THE GEOMORPHOLOGICAL RESPONSE TO CHANGING FLOW REGIMES OF THE SABIE AND LETABA RIVER SYSTEMS

by

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Report to the Water Research Commission on the Project
"The geomorphological response to changing flow regimes of the Sabie and Letaba river systems"

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EXECUTIVE SUMMARY

Preamble

Recently, South Africa has been responding to increasing demands on the region's limited water resources and is moving towards greater recognition of the rights of demand sectors which have not been catered for adequately; in particular, rural communities and the natural environment (DWAF 1995). There is, therefore, a need to determine the requirements of competing users (agriculture, forestry, industry, domestic, rural people and the natural environment).

Increasingly, it is being recognised that the natural river environment needs to be regarded as a national resource and as such should be maintained and guaranteed rights as a user. This shift towards regarding the natural environment as a legitimate demand sector in the competition for South Africa's water resources has required a change in emphasis of studies of water provision.

Riparian ecosystems have been shown to respond to both the flow regime (Bowman and McDonough 1991) and to physical characteristics of the river (Hupp 1986). Physical characteristics of river systems are also known to alter in response to changes in flow regime (Schumm 1969). Assessment of environmental water requirements, therefore, requires an understanding of the existing physical characteristics, the controlling processes and the vectors of change (magnitude and direction) in response to catchment control changes.

From a scientific perspective, this report contributes to the development of a rational approach to the study of South African rivers, within the context of rapidly changing perspectives on water resource management, through:

1. The development of an integrative methodology for assessment of the physical changes to river systems in response to changing water supply, using physical characteristics and processes as a basis (Fig. i).
2. Application and assessment of this methodology to studies on the Sabie and Letaba rivers in the Kruger National Park.
3. Development of descriptive and predictive tools for use by water resource managers to predict potential physical changes to the Sabie and Letaba rivers in response to management decisions.
4. Recommendations as to how the methodology may be utilised for other southern African rivers.
5. Recommendations as to how such studies may be integrated with studies of riparian ecosystem functioning and biodiversity.

In so doing, the project contributes to the objectives of the second phase of the Kruger National Park Rivers Research Programme (Breen *et al.* 1995) through:

1. Providing a means for assessing potential physical changes in response to changing flow regime and thereby, through ecological links, providing a means for assessing the ecological implications of different management actions.
2. Development and testing of methods for predicting physical responses of rivers flowing through the Kruger National Park, to changing patterns of water supply.

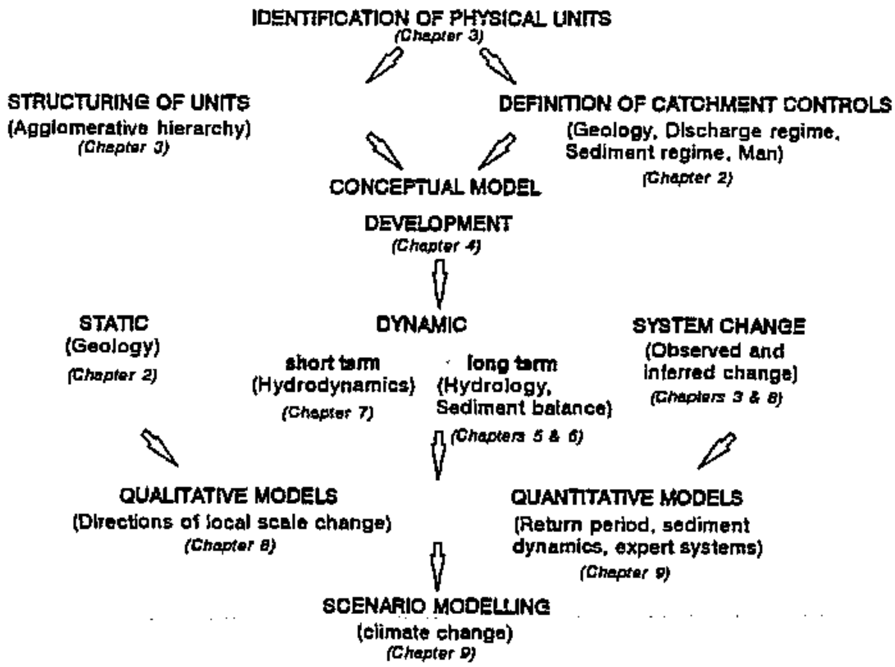

Figure i. Structured research rationale for the Sabie River in the Kruger National Park.

The executive summary comprises background and motives for the study, discussion of achievements of the stated aims, an outline of products and useability of the research findings and recommendations for further research. The body of the report focuses on the philosophy and development of the research methodology, data acquisition and model development and application.

In Part One, catchment characteristics and control variables (topography, geology, regional geomorphology, sediment production and hydrology) are described. The physical nature of the Sabie River is then detailed through the development of an agglomerative geomorphological hierarchical classification system and a description of the characteristics of units on the Sabie River at different levels in the hierarchy (chapter 3). The most attention is given to the morphological unit and channel type scales, since these are the smallest scales at which prediction of geomorphological change is currently possible and at which integration with ecological studies is most likely to be possible.

In Part Two, studies of recent control variables and geomorphological change on the Sabie River are discussed. Studies of the catchment control variables and their changes, the physical nature of the Sabie River and geomorphology led to the development of a conceptual model for change for the Sabie River and a consideration of appropriate temporal and spatial scales for predictive modelling (chapter 4).

Quantification of the driving variables and processes for the Sabie River are considered in Part Three. The conceptual model was used to direct data collection and analysis on the catchment control variables (hydrological regime and sediment production: chapters 5 and 6) and channel dynamics (hydraulics and in-channel sediment dynamics: chapter 7) at appropriate scales.

Model development and application on the Sabie River is described in Part Four. Data collection and analysis led to a description of recent channel change and the development of qualitative models for change on the Sabie River (chapter 8). The studies were finally translated into quantitative models (statistical and deterministic) of channel change (chapter 9). The deterministic model was designed for use in predicting channel change in response to different flow scenarios through the utilisation of daily flow time series. Use of the model is demonstrated using average daily discharge data from weirs to predict directions of change in response to recent climatic cycles.

In Part Five, the transference of the research methodology and theory to other systems is examined. The methodology which was developed on the Sabie River is summarised (chapter 10) and demonstrated in a less rigorous study of the Letaba River, to provide an assessment of the potential for transferability to other South African river systems (chapter 11). The methodology and models can be applied using data from standard Department of Water Affairs and Forestry flow archives, coupled with map, ground and aerial photograph interpretation and limited field measurement.

Background and motivation

Given the current premise that the riverine environment is considered a resource in South Africa, it has a legitimate demand in the competition for the nation's limited water resources (African National Congress 1994, DWAF 1995). It is thus essential to quantify reliably the water requirements of the environment if the country's water resources are to be optimised for all demand sectors, while successfully managing the environment. This issue is of particular concern in conservation areas such as the Kruger National Park, where there is an imperative to maintain biodiversity in a functional ecosystem. Water managers require predictions of the physical and environmental consequences of altering the flow regime of a river. Thoms *et al.* (1990) recognised that fluvial geomorphology was the logical integrating discipline to link river response to ecological functioning, as it is the geomorphology that forms the physical template for habitat development. Also, river response may be predicted at a geomorphological scale that can be directly related to habitat units (Fig. ii).

The form of river channels is primarily determined by the influence of water and sediment and any alteration to this balance will result in geomorphological change. Conventional static ecological assessment techniques, such as PHABSIM (Bovee 1982), link ecological response to hydraulic change (Fig. ii) and are inappropriate on dynamic river systems, since geomorphological change overrides local hydraulics as the principal factor determining biotic preferences (Russell and Rogers 1989). In a dynamic system, if the geomorphological template is altered this directly affects the habitat availability. Also, geomorphological change is likely to be longer term and less reversible than changing hydraulic conditions (for example, flow depth or wetted perimeter) in response to a modified flow regime. There is thus a need to integrate geomorphic studies in assessing the ecological implications of flow regime modification, as such studies generate a more holistic picture of the functioning of the system (Russell and Rogers 1989) (Fig. ii).

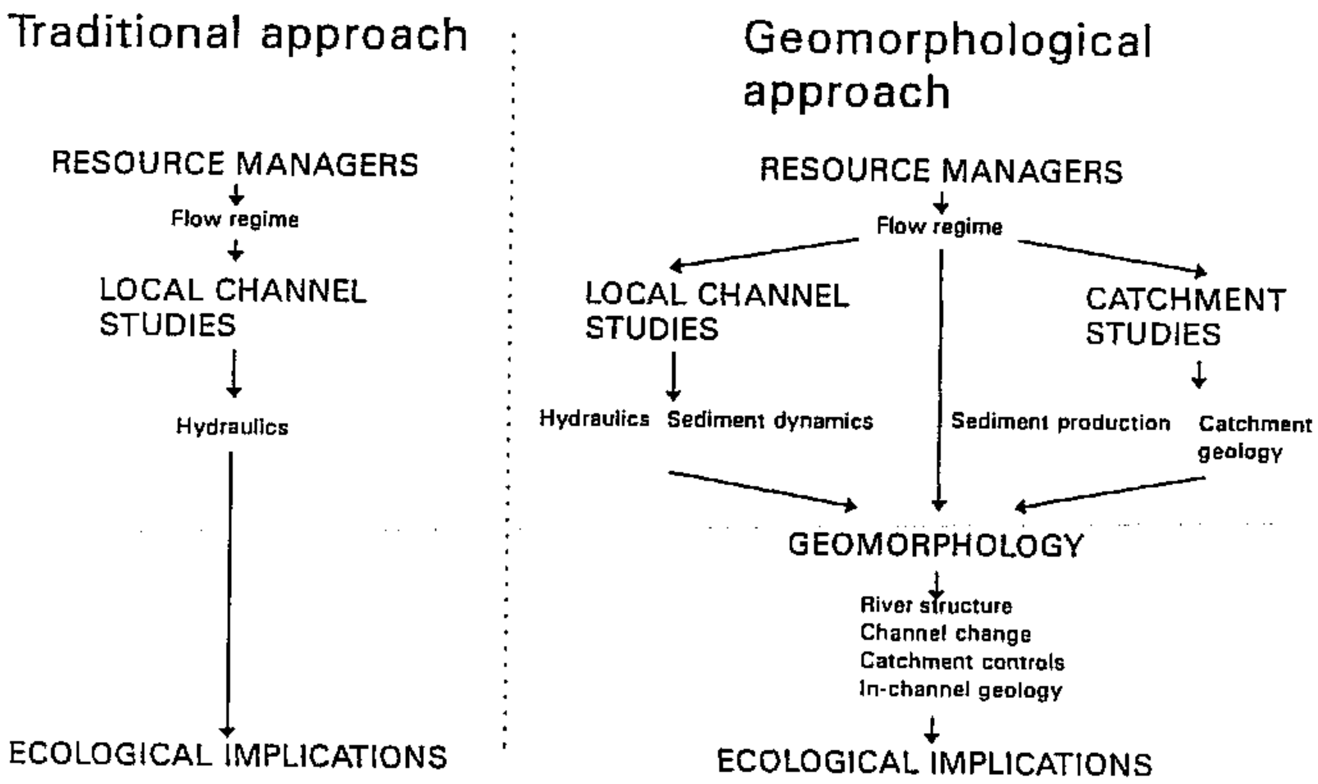

Figure ii. Geomorphological approach to a holistic study of river system functioning.

The requirement for a detailed understanding of the geomorphological dynamics of South African river systems was first recognised by Thoms *et al.* (1990) and Rogers *et al.* (1992). It was viewed as part of an integrative, holistic research programme into water requirements for the Kruger National Park rivers that aimed to address the question of quantifying the water demand of the environment. The form of river channels, which defines the physical environment for biota, is determined by the landscape through which the river flows and the water and sediment supply. Specification of water allocations for conservation, therefore, requires understanding of the river response to changes in flow and sediment regime in a quantitative and predictive sense. The overall aim of this project was to develop the capability to predict the geomorphological response to changing flow regimes in the Sabie and Letaba river systems with a view to providing information and protocols for environmentally sound management of the water resources of these catchments. This has been achieved through the following objectives which were as originally stated in the initial proposal:

1. **Description of the contemporary morphology of the rivers.**

2. **Establishment of the temporal pattern of change in the channel morphology.**

3. **Construction of a conceptual model of channel change and on the basis of this model, identification of ecological and management requirements, and processes and scales for further research.**

4. **Quantification of catchment processes and their effects at the appropriate spatial scales.**

5. **Development of predictive models for fluvial geomorphological change.**

Use of existing geomorphological understanding for prediction of potential channel change as a basis for management often succeeds after reference to established fluvial geomorphological theory. Many southern African rivers, being bedrock controlled and hydrologically variable, do not conform to classic temperate alluvial models (van Niekerk *et al.* 1995). It was, therefore, imperative to develop a new and flexible research strategy with the capability to investigate and understand the dynamics of bedrock influenced river systems (Fig. i). Such a strategy forms the basis of this document and its rationale may be easily and quickly transferred to other river systems. This has been demonstrated with reference to the Letaba River study, where geomorphological classification and conceptual models of change were rapidly constructed and monitoring networks installed.

Both the Sabie and Letaba rivers are mixed bedrock-alluvial systems and existing alluvial channel theory was of limited use. The approach adopted in this study (Fig. i) involved firstly, the detailed description of the physical characteristics of the river, in order to unravel the complexities of the system and generate a firm foundation for structured research. Similarly, an investigation of short-term geomorphological changes was necessary to begin to qualify the dynamic nature of the river system and determine how it responds to changes occurring in the catchment. This information was also used in validating quantitative channel change models. These steps facilitated the classification of the system into ecologically-relevant sections.

Secondly, the dominant catchment control factors were isolated. Combining the knowledge gained from these two components of the approach allowed the development of conceptual models of change. These models focused the field study which refined the level of system understanding. This information was then incorporated into a series of models for predicting changes in river morphology and habitat, induced by changing flow regimes.

Semi-quantitative models of channel change were developed to predict timescales (return period), and degrees of channel change in response to altered sediment and flow regimes. Actual evidence of geomorphological change was used to verify the performance of these models on the Sabie River (Fig. i).

Achievement of the stated aims

In order to integrate fully with the Kruger National Park Rivers Research Programme, the major part of this study was devoted to developing an understanding of the geomorphological dynamics of the Sabie River system. The research rationale that emerged was then transferred to the Letaba River. All of the original aims were achieved using this approach and are expanded on below.

1) Description of the contemporary morphology of the rivers

It was recognised that both rivers exhibited a composite-channel structure, with low flow channels contained within a large macro-channel which has been incised into the bedrock over geological time (during the late Miocene and early Pliocene). This macro-channel is large enough to contain even extreme flood events (of the order of 2000 m^3s^{-1}). Within its confines, another system of channels exists that convey the lower flows and these form the active (perennial) and seasonal channels defined by the classification system.

Both the Sabie and Letaba rivers have been classified according to the hierarchical system of van Niekerk *et al.* (1995). The proposed approach uses the principle of agglomerative association to generate successive levels in the geomorphological hierarchy, beginning with groups of morphological units and progressing through channel types, reaches, macro-reaches and zones, through to the whole river system (Fig. iii).

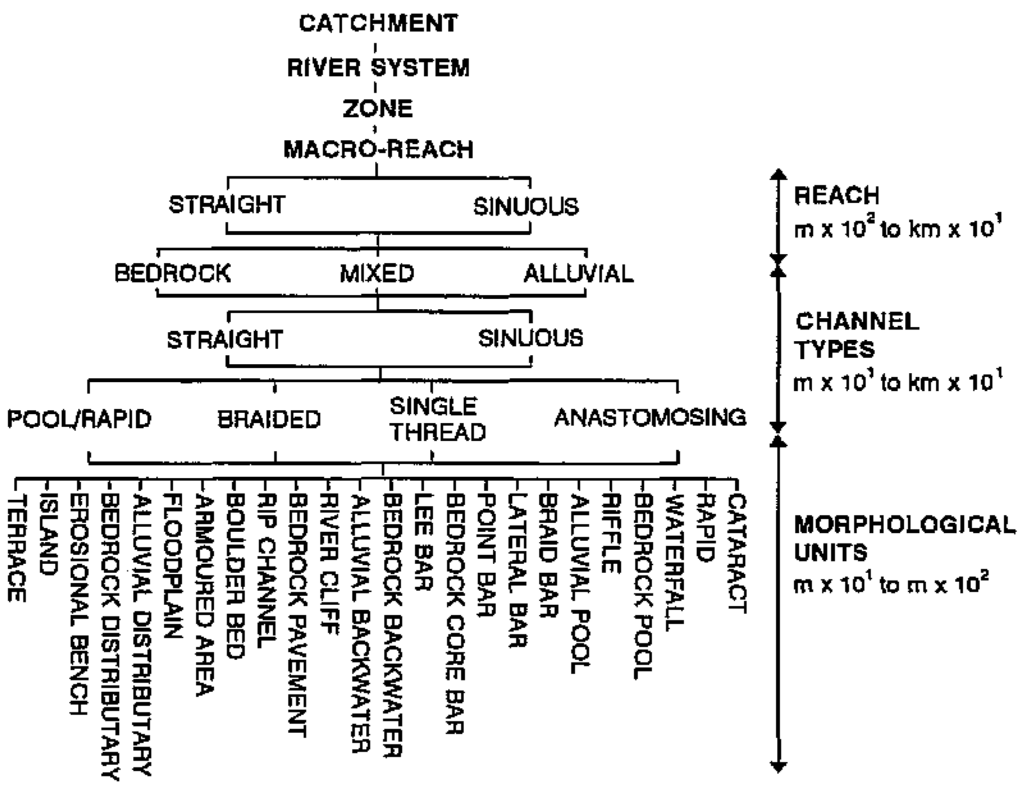

Figure iii. Agglomerative geomorphological hierarchy of the Sabie River in the Kruger National Park.

Such a classification has allowed the descriptive mapping of the geomorphological structure of both rivers along their full length in the Kruger National Park and has formed the geomorphological basis for structuring all subsequent studies on these rivers.

A continuum of channel types from bedrock to alluvial exists on the Sabie River depending on the degree of sedimentation. In the hierarchy (Fig. iii) channels may be classified as bedrock, mixed, or alluvial, leading to a total of ten possibilities (bedrock single thread, mixed single thread, alluvial single thread, bedrock pool-rapid, mixed pool-rapid, bedrock anastomosing, mixed anastomosing, alluvial anastomosing, mixed braided and alluvial braided). On the Sabie River, five principal channel types are common and readily recognisable (the other five being rare and localised):

- Alluvial single thread
  Fully alluvial, regular single channel river. May have a straight or sinuous planform.

- Alluvial braided
  Alluvial multi-channel network of distributaries. Channel convergence and divergence is at the scale of the active channel width.

- Mixed anastomosing
  Multi-channel network of distributaries in both bedrock and alluvium.

- Bedrock anastomosing
  Multi-channel network of stable bedrock distributaries.

- Mixed pool-rapid
  System of alternating steep bedrock rapids and associated upstream pools.

2) Establishment of the temporal pattern of change in the channel morphology

Vogt (1992) and Carter and Rogers (1995) have shown, through studies of aerial photographs from 1940, 1944, 1965, 1974, 1977 and 1984/85, that the Sabie and Letaba rivers are changing form through progressive sedimentation over ecologically relevant timescales. The primary causes of such changes appear to be the increase in sediment production in the catchment (van Niekerk and Heritage 1994) and a reduction in flow volume and frequency. It is these factors which require detailed investigation, in order to begin to understand the channel dynamics of the Sabie River.

