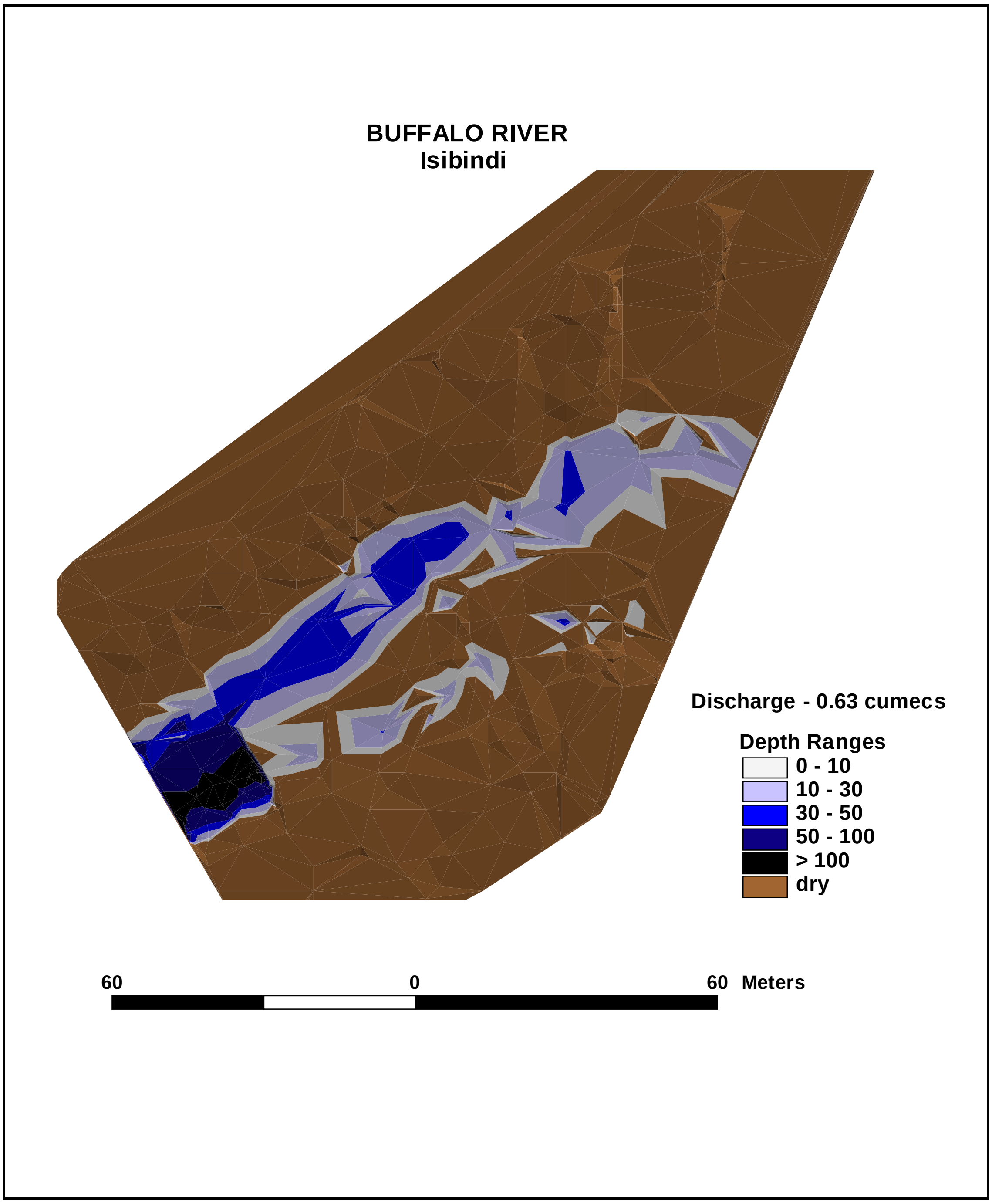


Figure 4.1 Modelled depth data for the Isibindi Site on the Buffalo River at a discharge of 0.63 m^3s^{-1}