Channel change on both rivers has been investigated on two temporal scales. The first involves short term (annual) channel change, as evidenced by aerial photographs of certain sections of the rivers from 1986 to 1993. Change on this timescale appears to be largely restricted to erosion and deposition in the active channels within the incised macro-channel. During average flow periods (± 20% from the mean annual flow volume 1959-1993) there appears to be little observable change in the various channel types. Bedrock and mixed pool-rapid areas exhibit moderate sedimentation, mixed anastomosing sections display minor sediment accumulations and braided channel types and bedrock anastomosing sections show no significant change at the morphological unit scale. Periods of reduced annual runoff (< 80% of the mean annual runoff volume 1959-1993) result in more significant build up of sediments in mixed anastomosing and mixed pool-rapid, bedrock pool-rapid and braided areas. Accumulation in the bedrock pool-rapid and braided areas is less marked than in the mixed anastomosing and mixed pool-rapid areas. Bedrock anastomosing channel types show a limited increase in bar deposits. This study enabled a direct association to be drawn between change at the channel type scale and measured flows.

Long term (> 50 years) direction of channel change has been inferred from a single set of aerial photographs, utilising space-for-time substitution. This concept is based on the recognition that there is a continuum of channel types ranging from fully bedrock through to fully alluvial and different channel type sections are at different stages of the continuum down the length of the river. It was thus possible to identify potential directions of change by looking at two different areas of the river in different stages of evolution in relation to the influence of the catchment control variables. Pathways of geomorphological evolution in response to increasing sedimentation have been proposed based on the work of Vogt (1992), Carter and Rogers (1995) and the short and long term aerial photograph studies.

3) Construction of a conceptual model of channel change and on the basis of this model, identification of ecological and management requirements, and processes and scales for further research

The hierarchical classification (Fig. iii) lead to the identification of ten potential channel types in the continuum from bedrock to alluvial rivers (given that pool-rapids can only be bedrock or mixed and braided channels can only be mixed or alluvial). Utilising the results of the aerial photograph interpretations (in which directions of change were identified and related to flow regime), the sediment yield studies (which show an increase in sediment yield over the period of photographic record) and the descriptive studies (which isolated the influence of geology) a conceptual model was constructed. The model defines the probable change in channel type as a function of the catchment factors that control their form.

Of these factors some were identified as static, and as such could not change to influence the river geomorphology over ecologically relevant timescales, and others were found to be dynamic requiring further detailed investigation for incorporation in quantitative models:

Static:		Geology
Dynamic:	Short term:	Flow dynamics Sediment dynamics
	Long term:	Hydrology Sediment production

Flow variability, flow magnitude, sediment inputs and local channel sediment transport potential were identified as the principal controls on channel form and the model represents the probable directions of channel type change, as a result of altering one or more of the control variables (Fig. iv).

4) Quantification of catchment processes and their effects at spatial scales relevant to the processes influencing channel change

Field monitoring of the catchment control factors was necessary to quantify the processes operating in both catchments. Sediment production within the catchments was evaluated using GIS techniques and sub-catchment production figures were estimated. The principal production areas coincide with the former homeland areas to the west of the Kruger National Park, where poor land management coincides with highly erodible soils. However, overgrazing by large populations of game inside the conservation area was also in evidence during drought periods. The technique employed was of insufficient resolution to detect increased inputs in the upper catchment from forestry roads. The studies concluded that sediment production in the catchments was likely to increase.

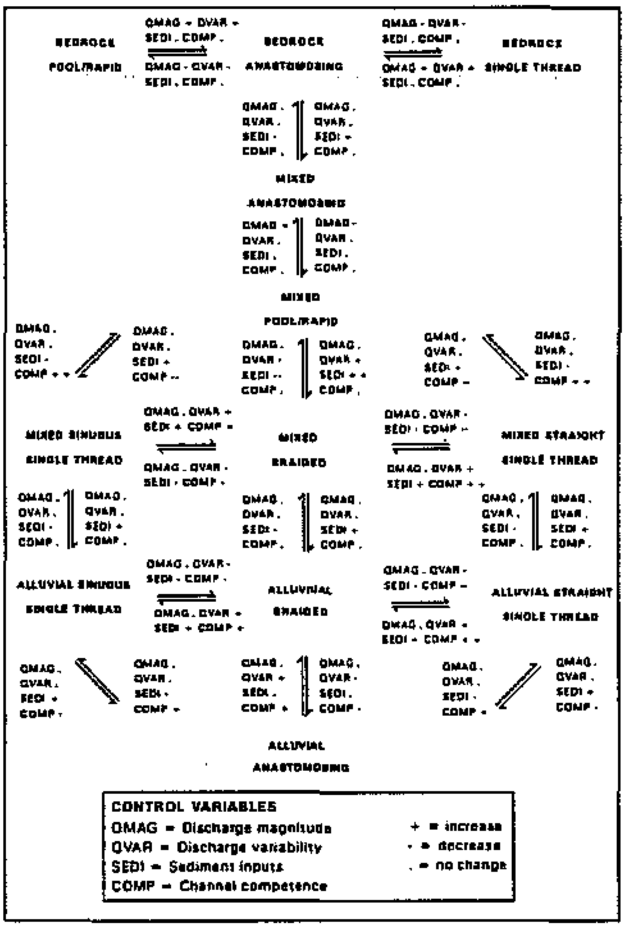

Figure iv. A conceptual model of channel type change for the Sabie River in the Kruger National Park.

A detailed hydrological study of recorded daily average flows within the Sabie River catchment was conducted using data from Perry's Farm Weir, Kruger Weir and Lower Sabie Weir. This revealed considerable fluctuation in the flow regime on a daily, seasonal, annual and decade scale (analysis of the average flow record for the gauging station at Perry's Farm, 60km upstream of the Kruger National Park, revealed a mean wet season flow of $12.4m^3s^{-1}$, with a range between $0.5m^3s^{-1}$ and $258m^3s^{-1}$; the mean dry season flow was $8.6m^3s^{-1}$, ranging between $0.4m^3s^{-1}$ to $197.2m^3s^{-1}$). Wet, dry and average flow regimes were constructed based on the recommendations of Tyson (1987). Differences between these regimes were most evident at lower flows, whereas larger flood events appear to occur under any climatic condition in response to high magnitude rainfall events, which are relatively consistent regardless of climatic variability. However, this may be a function of the short period of record. Flow variability and magnitude were difficult to evaluate for the Letaba River due to its ephemeral nature, hence, only river response to individual flood events was investigated.

Investigations of the flow and sediment dynamics were instigated in order to determine the geomorphological behaviour at the regional 'whole river' and local 'channel type' scale. The first involved a regional investigation of the dynamics of the entire length of the Sabie and Letaba rivers within the Kruger National Park, in order to 1) investigate the dynamics of the whole river system so as to identify areas of potential sediment accumulation or erosion and 2) select reaches for more detailed investigation. The regional study was based on 24 cross-sections on the Sabie River and 21 on the Letaba River. The results of the regional study revealed zones of higher or lower stream energy along the rivers and these corresponded closely to long term large scale sedimentary deposits in the macro-channel.

The second scale involved detailed studies of representative examples of the principal channel types identified by the hierarchical classification, in order to provide information for modelling at the channel type and morphological unit scale. These are the smallest scales for which predictions of morphological change can be modelled at present and information at these scales is potentially of most use to river ecologists. This was possible for the Sabie River only, as there were insufficient flow events on the Letaba River during the period of research. A detailed flow monitoring network was established at hydraulic controls for each of the channel types and data were collected on cross-sectional hydraulics for investigation of channel flow resistance and sediment dynamics. Each channel type was found to have distinct hydraulic and channel flow resistance parameters which were used in the semi-quantitative modelling procedure.

5) Development of predictive models for fluvial geomorphological change

Conventional quantitative modelling techniques assume a large degree of geomorphological homogeneity. Since the Sabie and Letaba rivers are extremely variable, with multiple distributaries and large numbers of hydraulic controls, particularly in the bedrock controlled reaches, the large amount of field data required to run such models for these rivers are prohibitive. A new approach, which linked the quantitative research findings and a qualitative spatial model of the river, was developed in order to predict change at the scale of channel type on an annual basis. Such a detailed analysis was not possible on the Letaba River due to the lack of hydraulic information.

Details of the hydraulic and sediment dynamics of the Sabie River channel types were used. in conjunction with the map of their distribution, to construct a model of sediment movement through the system. The ability of the river to transport sediment was evaluated for each consecutive channel type along the river, based on sediment inputs from the channel type immediately upstream and lateral sediment inputs from the catchment. Excess inputs that exceeded the local competence were deposited and where the channel sediment transport capacity exceeded the combined upstream and lateral sediment inputs, erosion of deposited material was possible (Fig. v). The model routes daily flows through the series of channel types and generates annual bulk sediment volume change at the scale of channel type for any daily time series. Any period of a day or greater may be considered and the consequences of sedimentation downstream through each channel type evaluated.

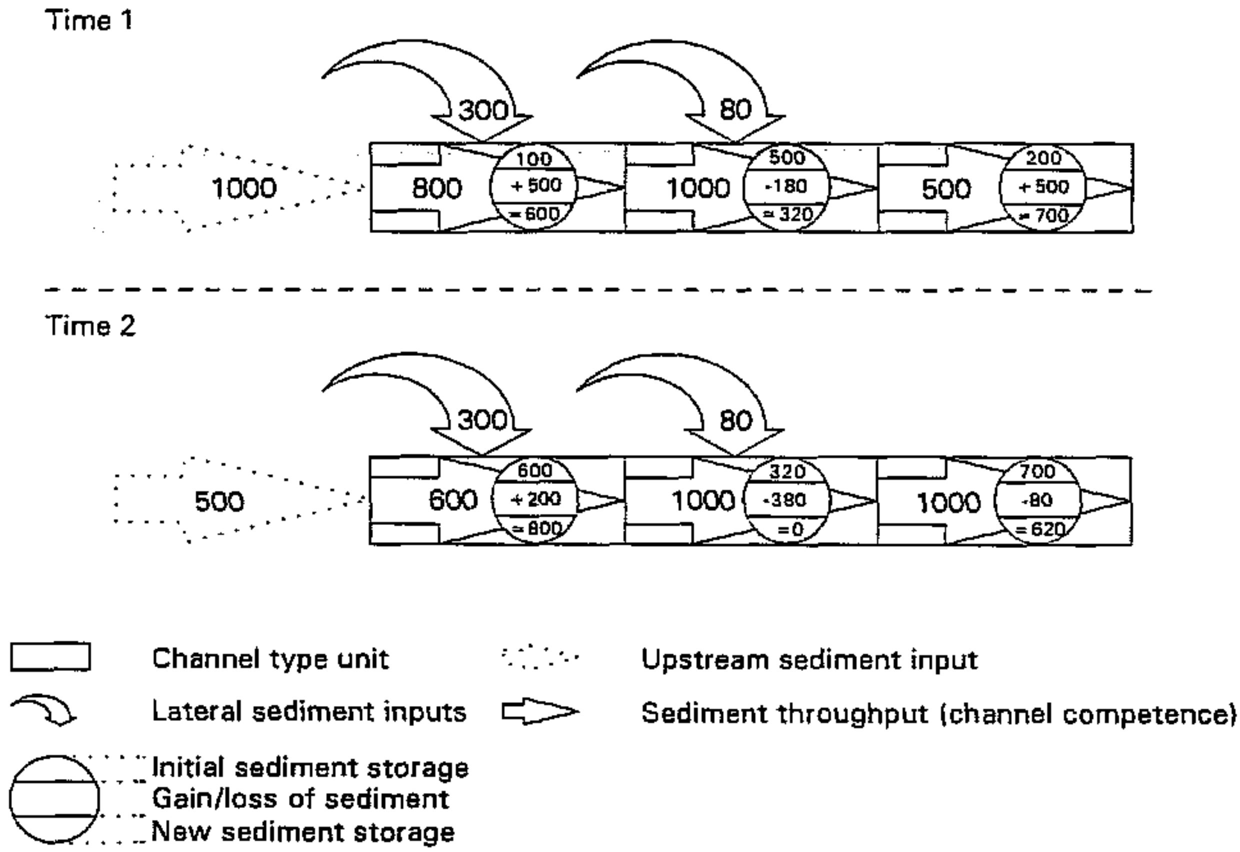

Figure v. Diagrammatic representation of the semi-quantitative model developed to predict channel change on the Sabie River in the Kruger National Park.

Validation of the model against observed channel change indicated that it predicted the erosion and sedimentation observed for each of the channel types along the Sabie River, as evidenced from aerial photographs. The observed combination of channel type units was linked in the model and the gauged daily flow time series was routed through the system. Predicted changes for the years 1989 and 1992 were then compared against channel change for several points along the river where aerial photographs exist. For example, the model predicted well the temporal pattern of sand and fine gravel sedimentation in a mixed anastomosing channel type downstream of a pool-rapid, as a result of flows between 1989 and 1992 (Fig. vi). The model was also run for silt sized material and this revealed that all sections of the Sabie are generally competent to move this fraction downstream. Extensive sedimentation was predicted for the mixed anastomosing channel type downstream of Lower Sabie Weir. This is supported by field and aerial photographic evidence of active channel bar deposition in the area. The bedrock anastomosing section close to the Mozambique border remained unchanged from the period 1989-1992; the model also predicted no erosion or deposition in this area.

Products and usability of the research findings

The Sabie and Letaba rivers behave differently from temperate alluvial river systems and hence must be investigated outside the framework that exists for these river types. A number of useful concepts and methods have emerged from this study which will prove invaluable in managing rivers in southern Africa:

1. A research philosophy that relates the geomorphological structure of a river to the principal catchment control variables, in order to conceptualise pathways of possible channel change.
2. A research approach for investigating bedrock influenced semi-arid river systems in a manner which will provide structured information for the prediction of their response to management actions.
3. A method for the classification of fluvial systems based on their geomorphological components. This classification is an agglomerative one and as such, is more suited to the discrimination of finer spatial groupings than a divisive approach. The classification encompasses the morphological units that allow for the detailed spatial categorisation of rivers influenced by both bedrock and alluvium. The classification has been designed to provide easy application to any river system, allowing direct standardised comparison between different rivers.
4. An integrative framework for field research that quantifies the importance of the catchment control factors and provides information on channel structure and dynamics on regional (whole river) and local (representative channel type) scales.

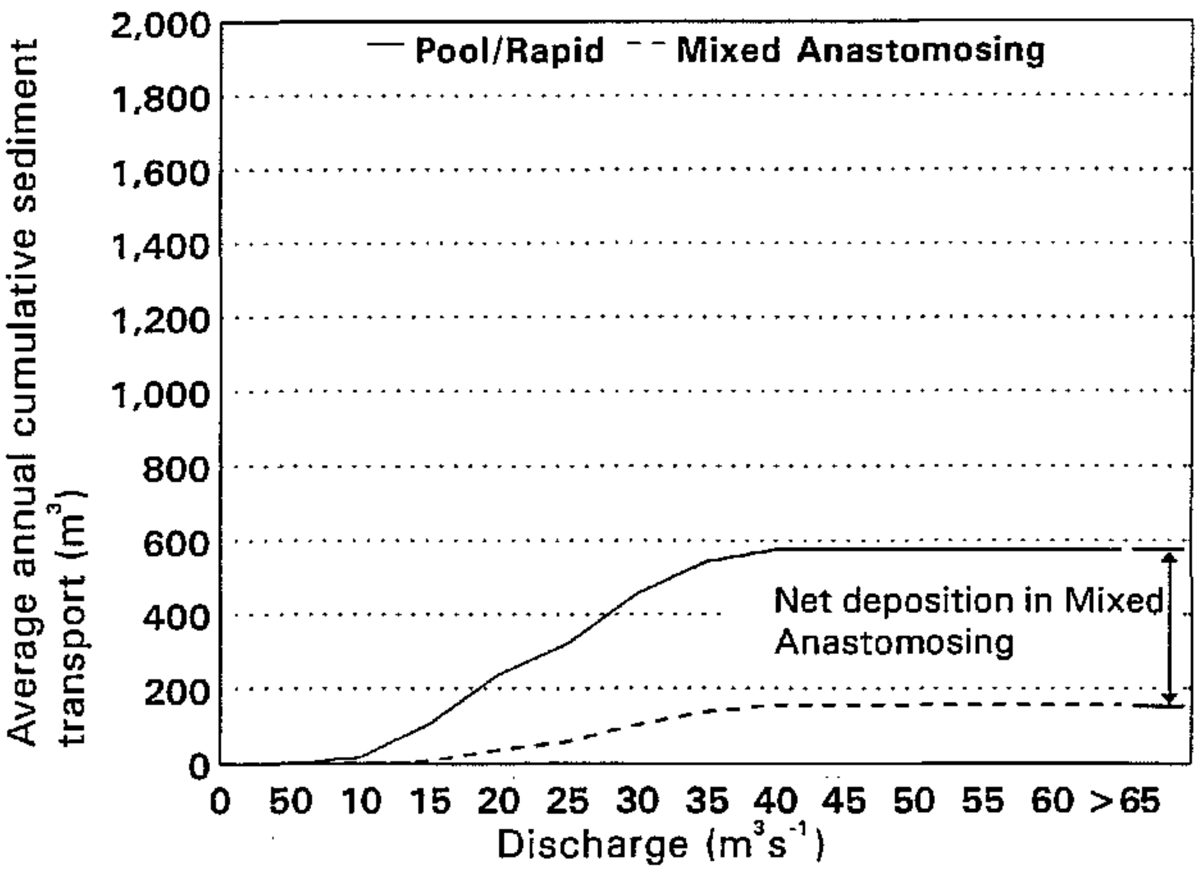

Figure vi. Example results from the semi-quantitative channel change model developed in this study.

The research philosophy, new method and field research programme have resulted in the generation of information on the physical nature of the rivers (structure), catchment controlling factors and channel dynamics which can be used by biologists and catchment managers (Fig. vii). The studies have led to the development of models for geomorphological change (Fig. vii) which provide the potential to predict ecological change in response to habitat change. These models fall into two categories:

1. Qualitative models of short (annual) and long term (> 50 years) channel change for mixed alluvial/bedrock rivers.
2. A semi-quantitative model of channel response that routes sediment through a series of channel types as defined by the hierarchical classification and river structuring. The model operates using daily average flow time series and generates changes in the sediment balance at the scale of channel type over the period being investigated. The model can be used to investigate the potential effects of different management strategies through the analysis of simulated daily flows for different river basin development and dam construction scenarios. Similarly, the results of the modelling can be used as a basis for the construction of a series of biotic response models.

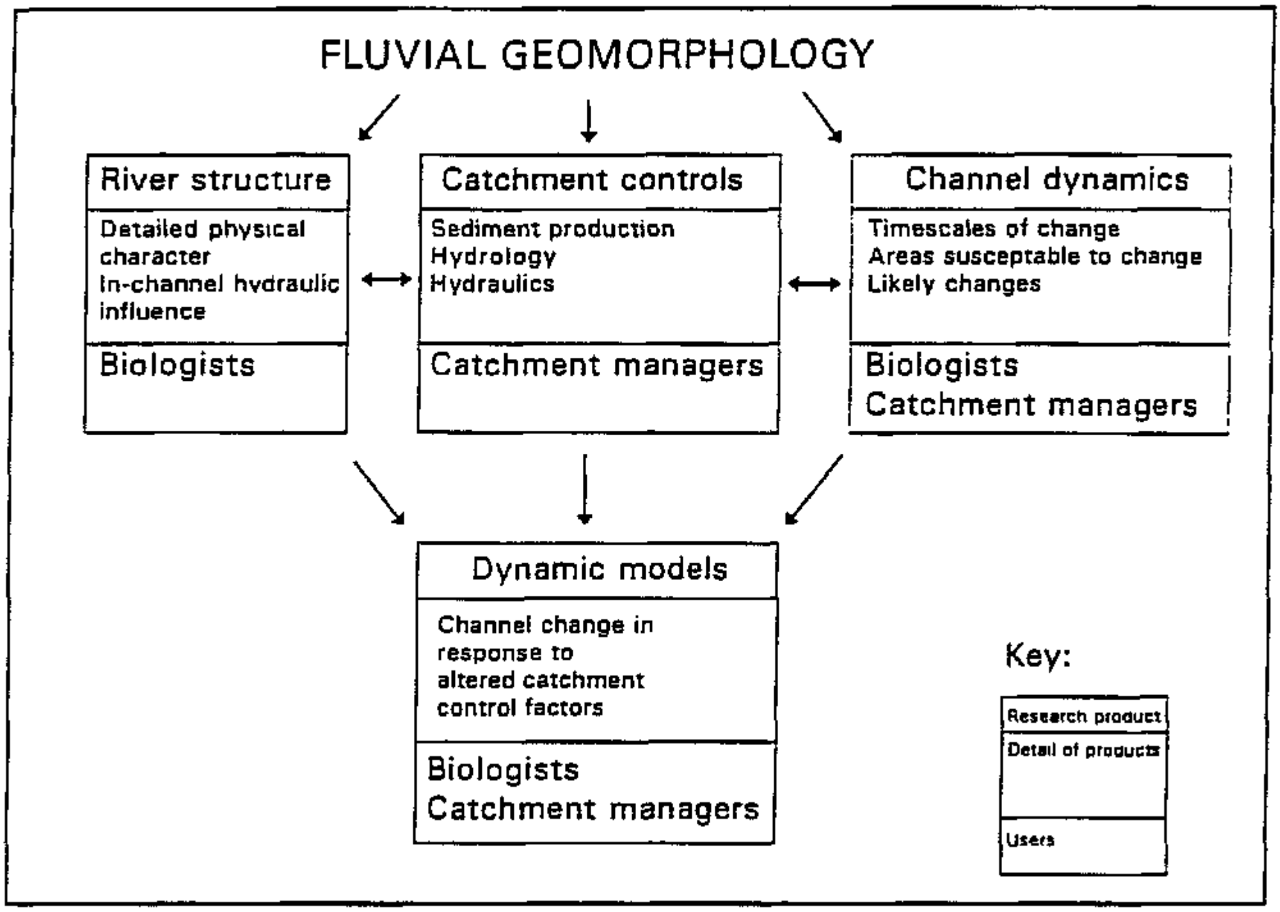

Figure vii. Products and users of the geomorphological change project findings.

Further research

This report details the research findings of a four-year study into the structure and functioning of two bedrock influenced rivers subject to highly variable flow regimes. New methods and models have been developed and the focus of future research should be to improve integration of the models into the Kruger National Park Rivers Research Programme (KNPRRP) Decision Support System (DSS) and transferring the methods to other systems. These research needs can be met through:

1. Refinement and verification of the suite of geomorphological change and hydrodynamic models through model application.
2. Integration of geomorphological and ecological studies at the spatial and temporal scales at which geomorphological change can realistically be predicted.
3. Development of models for prediction of ecological change in response to geomorphological change.
4. Modelling of geomorphological change to the Sabie River under scenarios specified through the DSS.

Development of hydrodynamic models and procedures on seasonal alluvial rivers such as the Letaba (incorporating subsurface flow components) and linking these to the geomorphological change model.

The daily time step model for simulating sediment and water runoff in the Sabie River catchment proposed in this report is currently being tested and refined in the KNPRRP. Output from this model for natural and historic development scenarios should be used in the geomorphological change and hydrodynamic models to predict change for these scenarios. Comparison of model predictions for the natural development scenario with aerial photographs over the 50 year photographic record will facilitate refinement and verification of the models. Comparison of model outputs for the historic and natural development scenarios will enable the isolation of past climatic and anthropogenic effects. Such a comparison will assist in defining the natural directions of change and thus provide a basis for defining the desired geomorphological state of the Sabie River.

Studies 2, 3 and 4 above will facilitate the prediction of ecological response to different management options. As water resources come under pressure, seasonal rivers are being considered for potential impoundment. Many of these are also alluvial (the Sand River in the KNP) and the dynamics of such seasonal alluvial systems are poorly understood, since ground water dynamics are not well defined. Study 5 above should be aimed at generalising the models sufficiently to ensure transferability of the models to other southern African river systems.

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Acknowledgements

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Dr S Mitchel	Water Research Commission (Chairman 1995)
Mr D Hutser	Water Research Commission (Secretary)
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1. INTRODUCTION

The environment is conventionally accepted as a resource to be protected in South Africa and as such it exercises a legitimate demand in the competition for limited water resources in southern Africa. It is thus essential to quantify the water requirements of the environment reliably. This issue is of particular concern in conservation areas such as the Kruger National Park, where there is an imperative to maintain the biotic system. In particular, the role of rivers has been highlighted as playing an important part in the functioning of the entire riparian system. Therefore, changes to this system will impact on the environment.

The geomorphological state of a river has been recognised as forming an important template for biotic habitat and change to this template has a direct impact on the ecosystem. The contemporary form of river channels is primarily a reflection of the influence of water and sediment and any alteration to either of these two factors results in geomorphological change. Ecological assessment techniques such as PHABSIM (Milhous *et al.* 1989) assess channel stability, but do not incorporate channel change into their predictions (King and Tharme 1994), making them inappropriate on geomorphologically dynamic rivers in which habitat change overrides local hydraulics as the principal factor determining biotic preferences.

The requirement for a detailed understanding of the geomorphological dynamics of the Sabie River was recognised by Thoms *et al.* (1990) and Rogers *et al.* (1992). It was viewed as part of an integrative holistic research programme that aimed to address the question of quantifying the water demand of the environment by linking with other control factors such as local hydraulics and water quality (Fig. 1) (Rogers *et al.* 1992).

The overall aim of this project was to fit into the holistic framework, through development of the capability to predict the geomorphological response to changing flow regimes in the Sabie and Letaba river systems, hence providing information and protocols for environmentally sound management of the water resources of these catchments. This has been achieved through pursuing the following objectives:

- **Description of the contemporary morphology of the rivers.**

- **Establishment of the temporal pattern of change in the channel morphology.**

- **Construction of a conceptual model of channel change and on the basis of this model, identification of ecological and management requirements, and processes and scales for further research.**

- **Quantification of catchment processes and their effects at the appropriate spatial scales.**

- **Development of predictive models for fluvial geomorphological change.**

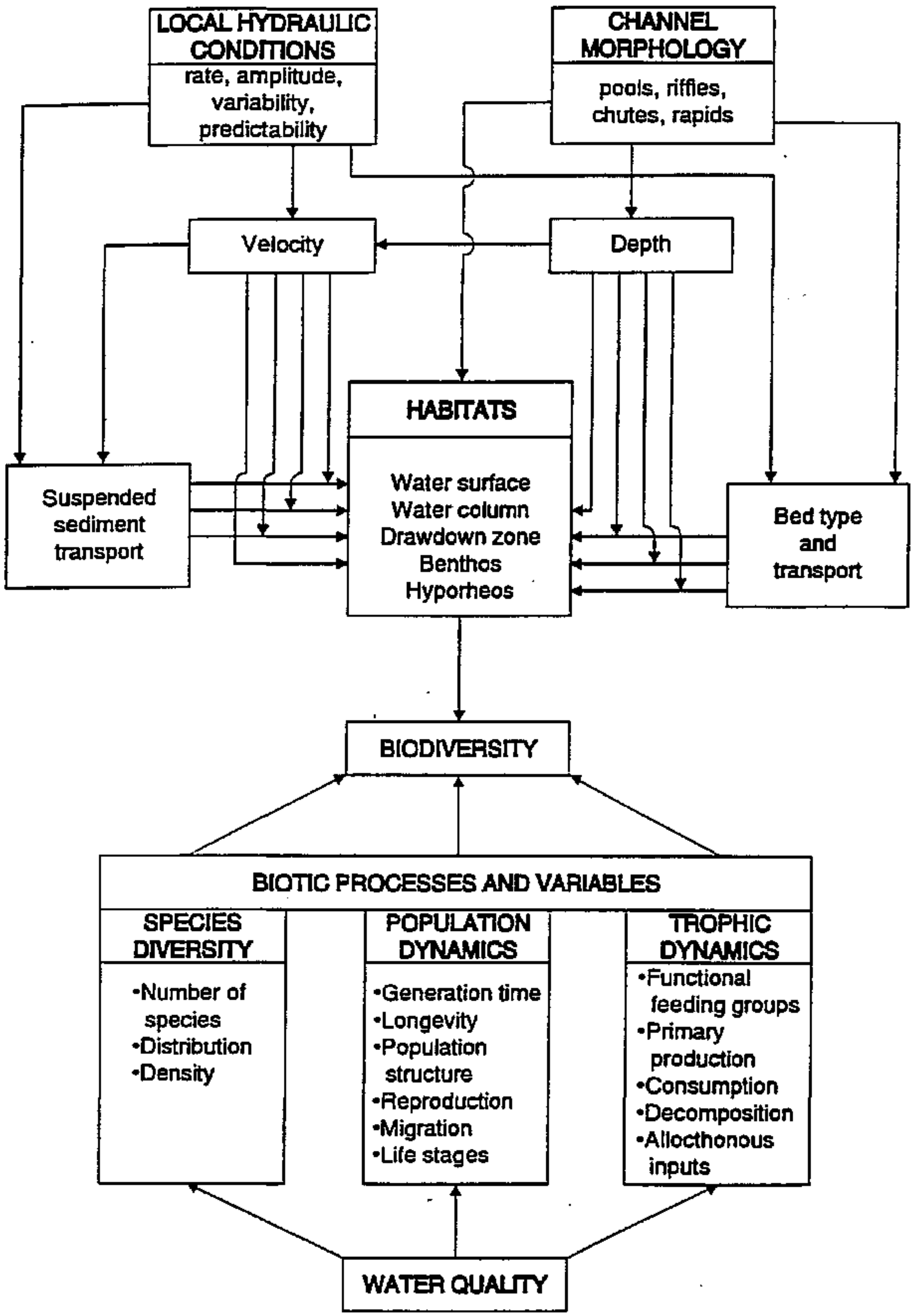


Figure 1. The role of geomorphology in the structure and functioning of riparian biotic systems (after Rogers *et al.* 1992).

All scientific investigation rests on a sound conceptual basis which dictates data collection and information utilisation. In this study a framework was required which could be used to assess river state and predict changes in that state and had to be transferable from river to river. Established geomorphological theory can form the basis of successful management of many rivers, but many southern African rivers, being bedrock controlled and hydrologically variable, do not conform to classic temperate alluvial models. The research rationale proposed in this study (Fig. 2) involves firstly, the detailed description of river structure and potential for short term change, in order to unravel the complexities of the system and generate a firm foundation for structured research. These steps facilitate the classification of the system into ecologically-relevant sections. Secondly, the dominant catchment control factors must be isolated from the many that are operating. Combining the knowledge gained from these two components of the approach allowed the development of a conceptual model of channel change. This model focused the study on relevant factors for further investigation in order to refine the level of system understanding, particularly of sediment and water dynamics, through detailed field evaluation (Fig. 2). This structured information in turn provided the ability to predict and model changes in morphology and habitat induced by changing flow regimes (Fig. 2). Such a process is iterative (Fig. 3) and many of the initial ideas on the functioning of the two rivers involving hypothesis and model development have been refined with time, leading to the ability to predict changes in river morphology and habitat induced by changing flow regimes.

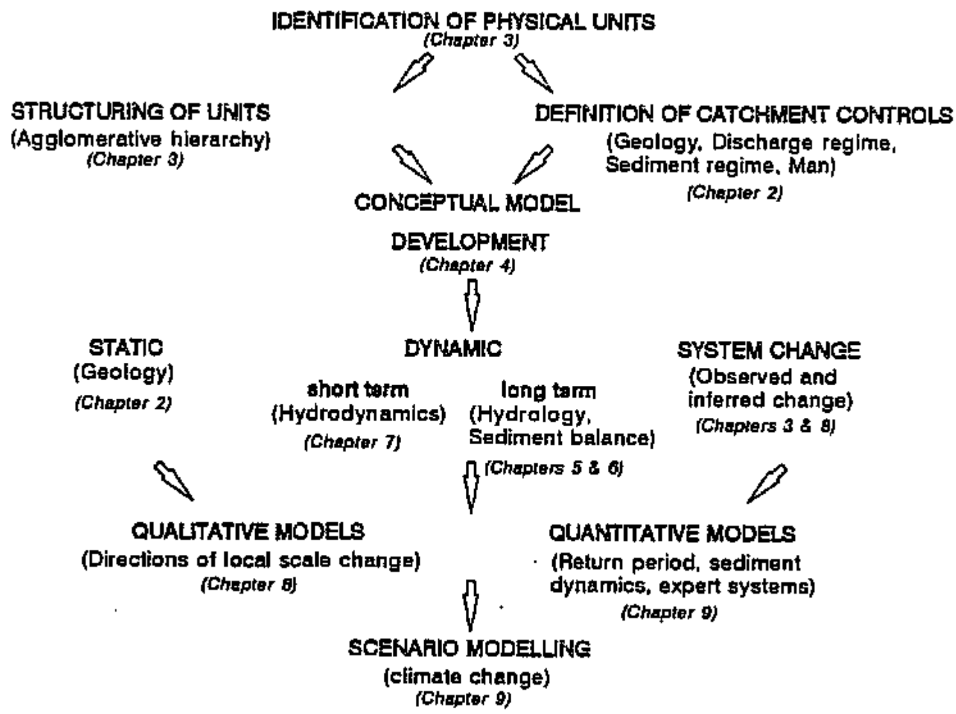


Figure 2. The overall research strategy developed to generate geomorphological change models for the Sabie and Letaba rivers in the Kruger National Park.

The model predicts channel change at the scale of channel type that can be used in scenario modelling of simulated flow regimes, making it possible to negotiate volume and distribution of water supply with resource managers. This framework can be used for all rivers, particularly those whose dynamics are poorly understood and where limited data are available. This report presents a detailed account of how the research rationale (Fig. 2) was applied to the Sabie River catchment, where considerable data were available and the Letaba River catchment, where a limited data set precluded such a detailed understanding.

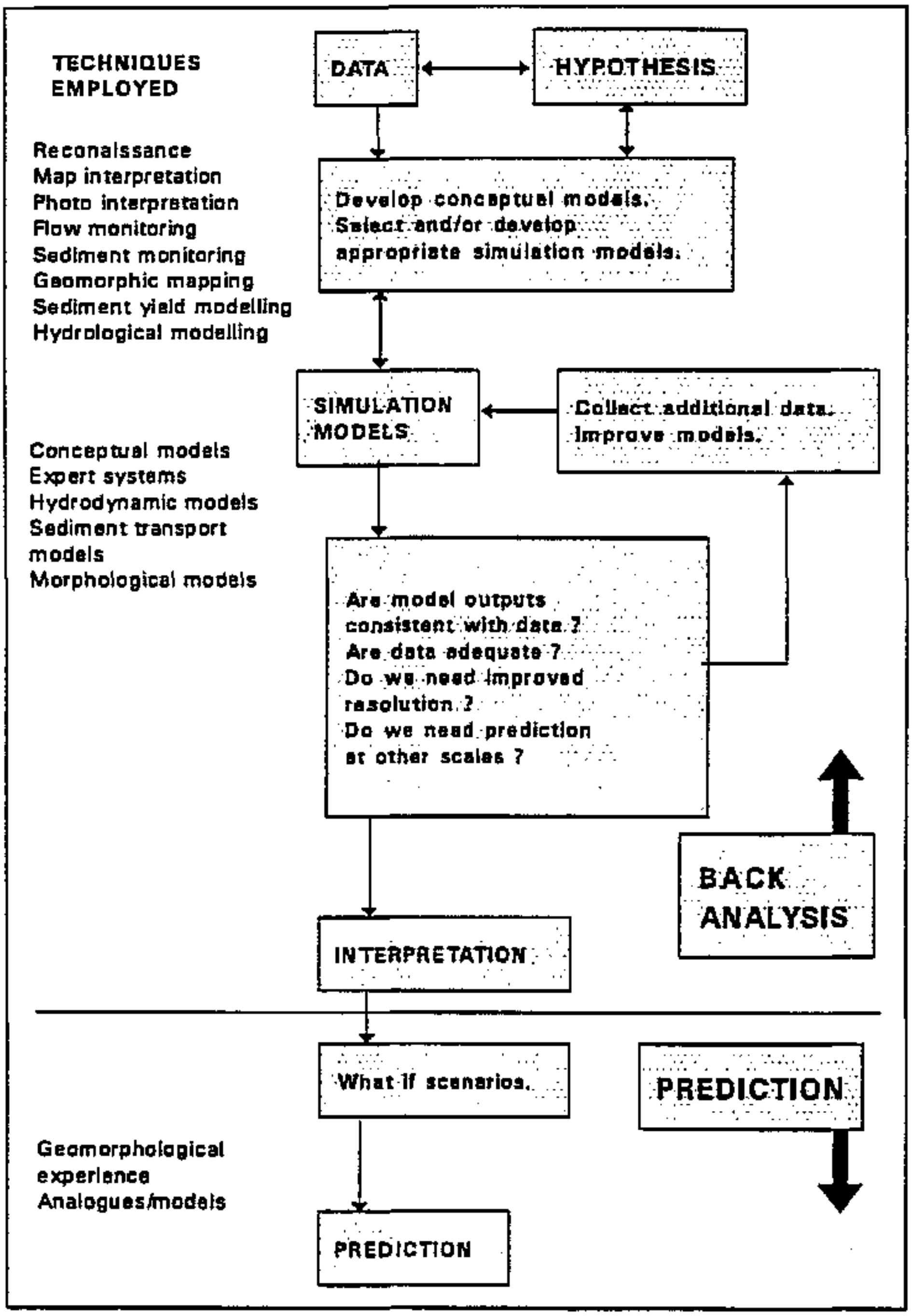


Figure 3. The iterative research process employed for geomorphological modelling aspects of the Sabie and Letaba rivers in the Kruger National Park.

From a scientific perspective, this report contributes to the development of a rational approach to the study of South African rivers, within the context of rapidly changing perspectives on water resource management, through:

1. The development of an integrative methodology for assessment of the physical changes to river systems in response to changing water supply, using physical characteristics and processes as a basis (Fig. 2).
2. Application and assessment of this methodology to studies on the Sabie and Letaba rivers in the Kruger National Park.
3. Development of descriptive and predictive tools for use by water resource managers to predict potential physical changes to the Sabie and Letaba rivers in response to management decisions.
4. Recommendations as to how the methodology may be utilised for other southern African rivers.
5. Recommendations as to how such studies may be integrated with studies of riparian ecosystems.