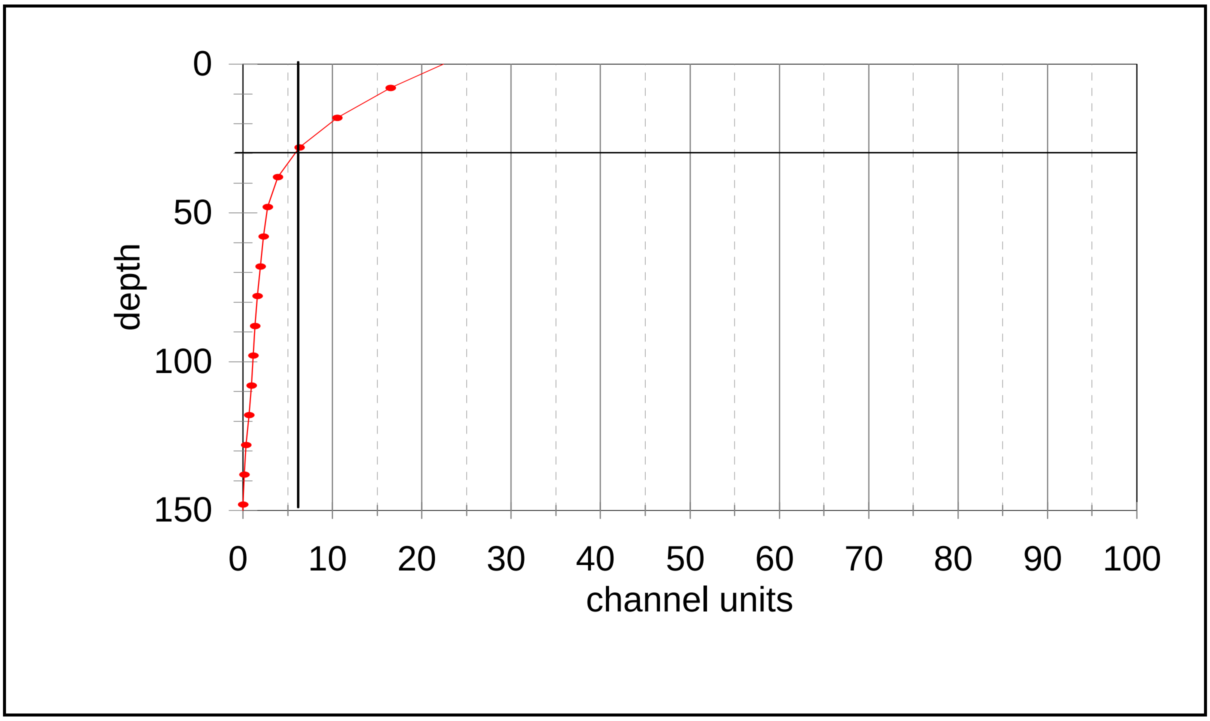


Figure 4.2 Graph to illustrate the proportion of the channel deeper than 30 cm for Isibindi Site (Buffalo River) at a discharge of 0.63 m^3s^{-1}.