In so doing, the project contributes to the objectives of the second phase of the Kruger National Park Rivers Research Programme (Breen *et al.* 1995) through:

1. Providing a means for assessing potential physical changes in response to changing flow regime and thereby, through ecological links, providing a means for assessing the ecological implications of different management actions.
2. Development and testing of methods for predicting physical responses of rivers flowing through the Kruger National Park and across South Africa to changing patterns of water supply.

The body of the report focuses on the philosophy and development of the research methods, data acquisition, model development and application on the Sabie River, and transferability to other river systems, using the Letaba River as a case study.

In Part One, catchment characteristics and control variables (topography, geology, regional geomorphology, sediment production and hydrology) are described. The physical nature of the Sabie River is then described through the development of an agglomerative hierarchical classification system and a description of the morphological characteristics of units on the Sabie River at different levels in the hierarchy (chapter 3). The most attention is given to the morphological unit and channel type scales, since these are the smallest scales at which prediction of geomorphological change is currently possible and at which integration with ecological studies is most likely to be achieved.

In Part Two, studies of the catchment control variables, the physical nature of the Sabie River and geomorphological dynamics are described. A conceptual model for change for the Sabie River is presented and consideration is given to the appropriate temporal and spatial scales over which modification is taking place (chapter 4).

Quantification of the driving variables and processes for the Sabie River is considered in Part Three. The conceptual model was used to direct data collection and analysis of the catchment control variables (hydrological regime and sediment production: chapters 5 and 6) and channel dynamics (hydraulic and in-channel sediment dynamics: chapter 7).

Model development and application on the Sabie River is described in Part Four. Data collection and analysis led to a description of recent channel change and the development of qualitative models for change on the Sabie River (chapter 8). The studies were finally translated into quantitative models (statistical and deterministic) of channel change (chapter 9). The deterministic model was designed for use in predicting channel change in response to different flow scenarios through the utilisation of daily flow time series. Application of the model is demonstrated using average daily discharge data from weirs to predict directions of change in response to recent climatic cycles.

In Part Five, the transference of the research approach and theory to other systems is examined. The approach which was developed on the Sabie River is summarised (chapter 10) and demonstrated in a less rigorous study of the Letaba River, to provide an assessment of the potential for transferability to other South African river systems (chapter 11). The approach and models can be applied using data from standard Department of Water Affairs and Forestry flow archives, coupled with map, ground and aerial photograph interpretation and limited field measurement.

2. CATCHMENT CONTROL VARIABLES ON THE SABIE RIVER

The geomorphology and nature of changes to the physical state of any river result from complex interactions of a number of control factors that operate on scales ranging from the whole catchment, down to the scale of individual boulder outcrops in the river bed. These controls include climate, geology, water discharge and sediment influx (both in the main channel and from tributaries), the bed and bank characteristics, the development of vegetation along the rivers and the effects of human interference (Morisawa 1985) (Fig. 4).

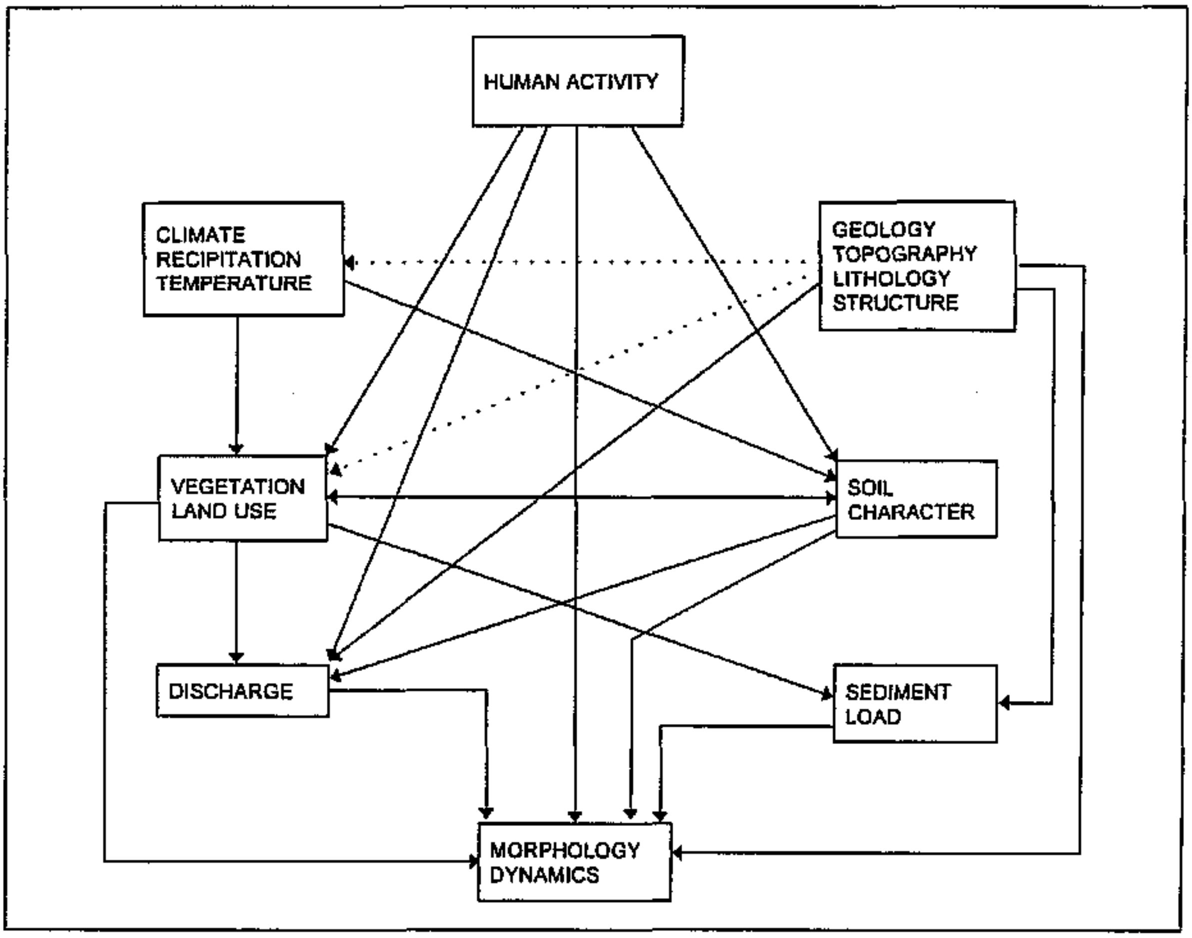


Figure 4. Generalised catchment factors that influence fluvial geomorphological dynamics (after Morisawa 1985).

Increased demands on limited water resources and changes in land usage lead to modification in the flow regime and a shift in the balance of the catchment control variables. These factors are being altered in the Sabie River catchment and are reflected in the changing geomorphological nature of the river. This has influenced the available habitat for different faunal and floral species dependent on the river and has resulted in an associated adjustment in species distribution. In this chapter, the catchment factors that influence the current physical nature of the Sabie River are identified and their influence on channel dynamics is reviewed.

2.1 Topography, geology and regional geomorphology

The Sabie River rises on the eastern slopes of the Mauch Berg in the Drakensberg, Mpumalanga Province, at an altitude of about 2200 m and flows eastward for some 210km to its confluence with the Incomati River in Mozambique. The catchment area is approximately 7096 km^2. In the Lowveld region (downstream of Hazyview), the major tributaries are the Marite and Sand rivers (Fig. 5). A large proportion of the Sabie River catchment drains the rural former homeland areas of Gazankulu, Lebowa and Kangwane, now incorporated into Mpumalanga Province. The river forms the boundary between the Kruger National Park and rural areas in Mpumalanga, before cutting east across the Kruger National Park to the Mozambique border (Fig. 5).

The Sabie River is underlain by a wide variety of bedrock, comprising sedimentary, intrusive and extrusive igneous and metamorphic rocks. The major strata over which the Sabie River flows are (from most proximal to most distal to the source) (Fig. 6), laminated, well bedded shale diamictite and occasional quartzite layers of the Pretoria Group, Chuniespoort dolomite and limestone, Nelspruit Suite biotite granite, potassic gneiss, also of the Nelspruit Suite and in the west of the Kruger National Park, Karoo sediments, Lebombo basalt and Lebombo rhyolite. The river is intersected by numerous dolerite and diabase dykes and sills, with a large outcrop of Timbavati gabbro along the western boundary of the Kruger National Park. Within the Kruger National Park, the strata have a north-south strike and an easterly dip. A large portion of the Sand River catchment is underlain by Cunning Moor tonalite and Makhtswi gneiss (Fig. 6).

A longitudinal section of the Sabie River has been drawn from 1:50000 topographic maps (Fig. 7). The Sabie River, between its source and the Mozambique border, has been divided into four main geomorphological zones (Fig. 8) based on the major breaks in slope.

1. Mpumalanga (previously Eastern Transvaal) Highlands.
2. Granite Plain.
3. Lowveld Zone.
4. Lebombo Zone.

These zones are closely related to the underlying geology with the mountainous hinterland corresponding to the Pretoria Group sediments and the Chuniespoort dolomite and limestone deposits; the Granite Plain zone corresponding to the biotite granites; the Lowveld zone corresponding to the potassic gneiss, and Karoo sediments and basalt; and the Lebombo zone to the rhyolite.

2.2 River history

The Lowveld represents a relatively young erosion surface which resulted from the westerly retreat of the Great Escarpment after the break-up of Gondwanaland through rift faulting about 100 million years ago (King 1978). Two major cycles of rejuvenation resulted in the development of the Post-African I and II surfaces (Partridge and Maud 1987) into which the Sabie River is incised (Table 1). The slow process of planation and lowering of the land surface enabled the rivers to cut gorges in resistant rock formations without major directional changes, as is seen at Sabiepoort (Venter 1991). These processes have resulted in incision of the Mpumalanga Province rivers into the African surface. Thus, the Sabie River is confined to a narrow deep valley within the existing host rock and active channel evolution and sedimentation is restricted within this zone, which is termed the macro-channel (van Niekerk and Heritage 1993). As a result of this incision the morphology of the Sabie River is controlled by the underlying geological structure and bedrock lithologies, although it does display some alluvial characteristics within the macro-channel.

Table 1. Summary of major geomorphological events in the region of the present Lowveld (modified from Partridge and Maud 1987 and Venter 1991).

Event	Geomorphic manifestation	Age
Climatic oscillations and glacio-eustatic sea-level changes.	Slight to moderate incision of river channels resulting in localised erosion.	Recent - 0.011 Ma
Post-African II cycle of major valley incision.	Incision of coastal gorges, formation of Post-African II erosion surface.	~2.5 - 0.011 Ma
Major uplift (up to 900 m in eastern marginal areas).	Asymmetrical uplift of the subcontinent and major westward tilting of surfaces on interior with monoclinal warping along the eastern coastal margins.	~2.5 Ma
Post-African I cycle of erosion.	Development of imperfectly planed Post-African I erosion surface.	~18 - 2.5 Ma
Moderate uplift of 150 - 300 m	Slight westward tilting of African surface with limited monoclinal warping.	~18 Ma
African cycle of erosion (polycyclic).	Advanced planation throughout subcontinent. Development of African surface with deep-weathered laterite and silcrete profiles.	~100 - 18 Ma
Break up of Gondwanaland through rift faulting.	Initiation of Great Escarpment owing to high absolute elevation of southern African portion of Gondwanaland.	~100 Ma

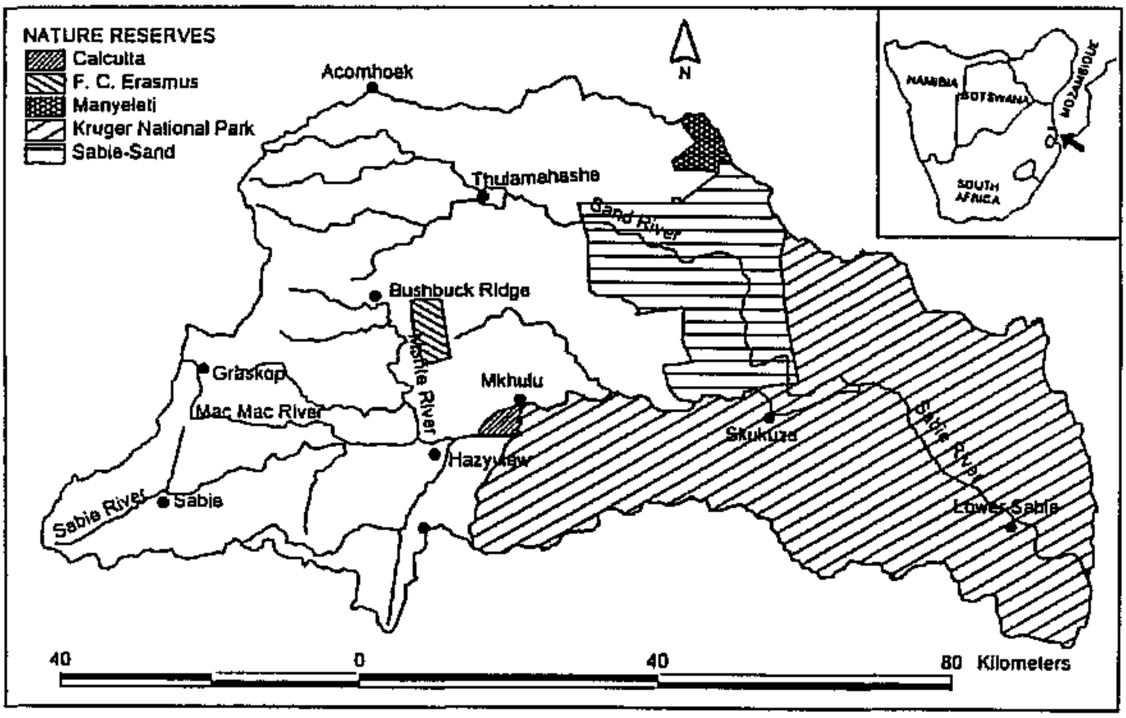


Figure 5. The Sabie River catchment, Mpumalanga Province, South Africa.

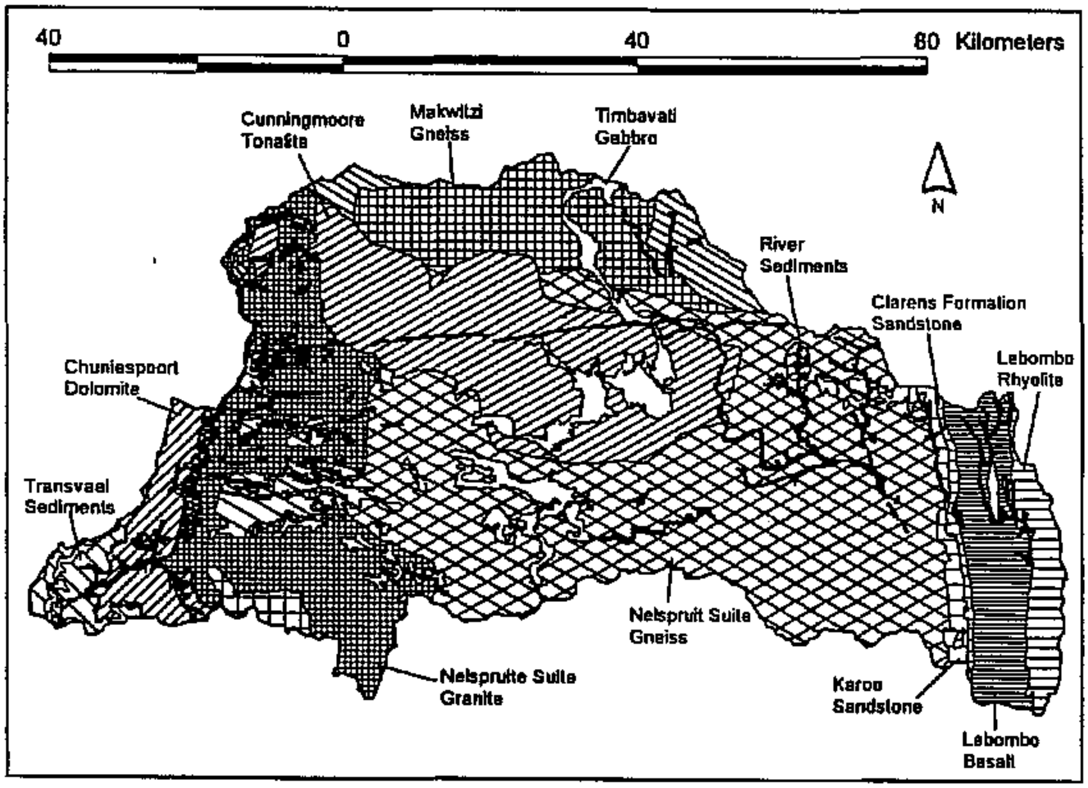


Figure 6. Simplified geology of the Sabie River catchment.

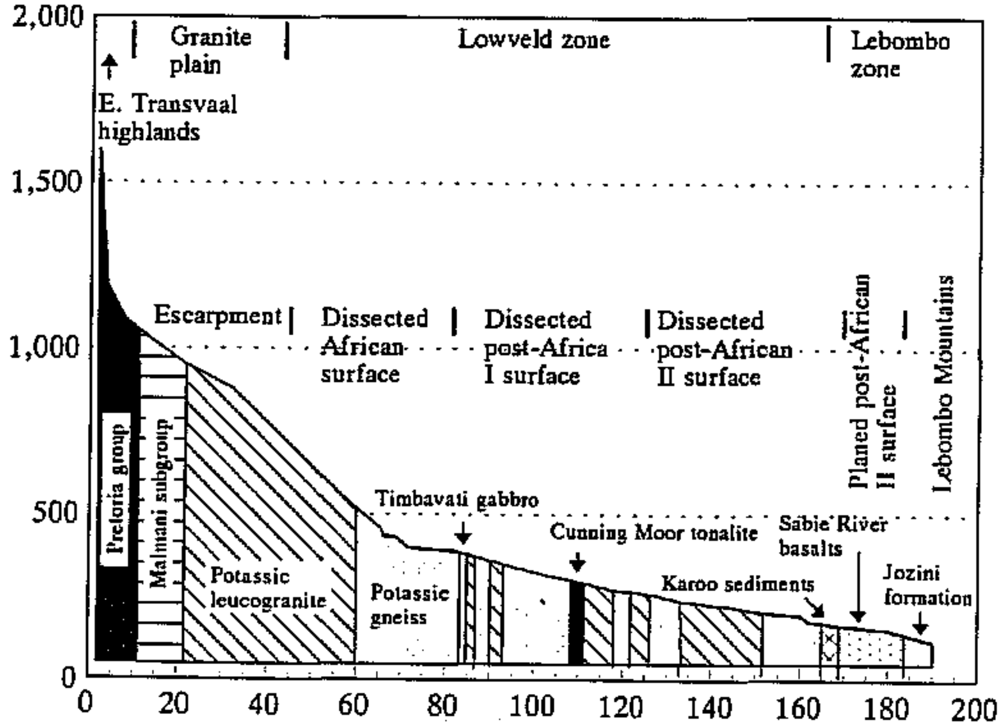


Figure 7. Generalised channel slope of the Sabie River.

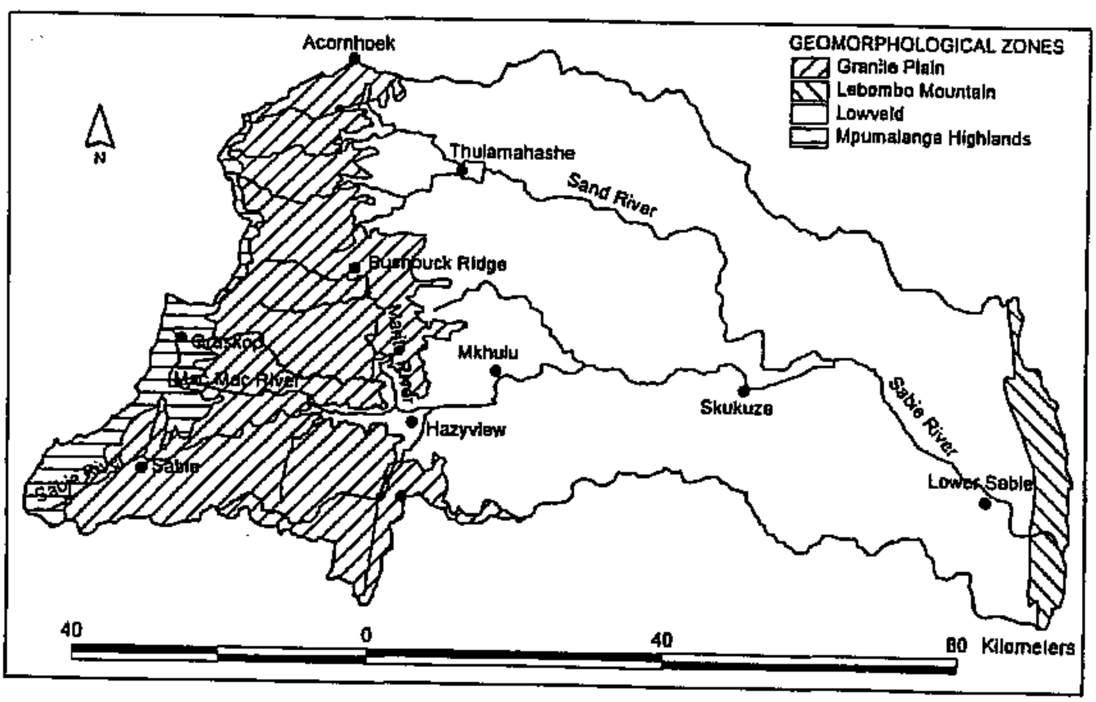


Figure 8. Geomorphological zones of the Sabie River catchment.

2.3 Sediment production

A number of studies have been conducted on the Sabie River catchment to quantify its sediment production potential (Rooseboom *et al.* 1992, van Niekerk and Heritage 1994, Wadeson and Rowntree 1995, Donald *et al.* 1995). The Rooseboom *et al.* (1992) model predicts an average sediment yield of $155tkm^{-2}a^{-1}$ for 50% confidence, $350tkm^{-2}a^{-1}$ (80% confidence) and $620tkm^{-2}a^{-1}$ with 95% confidence. van Niekerk and Heritage (1994) predict production rates between 250 and $400tkm^{-2}a^{-1}$, dependent on sub-catchment definition (Fig. 68). This compares with the sub-catchment estimates of Donald *et al.* (1995), which range from below 50 to $400tkm^{-2}a^{-1}$ (Table 2). In the study of Wadeson and Rowntree (1995) sediment production categories were not quantified and hence are not represented in Table 2. In all cases the estimates vary depending on the methodology. Donald *et al.* (1995) provides the most detailed field assessment and catchment breakdown of sediment production processes.

Table 2. Comparison of predicted sediment production figures for the Sabie River catchment.

	Sediment yield (tkm^2a^{-1})		
Sub-catchment	Rooseboom *et al.* (1992)	van Niekerk and Heritage (1994)	Donald *et al.* (1995)
Upper Sabie	155-620	327	100-150
Maritsane	155-620	345	<50
Noord Sand	155-620	402	>400
Sand	155-620	378	<50 and 300-400
Middle Sabie	155-620	401	200-300
Lower Sabie	155-620	246	<50

2.4 Hydrology

Chiew *et al.* (1995) have demonstrated that southern African rivers, like Australian rivers, have very extreme flow regimes, displaying twice the world average flow variability. Hydrological data for the Sabie River in the Lowveld region is limited. Gauging stations are located at Perry's Farm, Kruger Weir, and Lower Sabie (Fig. 9). Of these only Perry's Farm has an extensive flow record, extending back to 1959. Kruger Weir has operated only since 1990 and Lower Sabie since 1987. The Sabie River is perennial but it is subject to discharge extremes similar to other semi-arid systems in the eastern part of southern Africa.

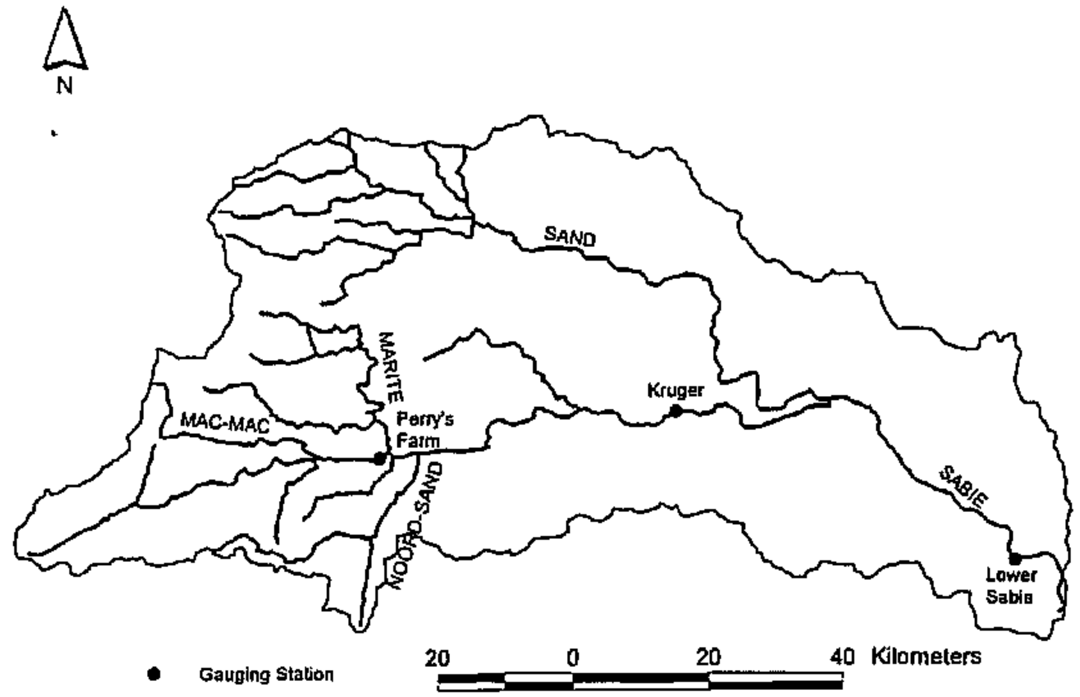


Figure 9. The locations of flow gauging structures in the study section of the Sabie River.

Precipitation is concentrated in the highland areas to the west of the catchment (1800-2000 mma^{-1}), declining to 450-650mma^{-1} over the Lowveld and Lebombo geomorphological zones (Fig. 10). In contrast, evaporation is lower in the west (1400mm), rising to 1700mm in the east (Fig. 11). Seasonal trends are clear in both the precipitation and the flow regime. At Perry's Farm gauge station, low flows of the order of 1 to 2 m^3s^{-1} occur in the dry winter months of April through to September. Elevated and more variable flows are linked to the rains between October and March (Table 3). Climatic variability has also been identified for the Lowveld region (Tyson 1987 and Mason 1996). A quasi 18-year rainfall cycle appears to exist and has been linked to the influence of El-Niño on the region, which is reflected in the flow pattern of the Sabie River. The recent 'double' El-Niño event led to an extended dry period in the region (Mason 1996) and much reduced flow magnitude and variability in the Sabie River.

Table 3. Summary daily average flow statistics for Perry's Farm gauge station 1959-1994.

Season	Statistic	Wet years	Dry years	Average years	All years
Wet Season (October-March)	Mean	30.58	5.86	8.87	12.36
	Minimum	22.64	0.50	3.14	0.50
	Maximum	258.00	16.22	25.18	258.00
Dry season (April-September)	Mean	25.43	3.10	4.28	8.60
	Minimum	21.94	0.10	2.97	0.10
	Maximum	197.17	5.13	6.27	197.17

The 1984 anthropogenic water requirements (Table 4) represented some 28% of the natural mean annual runoff (MAR) in the Sabie River catchment, with exotic afforestation in the upper catchment representing the largest usage. The projected water demand by the year 2010 is some 52% of the MAR, representing an 84% growth, the majority of which will be involved in development of the rural areas. Clearly there is currently a major anthropogenic impact on water resources and land-use at present, affecting flow regime and sediment production respectively. Anthropogenic effects on the two major catchment control variables are projected to expand, potentially resulting in geomorphological change to the Sabie River system.

Table 4. Present (1985) and projected (2010) land-use and water demands for the Sabie River catchment (Birkhead and Heritage 1995).

Catchment area (km^2)						7096
Natural MAR ($10^6m^3a^{-1}$)						762
Percentage of population living in underdeveloped conditions						92%
Demand sector		1985		2010		% Growth in water demand
		km^2	$10^6m^3a^{-1}$	km^2	$10^6m^3a^{-1}$	
Population	SA		1.1		3.5	218
(Urban & rural)	*		6.3		52.7	737
Irrigation	SA	66	51.2	66	51.2	0
	*	48	48.1	166	176.9	268
Livestock	SA	4230	0.4	4230	0.4	0
	*	2207	1.4	2207	1.4	0
Afforestation	SA	624	92.7	740+	95.5	3
	*	97	13.9	680+	14.5	0
Total	SA		145.4		150.6	4
	*		69.7		245.5	252
	Combined		215.1		396.1	84

+ Total net afforestation potential
* Former homeland areas of Gazankulu, Lebowa, Kangwane and Venda

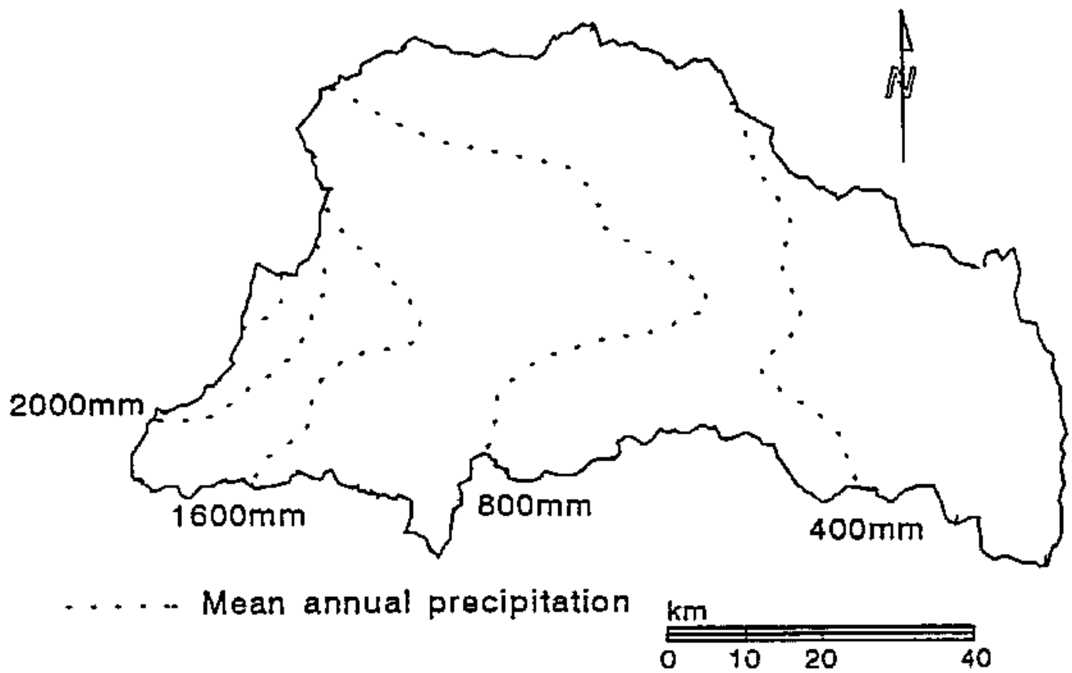


Figure 10. Average annual precipitation for the Sabie River.

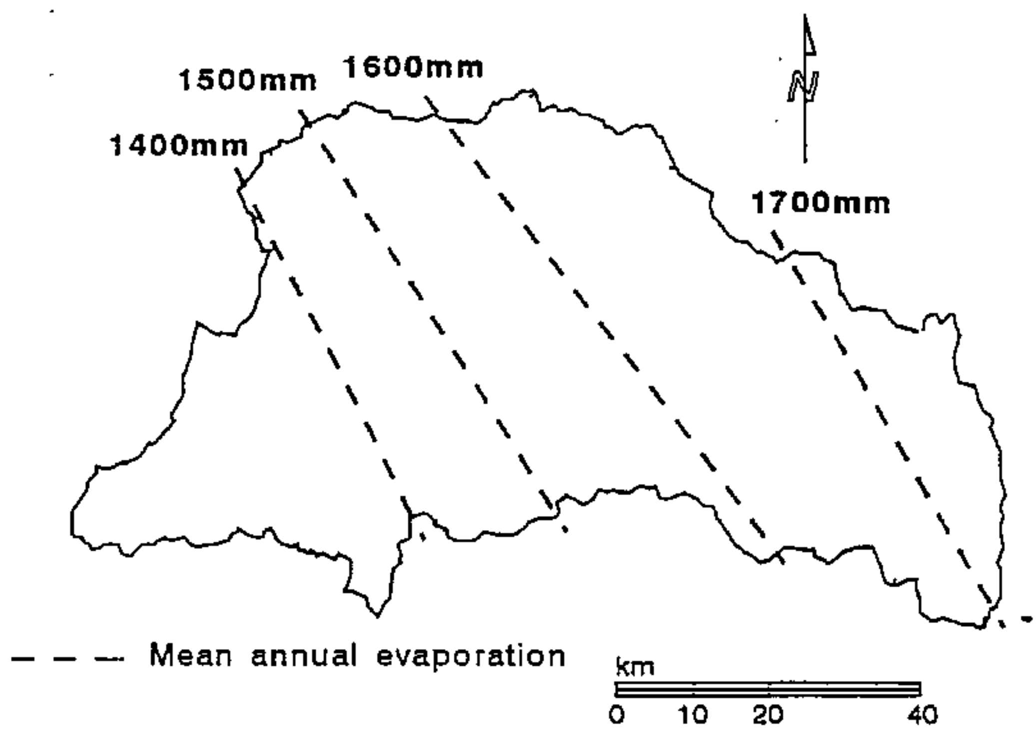


Figure 11. Average annual evaporation for the Sabie River catchment.

2.5 Summary

☺ The Sabie River catchment displays a diverse topography and regional geomorphology that is closely related to the underlying geology. Four principal geomorphological regions can be distinguished, the Mpumalanga Highlands, the Granite Plain, the Lowveld and the Lebombo Mountains.

☺ Land degradation and sediment production are high, particularly in the rural areas to the west of the Kruger National Park. This sediment is contributing to an increase in the area of sedimentary deposits observed in the Sabie River from aerial photographs.

☺ The hydrological regime of the Sabie River is characterised by a relatively constant low flow dry season and a variable higher flow wet season. Superimposed on this pattern are annual and decadal fluctuations due to the climate and abstraction of water for agriculture and human consumption.

☺ The principal dynamic catchment control factors influencing the Sabie River are the precipitation, influencing the hydrology (flow magnitude and frequency), catchment sediment production and local channel hydraulics.

3. SABIE RIVER: GEOMORPHOLOGICAL CLASSIFICATION AND DESCRIPTION

The Sabie River in the Kruger National Park is incised into African Surfaces I and II, which consist of gneiss west of the conservation areas, separated from the basalt in the east by a narrow band of Karoo Sequence sediments (Fig. 6). 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. Outcrops of resistant rocks in the bed and banks cause local downstream steepening of the river and upstream decrease in gradient, resulting in a reduction in channel energy and localised sediment accumulation. These rock outcrops are generally in the form of resistant areas in the gneiss host rock. Displacement in the host rock as a result of faulting has occurred in some areas, affecting the planform of the channel.

The Sabie River in the Lowveld consists of a macro-channel and one or more active channels (Fig. 12). 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 may become active during the higher summer flows. Sediment deposits occur in the active channels and along their edges, although bedrock outcrops frequently, controlling water surface slope. The morphology of the macro-channel is controlled by large magnitude, low frequency events, whereas the active channels are continuously evolving in response to all flows, via sedimentation (all channels) and erosion (all non-bedrock channels)(chapters 5 and 9).

The dynamics of alluvial channels are relatively well understood, however there have been very few studies conducted on bedrock channels and it is not known how variable most bedrock channel forms can be and on what scale variations occur (Baker 1984, Selby 1985). For these reasons, great care must be exercised in analysing the Sabie River in the light of previously published experience on alluvial rivers. In order to begin to understand this very diverse physical system with a large variety of morphological units, it is important to rationalise the system structure. This is achieved most readily through development of a classification system.