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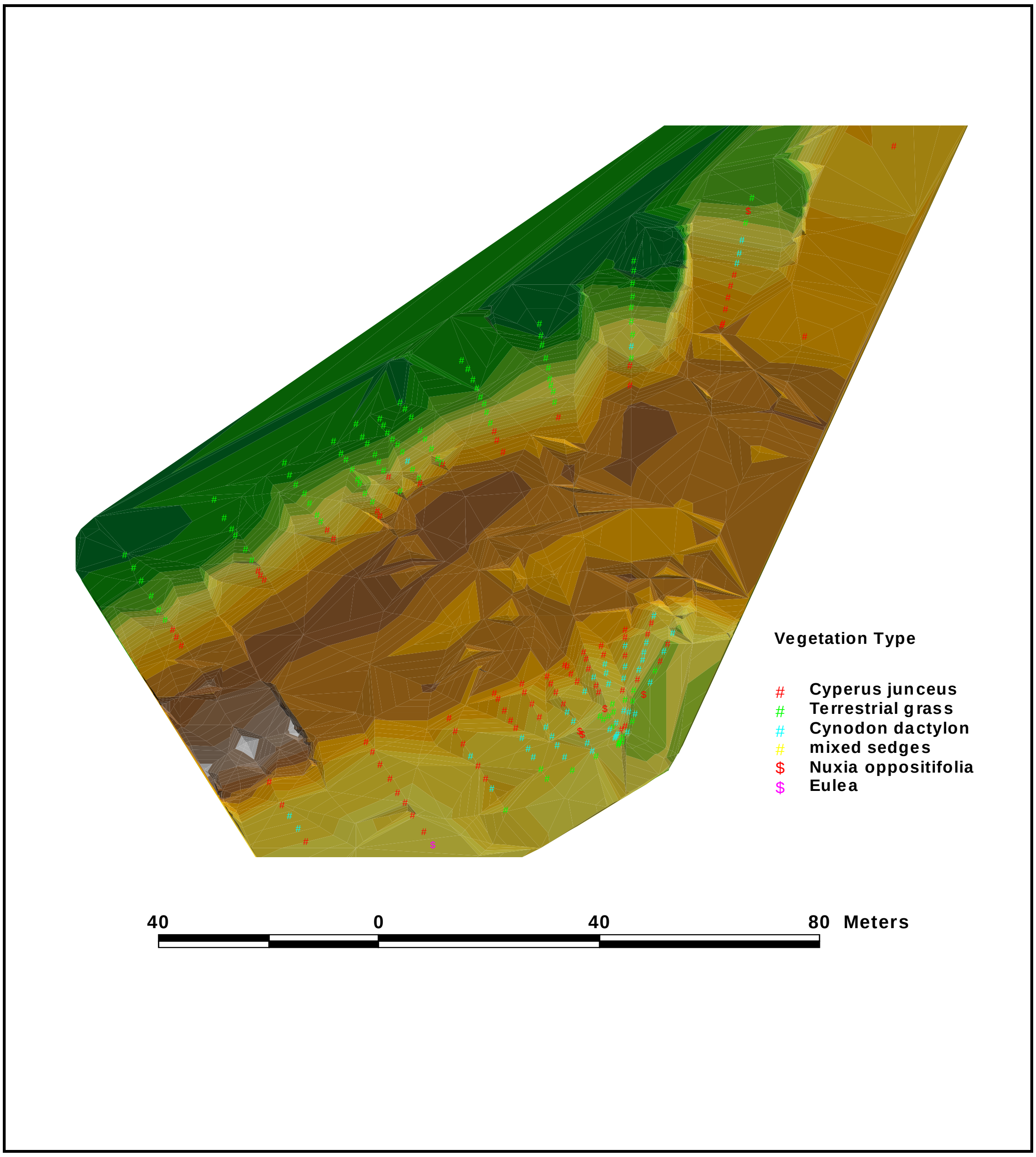

Figure 4.3 Topographical map of Isibindi site on the Buffalo River together with vegetation data.

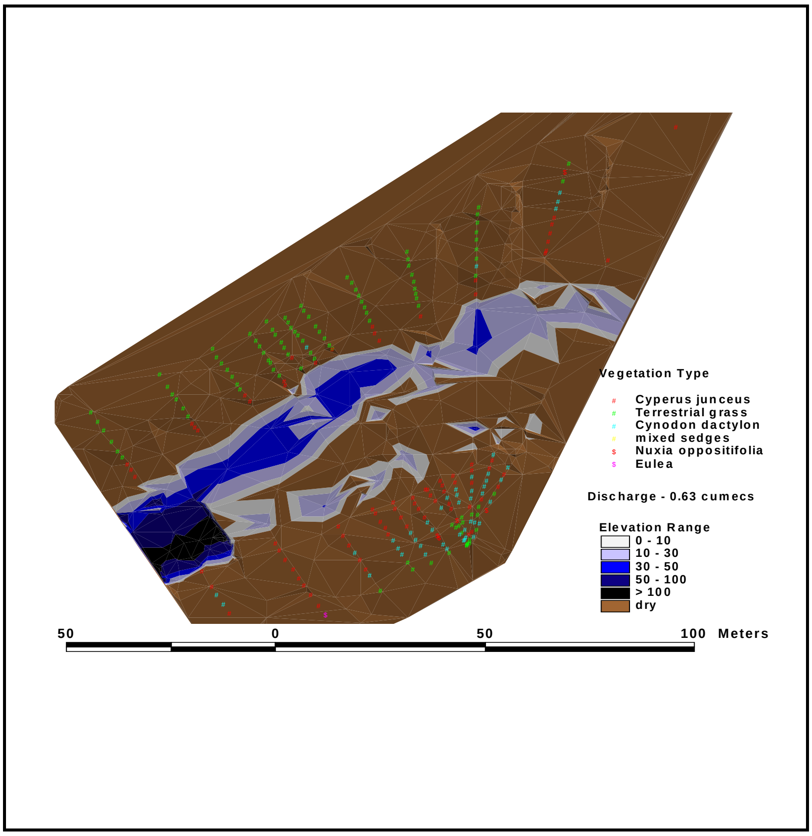

Figure 4.4a Isibindi Site - discharge 0.63 m^3s^{-1}.