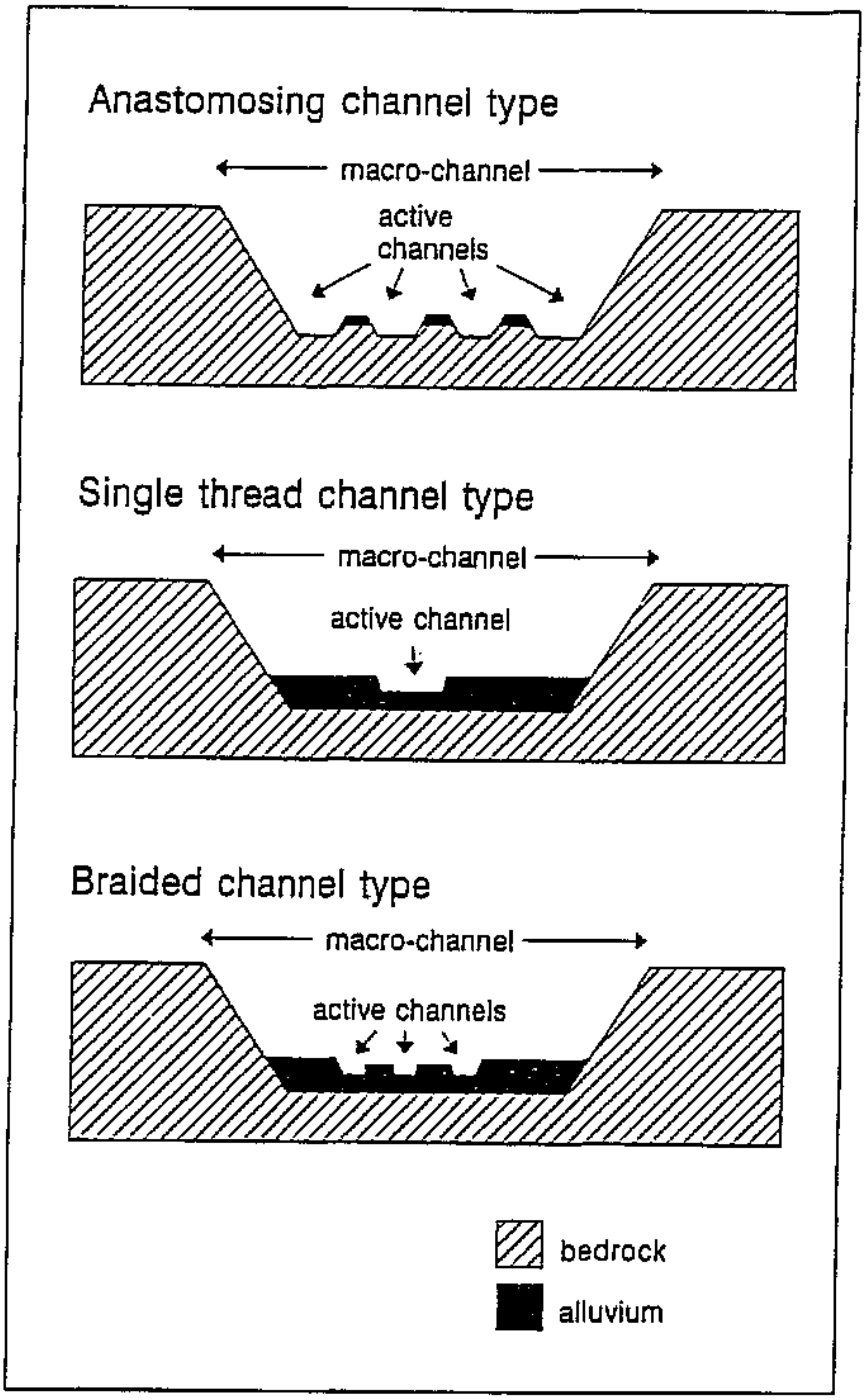


Figure 12. The structure of the Sabie River macro-channel.

3.1 Classification systems

The history of stream classification has been reviewed by Macan 1961, Hawkes 1975, Wasson 1989, Naiman *et al.* 1990 and Wadeson and Rowntree 1995. Many classification systems have been proposed 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 microhabitat (Brussock *et al.* 1985; Rosgen

1985; Frissell *et al.* 1986; Cupp 1989 and 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 river system can develop. A basic difference in constructing hierarchical classifications is whether to adopt a 'top down' divisive or a 'bottom up' agglomerative approach. In general, information detail is lost the farther removed a particular hierarchical level is from the initiating level. Thus, broad scale (regional) classifications generally adopt a divisive approach while finer scale (within catchment) classifications benefit from an agglomerative approach.

The majority of hierarchies are aimed at classifying different river systems or large scale river sections and are structured from the catchment scale downwards, on the basis that it is the catchment variables that control the dynamics and hence the broad morphology of river systems (van Deusen 1954). This divisive approach to hierarchical classification has been used where gross groupings are required, in that the whole is split into parts in stages, with a different criterion (usually a single variable) being used at each stage (Mather 1976). The spatially nested hierarchy developed by Frissell *et al.* (1986) is a divisive approach in which a system at one level forms the environment for the subsystems below and has gained wide acceptance within the research community. Essentially they recognise six spatial scales from drainage basin to microhabitat level (Table 5).

The problem with the top down approach to river classification is most apparent when it is imposed on a river where the catchment characteristics are very different from those of the rivers on which the classification system was developed. Such a classification is essentially empirical and imposes a structural rigidity which prohibits its meaningful use beyond the river types on which it was developed. Mosley (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 or agglomerative hierarchical system. It is impossible to apply a divisive approach, developed on well ordered temperate alluvial river systems, to semi-arid bedrock influenced systems, such as the Sabie River, as the catchment control factors responsible for the geomorphological state of the river work on much smaller spatial and temporal scales.

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.

Table 5. The hierarchical classification of second and third order forested mountain streams (Frissell *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 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, depth and velocity pattern.
Microhabitat	Patches within pool/riffle systems with homogenous substrate, water depth and velocity.

3.2 An agglomerative hierarchical classification for the Sabie River

The hierarchical geomorphological classification for the Sabie River in the Kruger National Park, proposed here (Fig. 13), follows that of van Niekerk *et al.* (1995) in adopting a bottom-up 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 scale and that it is the association of these features that progressively build to create a complete spatial classification of the river. This classification has been used to describe the river in terms of the association of morphological units observed, providing a structured order to a complex geomorphological system (Fig. 14a-d).

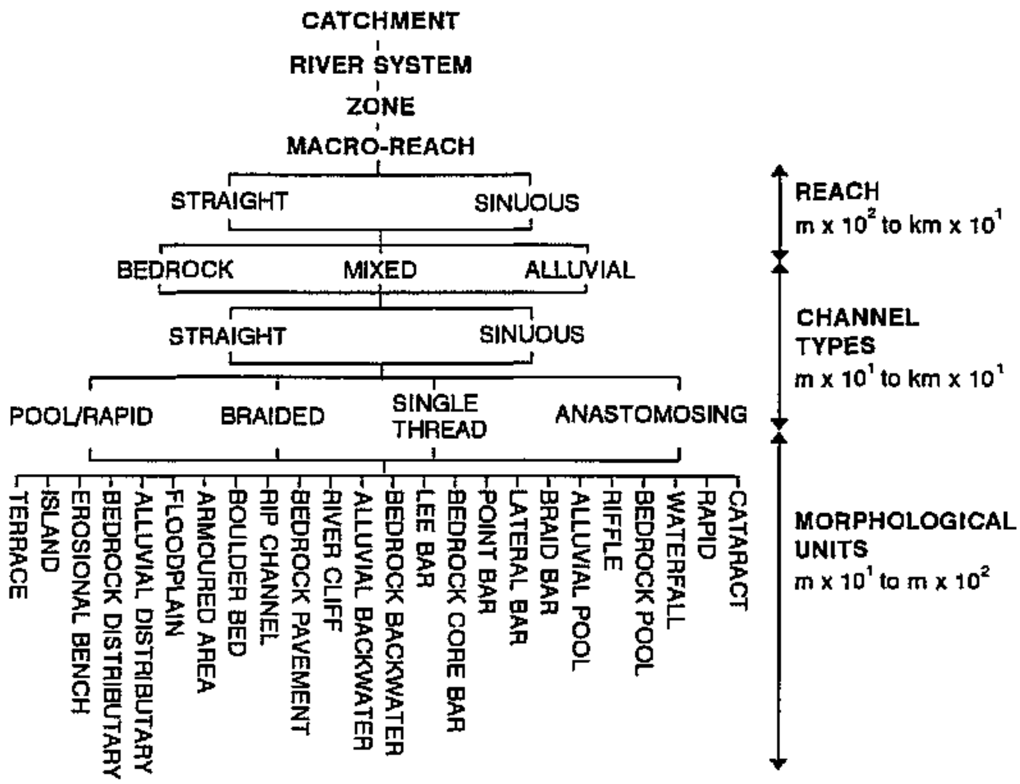


Figure 13. A hierarchical classification of the Sabie River in the Kruger National Park.

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 (Fig. 14a). 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 (Table 6, Fig. 13).

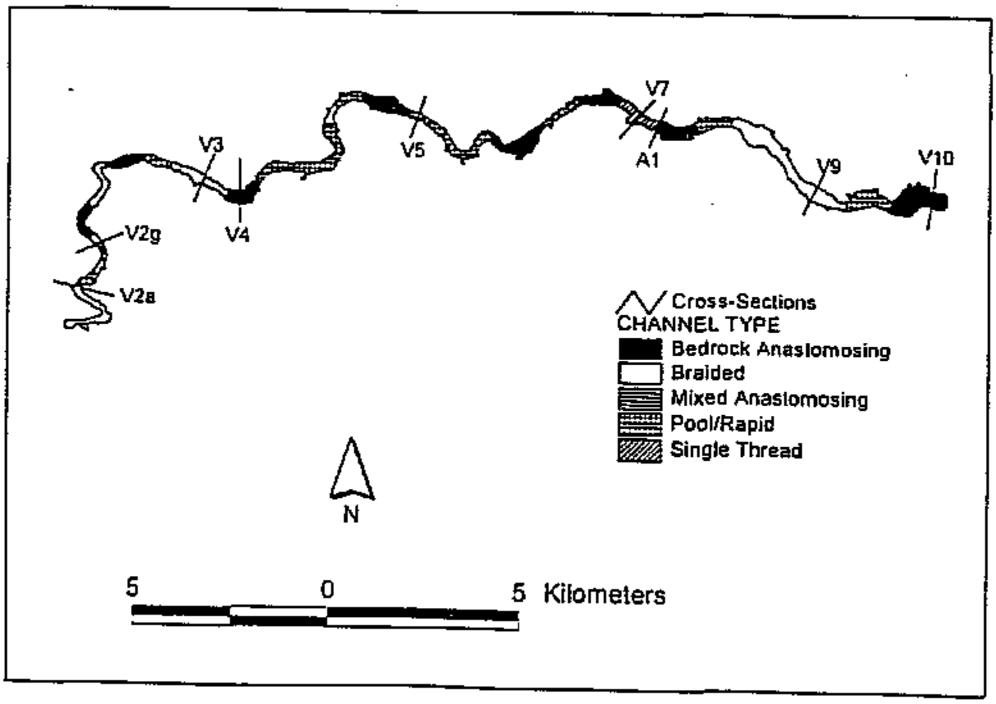


Figure 14a. Channel types along the Sabie River.

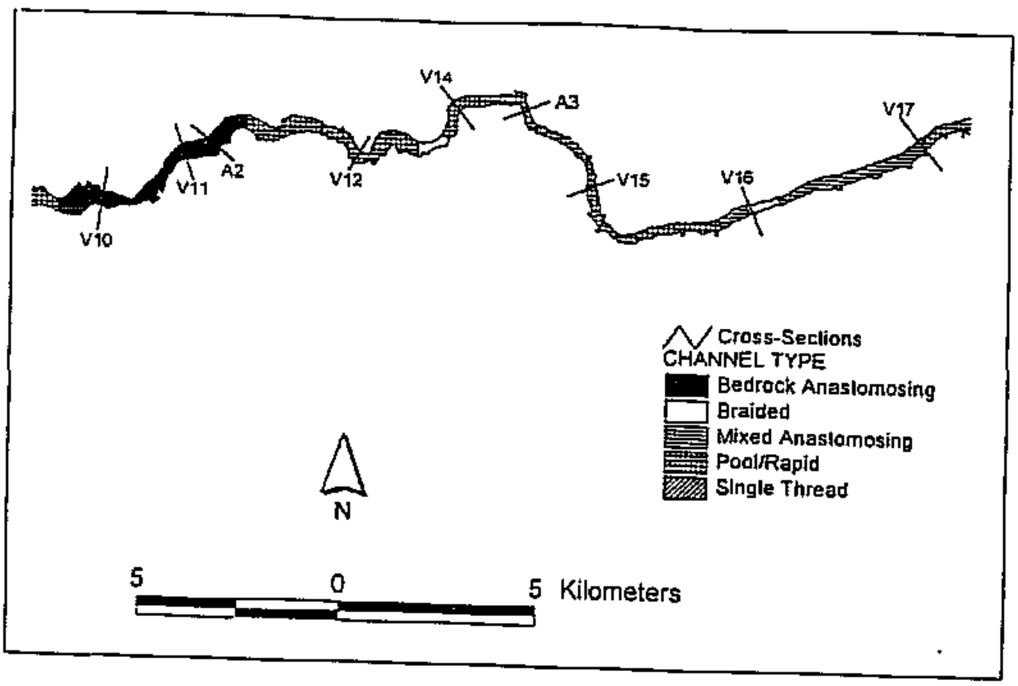


Figure 14b. Channel types along the Sabie River (cont.).

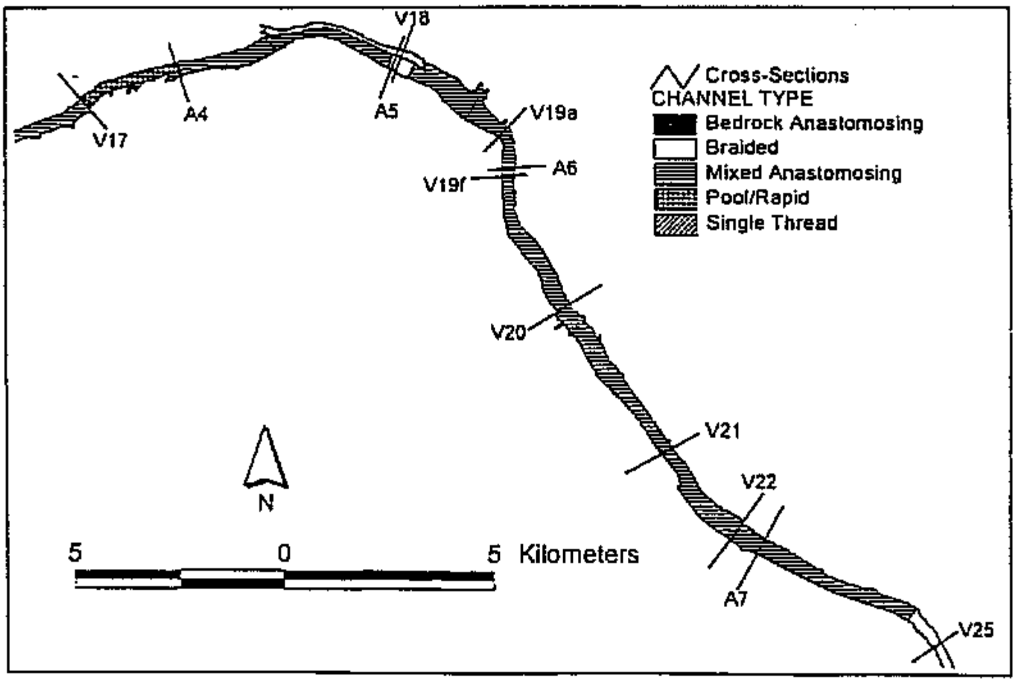


Figure 14c. Channel types along the Sabie River (cont.).

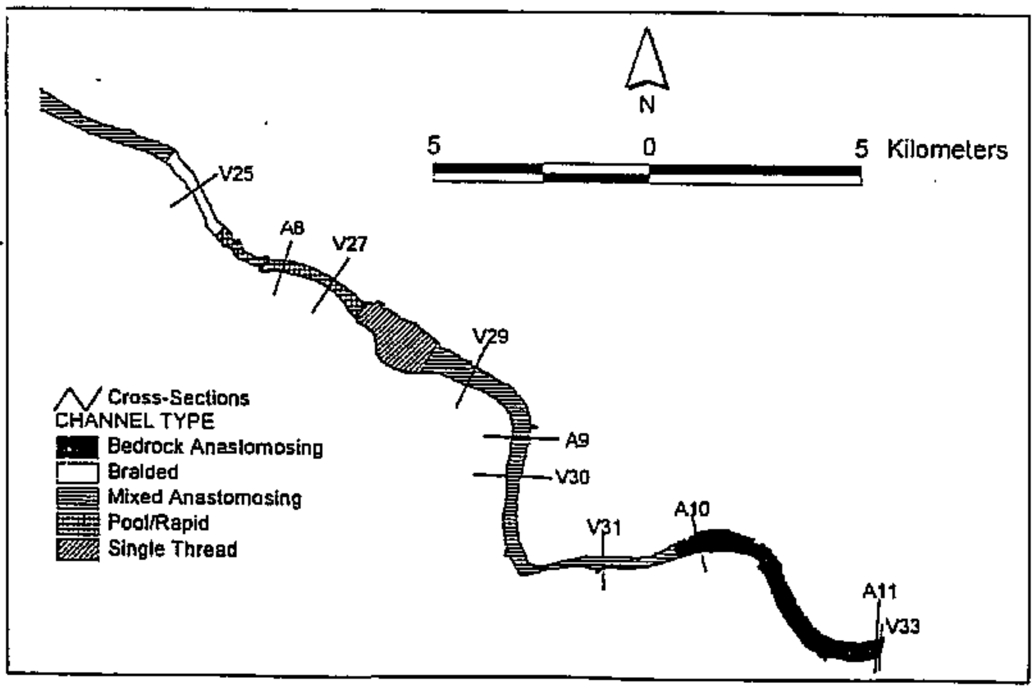


Figure 14d. Channel types along the Sabie River (cont.).

Table 6. Structural comparison of the hierarchical classification systems of Frissell *et al.* (1986), Wadeson and Rowntree (1995) and van Niekerk *et al.* (1995).

Frissell *et al.* (1986)	Rowntree and Wadeson (1995)	van Niekerk *et al.* (1995)
Drainage basin	Catchment	Catchment River system
Stream system	Zone	Zone
Segment	Segment	Macro-reach
Reach	Reach	Reach Planform Channel type
Pool/riffle	Morphological unit	Morphological unit
Microhabitat	Biotope	-

The microhabitat of Frissell *et al.* (1986) considers only local physical characteristics excluding flow, whereas biotope incorporates flow components such as flow depth and velocity. The classification used here did not consider levels below morphological unit, as detailed knowledge of biological interaction with geomorphology is needed to define these accurately and this was not available for this report.

3.3 Morphological unit characteristics

The interaction of bedrock and alluvium along the Sabie River has generated a very varied assemblage of morphological units. Many of these have been described in detail in standard texts on fluvial geomorphology (Reading 1986, Selby 1985). A brief description of the morphological units found on the Sabie River is given in Table 7. These units combine to form ten channel types of which five are commonly found on the Sabie River in the Kruger National Park.

Table 7. Description of the morphological units found on the Sabie River in the Kruger National Park.

Morphological Unit	Description
Cataract	Step-like successions of small waterfalls, seldom drowned out at high discharges.
Rapid	Steep bedrock sections, high velocity concentrated flow.
Waterfall	Abrupt vertical discontinuity in channel slope.
Bedrock pool	Deeper low velocity area upstream of a bedrock control.
Riffle	Accumulation of coarser sediment as a topographic high point as part of a pool-riffle sequence.
Pool	Topographic low point characterised by finer sediments, as part of a pool-riffle sequence.
Braid bar	Accumulation of sediment in mid-channel causing the flow to diverge over a scale that approximates to the channel width.
Lateral bar	Accumulation of sediment attached to the side of the channel, may occur sequentially downstream as alternate bars.
Point bar	Accumulation of sediment on the inside of a meander bend.
Bedrock core bar	Accumulation of finer sediment on top of bedrock in bedrock anastomosing areas.
Lee bar	Accumulation of sediment in the lee of flow obstructions.
Bedrock backwater	Stationary or near stationary bodies of water in bedrock, adjacent to the active channel.
Alluvial backwater	Stationary or near stationary bodies of water in alluvium, adjacent to the active channel.
River cliff	Vertical or near vertical alluvial erosion face.
Apical pool	Deep section of channel located on the outer bend of a meander, associated with point bars.
Rip channel	High discharge distributary channel on the inside of point and lateral bars.
Boulder bed	Accumulation of locally derived material exceeding 0.25m.
Armoured area	Accumulation of coarser sediments due to winnowing of finer material.
Floodplain	Extensive lateral accumulation of finer sediment as a result of flood deposition.
Alluvial distributary	Individual active channel in an alluvial braided or anastomosing system.
Bedrock distributary	Individual active channel in a bedrock anastomosing system.
Island	Large mid channel sediment accumulation that is rarely inundated.
Terrace	Relic floodplain or valley floor deposits above the present river level.

3.4 Channel type characteristics

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 river states that could be related to the build-up or erosion of sediments (alluvial anastomosing, bedrock single thread, bedrock pool-rapid, mixed single thread and mixed anastomosing) (Table 8). Differentiation between types was based on physical appearance and morphological unit composition (Table 9).

Table 8. 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 the natural environment				

The primary 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 (Fig. 15a and b, Table 9). Chemical differences in the host rock have generated resistant areas where the river is 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 dead zones.

Figure 15a. Characteristic geomorphology, planform and cross-sectional form of a bedrock anastomosing channel type in the Sabie River.

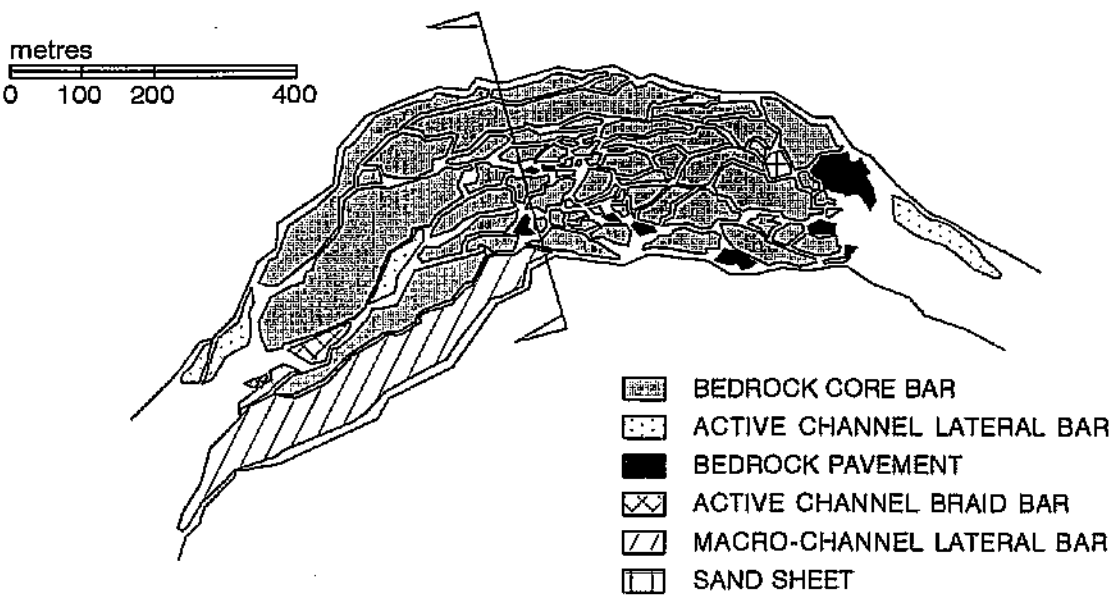


Figure 15b. Characteristic geomorphology, planform and cross-sectional form of a bedrock anastomosing channel type in the Sabie River.

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 or 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 (Fig. 16a and b, Table 9), 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. However, Table 9 is sub-divided based on the presence of certain morphological units such as point bars and apical pools that are common to sinuous channels. Single thread 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 (Fig. 17a and b, Table 9). Typically, these channel types contain a considerable range of the features noted in temperate alluvial single thread channels.

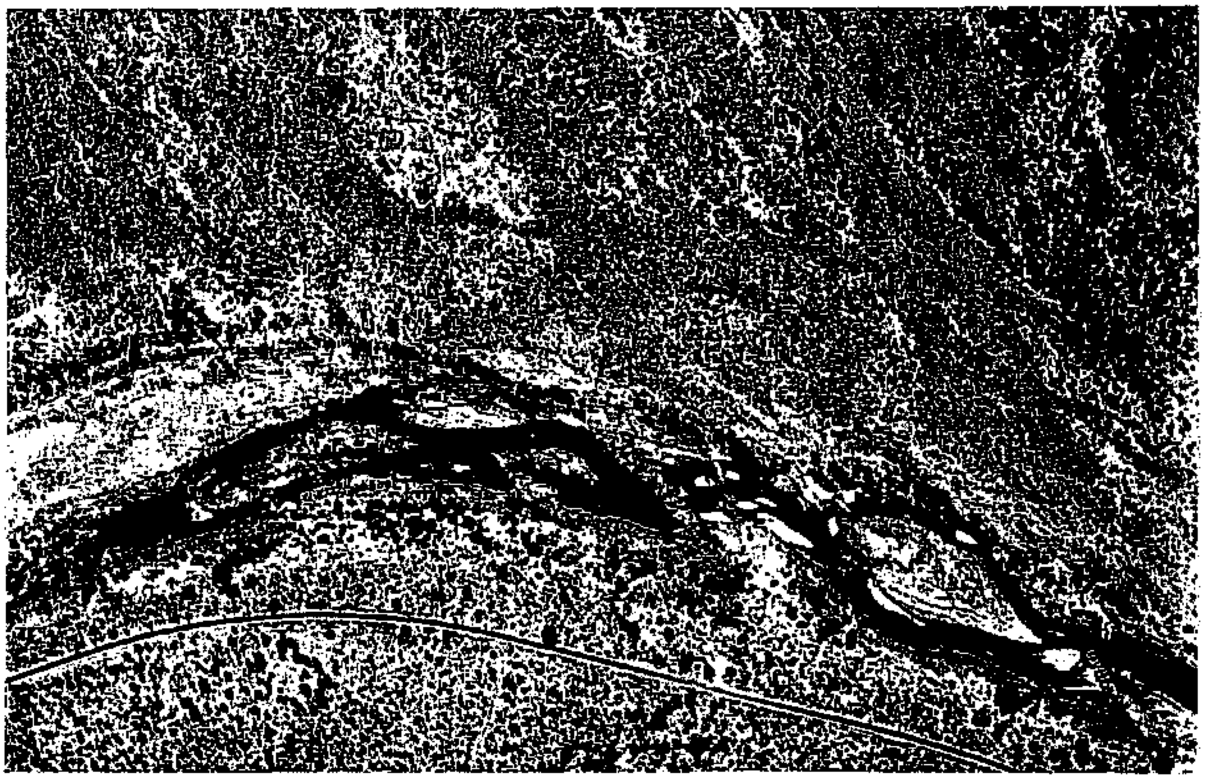


Figure 16a. Characteristic geomorphology, planform and cross-sectional form of a bedrock pool-rapid channel type in the Sabie River.

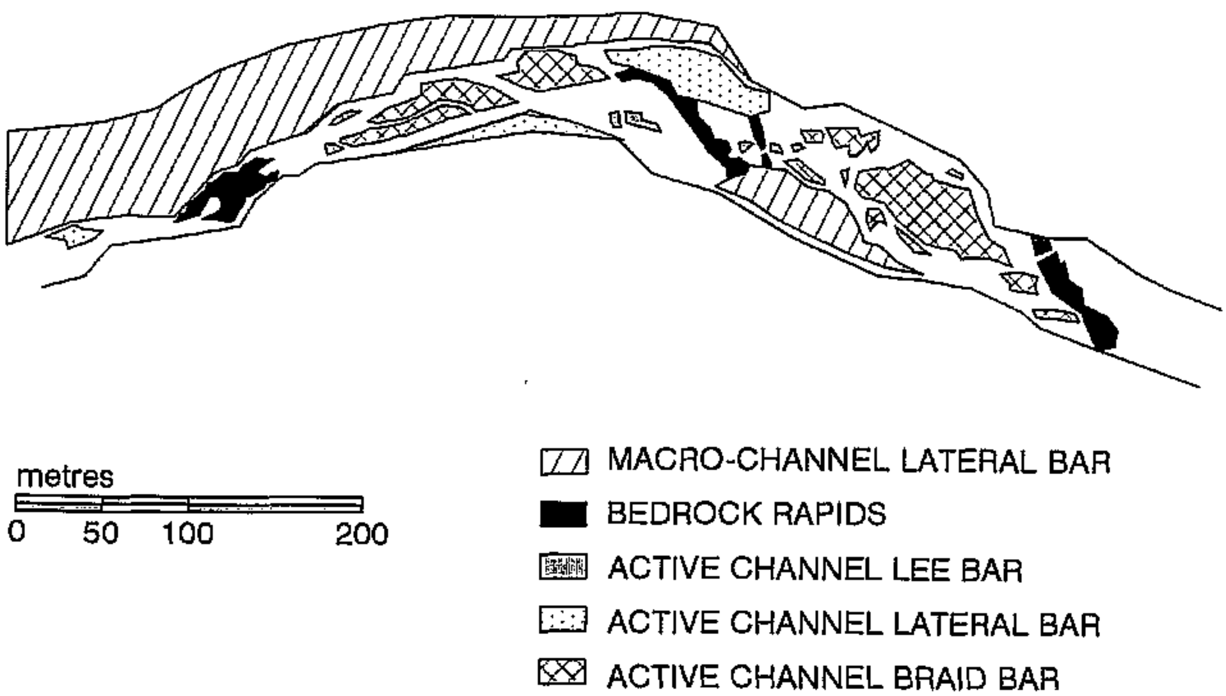


Figure 16b. Characteristic geomorphology, planform and cross-sectional form of a bedrock pool-rapid channel type in the Sabie River.

Figure 17a. Characteristic geomorphology, planform and cross-sectional form of an alluvial single thread channel type in the Sabie River.

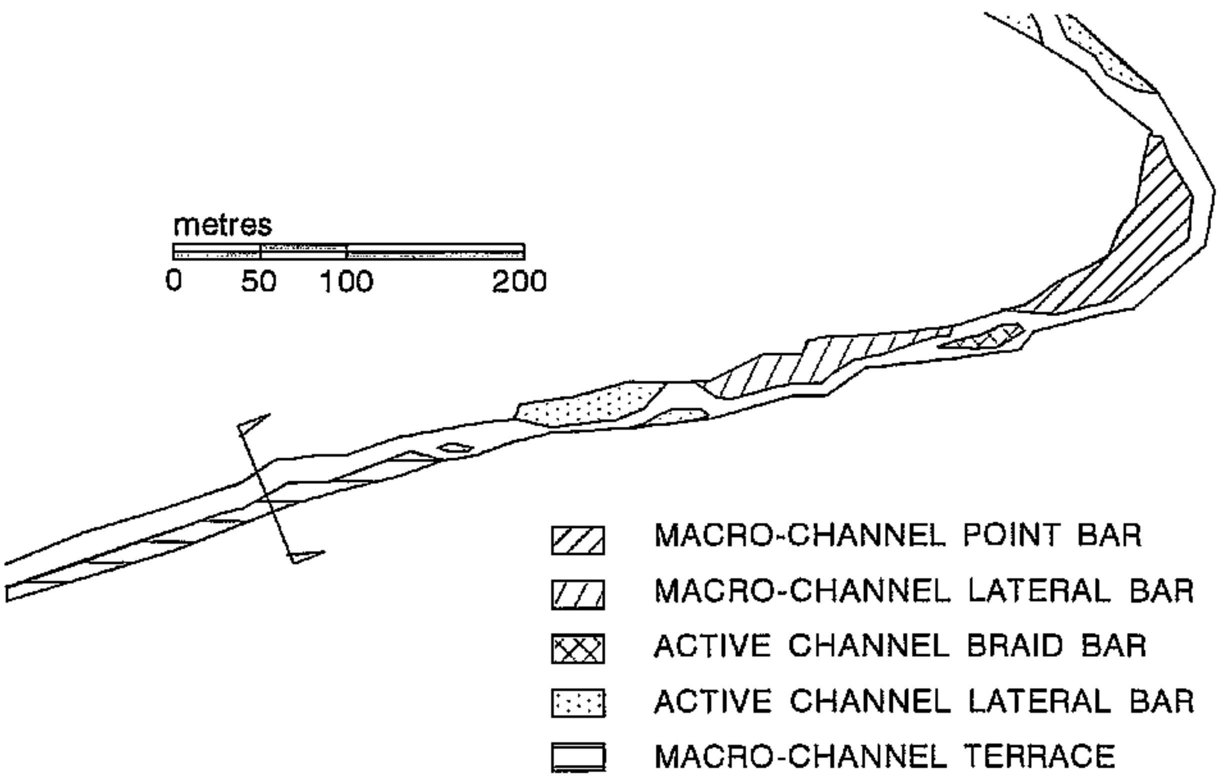


Figure 17b. Characteristic geomorphology, planform and cross-sectional form of an alluvial single thread channel type in the Sabie River.

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 (Fig. 18a and b, Table 9).

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 (Fig. 19a and b, Table 9). 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.

Variability between sediment transport ability 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. It is transition states, such as this 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. Other channel types that are possible from the hierarchical pathways described by the Sabie River classification (Fig. 13), including alluvial pool-rapid and bedrock braided are not found in the natural environment.

Figure 18a. Characteristic geomorphology, planform and cross-sectional form of a braided channel type in the Sabie River.

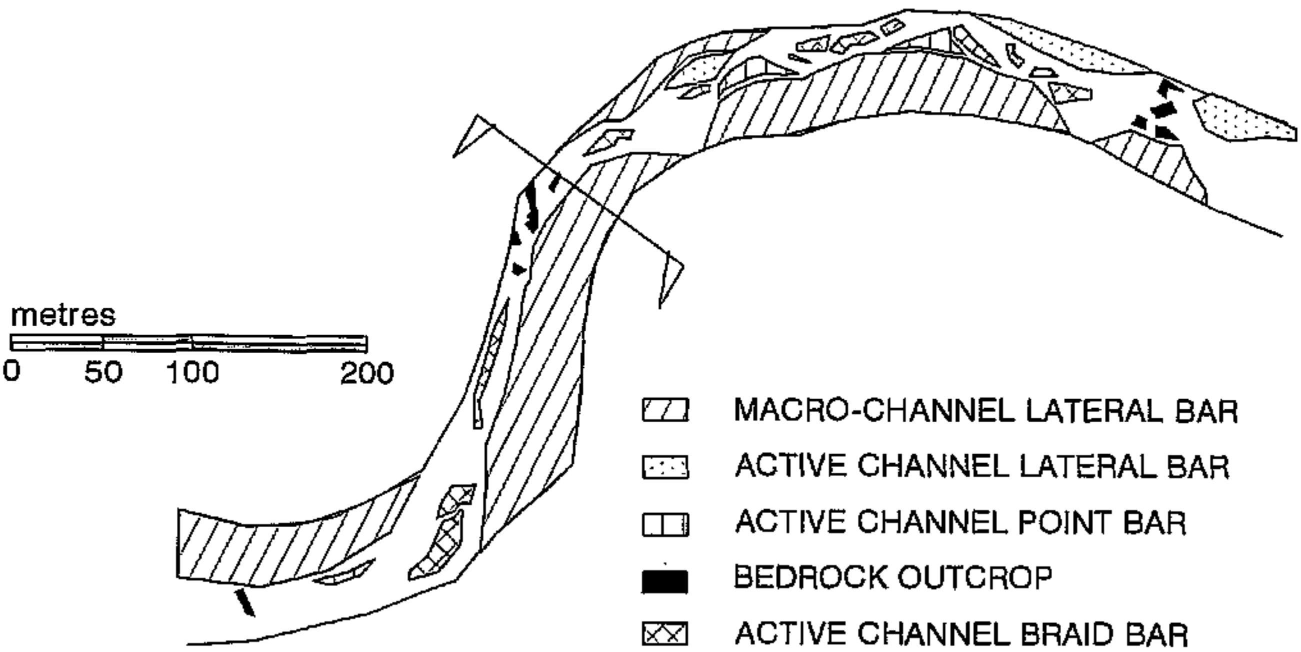


Figure 18b. Characteristic geomorphology, planform and cross-sectional form of a braided channel type in the Sabie River.

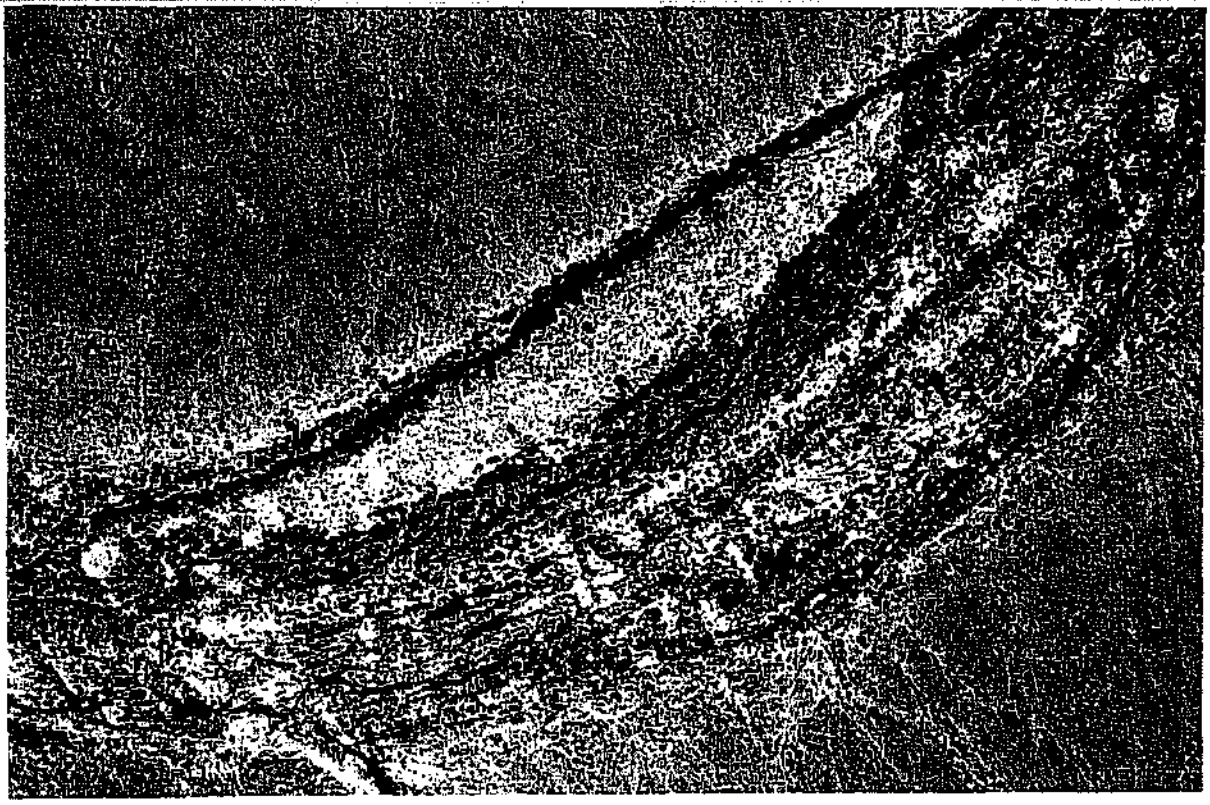


Figure 19a. Characteristic geomorphology, planform and cross-sectional form of a mixed anastomosing channel type in the Sabie River.