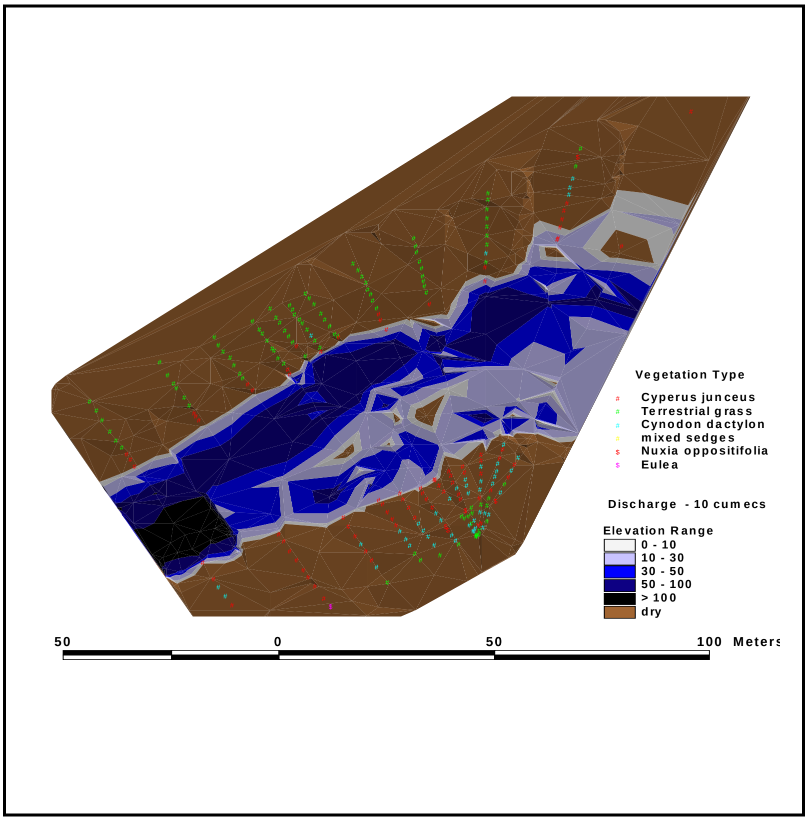

Figure 4.4b Isibindi Site - discharge 10 m^3s^{-1}

This has special significance for the riparian vegetation specialist, but is also important for the fish and invertebrate specialists who often require marginal vegetation in the water at specific times of the year. The technique used for the mapping of instream habitat was essentially the same as that outlined in the report. The main difference between the techniques described in the report and those used in the Thukela IFR are related to the way in which the data was presented to the specialists and the way in which this data was interpreted.

4.2.1 Mapping water depth

After consultation with the specialist concerned with fish requirements there was a request for the presentation of depth data in a number of specific classes rather than simply 10 cm intervals. The classes selected were: 0 -10 cm (very shallow), 10 - 30 cm (shallow), 30 - 50 cm (moderate), 50 - 100 cm (deep) and > 100 cm (very deep). It appears as though fishery biologists recognise 30 cm depth and 50 cm depth as critical break points between shallow and deeper water. These depths need to be considered together with flow velocity, of which 0.3 $m.s^{-1}$ (slow) and 0.5 $m.s^{-1}$ (fast) are considered to be most important. Depth and velocity together are important components for fish in that they influence the success of migration, feeding, spawning and cover.

The method used for the presentation of data in the EWR workshop was by way of an overhead projector connected to the laptop computer. An ecological specialist would then ask for a particular flow discharge, this was quickly converted to a maximum flow depth for the site in question using the look-up tables provided by the hydraulician. The maximum flow depth was then converted into the five depth classes within arcview and mapped (Figure 4.1).

Any number of maps could be produced quickly in this way and allowed the various specialists to determine the ultimate flow depth pattern for a site at a particular time of the year. The example in Figure 4.1 illustrates a lack of connectivity between water of a depth greater than 30 cm. We can see that there was a dominant channel (flowing from left to right) on the left hand bank. This channel was bounded by a deep pool upstream (greater than 50 cm depth) and a shallow flow of water downstream (less than 30cm depth). The map of water depth together with the look-up tables, provided by the hydraulician, allowed a general assessment of current speed. Hydraulic data provided an average velocity, average depth and maximum depth at a cross section. This data could be interpolated to areas between cross sections for use by the ecological specialists to determine a general flow condition (depth and velocity) for the site at each selected discharge.

Together with a map of flow depth, the specialist was provided with a graph illustrating the proportion of the channel which was deeper than a given depth (Figure 4.2).

4.2.2 Mapping vegetation

Lessons learned from the Olifants EWR indicated the need for a more rigorous and formal presentation of vegetation data. In the Thukela EWR, vegetation data was collected and mapped at each survey point that was used to produce topographical data (Figure 4.3).

From Figure 4.3 one can clearly see bands or zones of vegetation along the channel margin. By placing water on top of the topography and vegetation, the various specialist were able to determine at which stage the various vegetation “bands” were inundated (Figures 4.4a and 4.4b). This proved to be very important for the riparian vegetation specialist who was trying to provide water to roots, disperse seeds, recharge banks etc. The invertebrate specialists were also interested in this aspect as marginal vegetation in water provides a very important habitat at different times of the year. Fish specialists indicated the importance of marginal vegetation in water for cover for certain fish species at different life cycle stages at different times of the year.

The availability of habitat mapping data for five sites in the Thukela EWR procedure proved to be extremely useful. There was a unanimous agreement amongst specialists at the EWR post mortem that the maps had made an assessment of instream flow requirements much easier and allowed the various people concerned to make recommendations with considerably more confidence than they would usually have for a single transect. There was a general call for the use of habitat mapping in all future comprehensive reserve determination projects.

5. CONCLUSIONS

Specifying flows to provide a range of suitable habitat for in-stream organisms is one of the key activities in assessing water quantity requirements for the Ecological Reserve (the Ecological Water Requirement - EWR). Specialists are asked to agree on a suite of discharges that will provide habitat specifically for invertebrate and fish species found in the river reach. Habitats patches are described in terms of depth, velocity and the underlying substrate as well as the connectivity between patches, important for example for fish passage.

Conventional techniques used in South Africa base the assessment of discharge related habitat changes on the average depth and velocity estimated for one or two transects across the study site. There is a recognised need for an effective technique to map habitat within the context of the Ecological Reserve. Two dimensional models that can create velocity and depth distributions within a channel section are available, but the soft ware is expensive, requires intensive field data collection and, more importantly, the problems of modelling low flows in hydraulically complex channels are compounded as one moves form a one-dimensional to two-dimensional model. An alternative approach is to couple field mapping of hydraulic habitats with data manipulation using GIS. This is the approach developed in the project reported on here.

Field mapping of hydraulic biotopes Wadeson (1994) has been used as the basis of a technique to describe discharge related changes in instream habitat using hydraulic biotope mapping. The four sites selected in the upper Sabie River (Mpumalanga) and the Kat River (Eastern Cape). represented a range of channel morphology and discharge regimes. The mapping technique proved to be an effective way of producing information on the spatial distribution of habitats that can be used in an environmental flow requirement (EWR) workshop. Its application in the Thukela workshop is given by way of an example. Ecologists found the maps easy to follow and greatly increased their confidence in recommending flows. Habitat mapping is now recognised as an important component of an EWR determination.

The results showed that the habitat-discharge relationship varies with channel morphology. We are not yet in a position to predict this relationship from the morphological characteristics of the stream, but with wider application to different sites this might become possible.

It is relevant at this point to compare the method developed in this project with that of 2-D hydraulic modelling. Both approaches require a detailed topographic survey of the site. Substrate and vegetation mapping must also be done by direct field observation. The habitat mapping approach requires further field data in the form of flow-type mapping carried out for repeated field visits. This adds a significant field component. Hydraulic modelling can, in theory, be based on only one field visit, though the confidence is increased if a stage-discharge rating curve is derived for the site. This also requires repeated field visits, but the time spent on site is minimal. The output from the habitat mapping method depends on simple GIS modelling and field observation. It does not require complex hydraulic modelling. For observed flows this should give an accurate representation of habitat distributions and high confidence in the results. For flows intermediate to and outside the range of those observed, depth can be predicted, but the hydraulic biotopes, and hence the velocity class, must be interpolated or extrapolated subjectively. This is not easy given the type of data used in the process. Accuracy depends on the number of field visits and the range of discharge. Data collection is moderately time consuming in complex channels. In comparison, 2-D models are based on a one-off field visit for the topographic survey, plus repeated stage-discharge readings for the purpose of model calibration. Once calibrated it is possible to produce model output for a wide range of discharges, but the accuracy is uncertain because there is no field verification. There are inevitable problems of modelling the hydraulically complex channels that are often selected for EWR determinations. These conclusions point to a possible way forward in which the two approaches are combined.

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