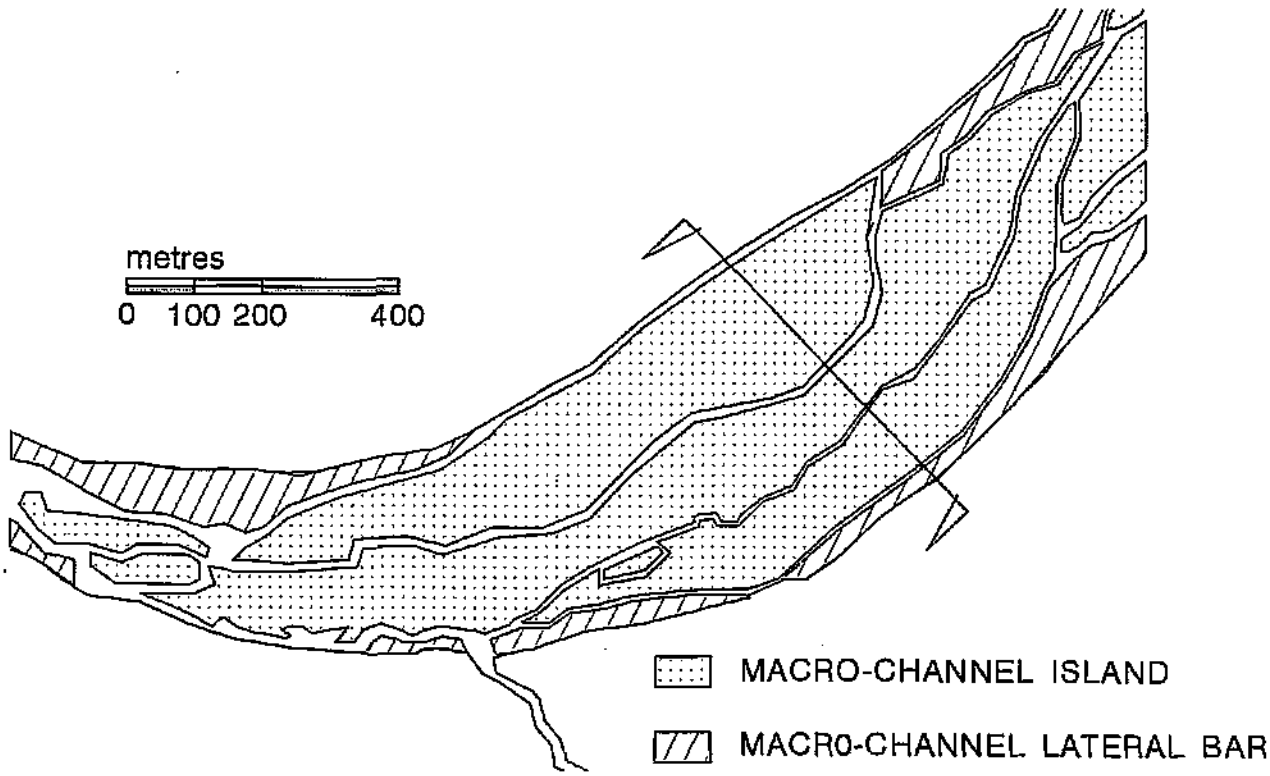


Figure 19b. Characteristic geomorphology, planform and cross-sectional form of a mixed anastomosing channel type in the Sabie River.

Table 9. Morphological composition of the common channel types found on the Sabie River in the Kruger National Park.

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

3.5 Reaches

Reaches (Fig. 20) are classified based on functional relationships between channel types and 22 have been identified on the Sabie River in the Lowveld (van Niekerk and Heritage 1993). 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.

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.

3.6 Macro-reaches and zones

A macro-reach (Fig. 21) 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 Rowntree (1995). The definition of zones was based on relief and geology as described earlier (chapter 2). The delineation of different zones from a process point of view could be enhanced through more precise definition of their boundaries by incorporation of the Wadeson and Rowntree (1995) concept of zones which are homogeneous with respect to 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 prediction of geomorphological change were at finer levels. Full reach and macro-reach descriptions for the Sabie River in the Lowveld can be found in van Niekerk and Heritage (1993).

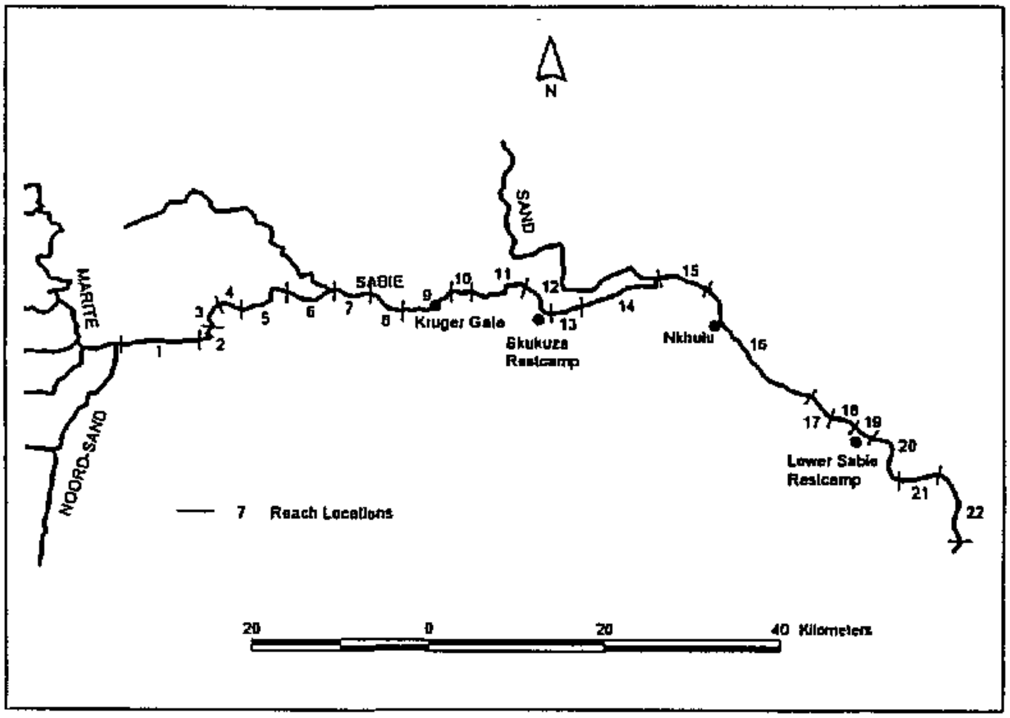


Figure 20. Breakdown of the reaches identified for the Sabie River in the Kruger National Park.

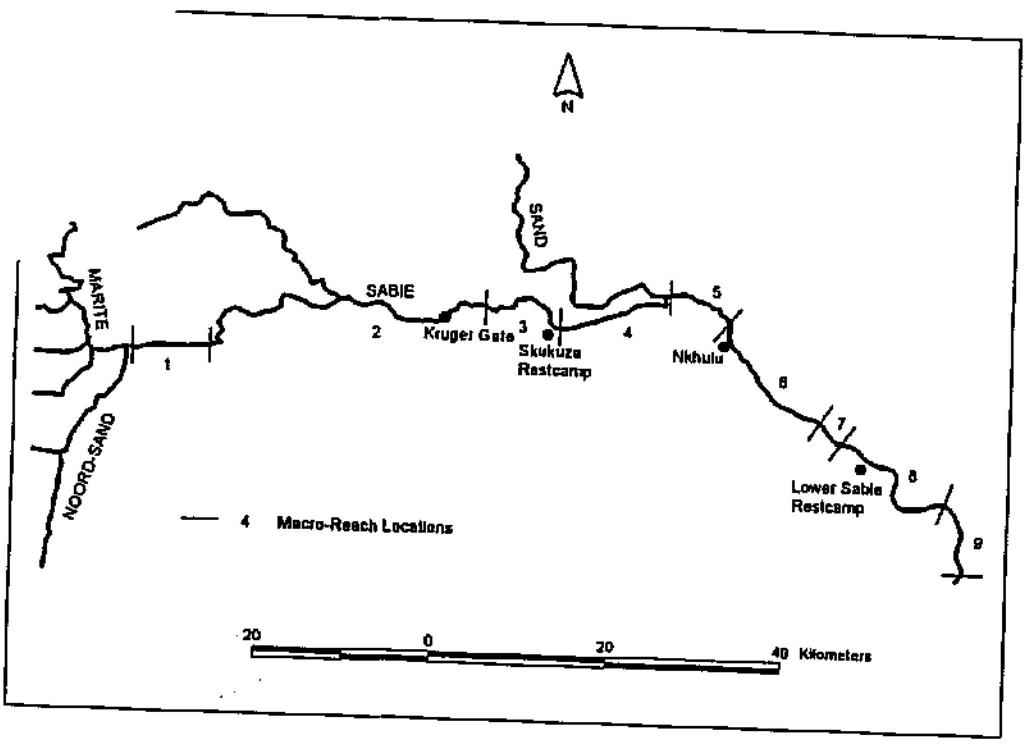


Figure 21. Breakdown of the macro-reaches identified for the Sabie River in the Kruger National Park.

3.7 Summary

☺ The Sabie River has incised into bedrock to form a macro-channel within which all recorded flows have been confined.

☺ A review of the literature on classification methods showed the divisive top-down approach to be most useful at the higher levels of a spatial hierarchy. This study specifically concentrated on predicting change at spatial scales that were much finer than this. Therefore, an agglomerative bottom-up approach to the classification of the Sabie River was adopted.

☺ An agglomerative hierarchical classification system is presented for use on the Sabie River to categorise the system on the basis of associative morphological units.

☺ A number of morphological units have been identified on the Sabie River that form associations as channel types. These channel types then associate to form reaches and macro-reaches.

☺ Five principal channel types have been observed on the Sabie River, these are bedrock anastomosing, mixed pool-rapid, mixed anastomosing, alluvial braided and alluvial single thread.

☺ The proposed classification based on the association of morphological components, covers a wide range of channel types and may be applied to any river system, providing an excellent framework for comparison between rivers. It has been used to delineate a structured geomorphological framework for the Sabie River in the Kruger National Park, which forms the physical basis for predicting the nature and degree of change to the river given an alteration to the balance of the controlling variables. Subsequent chapters demonstrate the dynamic nature of the Sabie River by means of illustrating how the geomorphological composition of the river has changed.

4. A CONCEPTUAL MODEL OF GEOMORPHIC CHANGE FOR THE SABIE RIVER

4.1 Timescales and the importance of change

The changing channel characteristics of the Sabie River reported by several authors (Vogt 1992, Heritage and van Niekerk 1994, Carter and Rogers 1995) attest to its dynamic geomorphological nature. This chapter focuses on combining the information on controls on channel behaviour and the physical character of the macro-channel, in order to generate a conceptual model of channel change for the river in the Lowveld.

This study is concerned with changes to the Sabie River over timescales of years, decades and centuries. Schumm and Lichty (1965) identified that over the modern and present timescales, channel morphology, water and sediment discharge and observed flow characteristics were dependent variables (Table 10). These variables were also identified as the important catchment control factors in chapter 2. As such, the overall catchment control model of Morisawa (1985) can be modified to define the principal dynamic variables that influence channel behaviour in this catchment. Channel flow regime, channel competence and catchment sediment production are thus highlighted as the major dynamic controls influencing geomorphological change on the Sabie River (Fig. 22). Factors such as geology are important (Cheshire 1996), but have a static influence at the temporal scale investigated in this study (Schumm and Lichty 1965) (Table 10). For example, the underlying bedrock lithology affects the form of the river, but tectonic movement which occurs over periods of millions of years may be ignored for the purposes of prediction at timescales considered here.

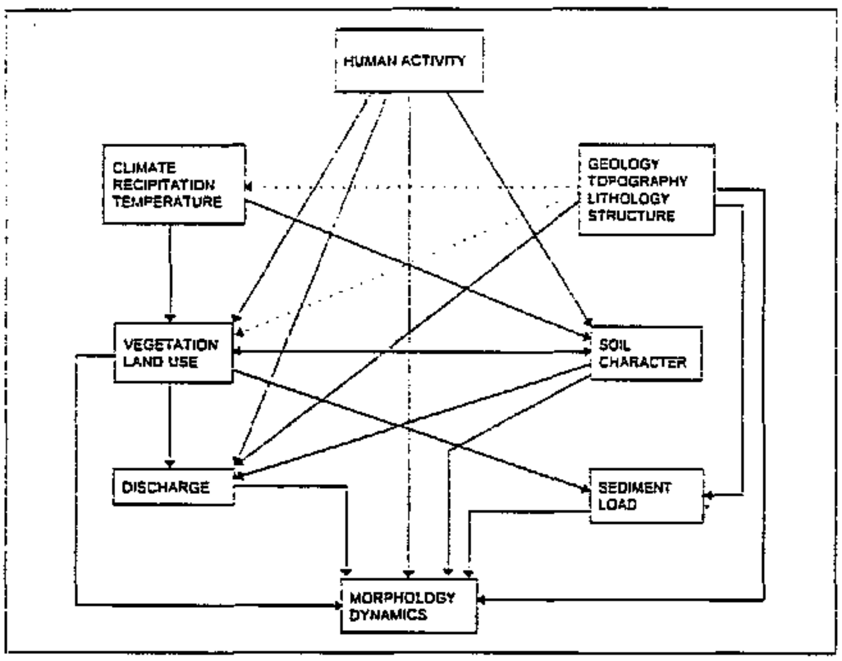


Figure 22. Principal catchment factors controlling channel form and dynamics on the Sabie River in the Kruger National Park.

Other factors including soil type, land-use patterns and catchment topography are also seen to influence the geomorphological dynamics of the Sabie River. Similarly, there are a number of positive feedback mechanisms operating to control channel form, in particular vegetative growth on new sediments influences the evolution of the sedimentary unit. Carter and Rogers (1995) has demonstrated the link between vegetative succession and bar formation. His successionary sequence from bedrock, through sand, reeds, and shrubs, to trees indicated a positive feedback mechanism operating between progressive sedimentation and vegetative colonisation.

Such mechanisms have been recognised by the authors of this report, however, the complex nature of the feedback mechanisms has precluded their explicit inclusion in the models derived here. In the qualitative modelling the feedback mechanisms are implicit as the evolutionary pathways suggested are from photographic evidence and hence include all of the processes operating in the Sabie River. The semi-quantitative models presented in chapter 9 are not sufficiently sensitive at present to warrant the detailed investigation and inclusion of vegetative feedback mechanisms. However, it is emphasised here that such mechanisms must be considered in any further refinement of such a model.

Table 10. Change in the status of channel variables with temporal scale (after Schumm and Lichty 1965).

River variables	Status of channel variables		
	Geologic ($>10^3$ years)	Modern (10^1 to 10^2 years)	Present (1 to 10 years)
Time	independent	irrelevant	irrelevant
Geology	independent	independent	independent
Climate	independent	independent	independent
Vegetation (Type and density)	dependent	independent	independent
Relief	dependent	independent	independent
Palaeohydrology	dependent	independent	independent
Valley dimensions	dependent	independent	independent
Mean discharge of water and sediment	indeterminate	independent	independent
Channel morphology	indeterminate	dependent	independent
Observed discharge of water and sediment	indeterminate	indeterminate	dependent
Observed flow characteristics	indeterminate	indeterminate	dependent

4.2 Observed channel change on the Sabie River

The Sabie River system is not in a state of dynamic equilibrium and is still evolving, largely in response to altered flow and sediment regimes. Vogt (1992) records changes to the river, from an analysis of the aerial photographic record, between the 1940s and 1980s. Single thread channels have shown a tendency to braid, due he hypothesised, to an increase of sediment stored within the macro-channel. In-channel and lateral deposits increased in size and abundance and often amalgamated to form larger sedimentary units. Point and lateral bars showed significant size increases particularly between 1965 and 1984. He also noted the reduction in backwater areas, possibly as a result of reduced flow volumes. Generally he concluded that there was sedimentation between 1940 and 1960, stability between 1960 and 1970 and further deposition between 1970 and 1980.

From a study of aerial photographs taken of the Sabie River in 1944 and 1986, Chunnet, Fourie and Partners (1990a) observed that of fifty current hippo pools, seven did not exist in 1944, twelve were smaller in 1944, five were larger in 1944 and the remaining six were essentially unaltered. Aerial photographs of the Manuli hippo pool on the farm Ravenscroft in the Sabie Sand Game Reserve show that the hippo pool there was almost undetectable in 1944, but that it cleared between 1944 and 1965. It then started to trap sediments, and by 1986 was substantially reduced in size, but still larger than that which existed in 1944. These studies indicate that there was scouring of the river channel at some stage between 1944 and 1965 and subsequent infilling of the channel until the present. However, there appears to be some contradiction between the observations of Vogt (1992) and Chunnet, Fourie and Partners (1990a). The findings of Vogt (1992) indicate that there was an increase in sedimentation between the 1940s and 1960s, a stable or slightly erosional period between the 1960s and 1970s and a depositional period between the 1970s and 1980s. The Chunnet, Fourie and Partners (1990a) findings indicate erosion of sediment in the 1940s and 1960s, stasis or slight deposition between the 1960s and 1970s and a depositional period between the 1970s and 1980s. Both studies, however, show an overall increase in sedimentation between the 1940s and 1980s, with a relatively static period between the 1960s to the 1970s. Chunnet, Fourie and Partners (1990a) observation of erosion between the 1940s and 1960s is based on studies of a single pool and cannot be regarded as representative of the direction of change in a dynamic system.

Carter and Rogers (1995) adopted Markovian analyses of change in landscape state-composition for the Sabie River in order to identify directions and rates of state transitions for water, sand, rock, reed, herbaceous and woody vegetation for the periods 1940/1944 to 1965, and 1965 to 1984/1985. For the period 1940/1944 to 1965, Carter and Rogers (1995) found that 10.7% of all state changes involved a transition from rock or sand to open water (Table 11). His finding implies a slightly higher water level in 1965, as opposed to the 1940/1944 aerial photographs. Unstable sandbars could potentially have shifted, but rock exposed in 1940/1944 would require a higher water level to have disappeared in 1960. There was, however, some reed encroachment by 1960 in previously open water (13.8%, Table 11). This reed encroachment is probably a result of deposition of bars which remained stable long enough for establishment of reeds. Rocky areas were covered by sand (4.4%) and herbaceous vegetation (23.2%), indicating deposition during this period. Most state changes (Carter and Rogers 1995) were either from non-vegetation (rock, sand, water) to vegetation states (57.2% of all changes) or involved only vegetation states (30.1%). Most state changes (55%) were directed towards the establishment of reeds (primarily from sand, but also from water, rock and herbaceous vegetation). Reeds were most persistent (Carter and Rogers 1995) but were almost always replaced by woody vegetation. These findings indicate that landscape change during this period was dominated by reed establishment on pre-existing bars rather than by changes in sedimentation patterns. There was minimal change from previously rocky areas to water and from water to rock (Table 11), indicating that water levels were similar in 1965 and 1984/5. During the period 1965 to 1984/5, 71.3% of water areas were replaced by sand (5.4%), minimal woody and herbaceous vegetation or, most likely, reeds (64.3%) (Carter and Rogers 1995), with only 10% of previously sandy areas being removed (Table 11). Also, during this period, rocky areas were replaced by reeds (48.8%) and limited herbaceous and woody vegetation (11.7%). Since the establishment of vegetation is dependent on sediments which are stable for a period, the extensive colonisation of rocky areas and water indicates ongoing deposition on bedrock outcrops and in the active channel. Again, previously exposed sandy areas and areas under herbaceous vegetation were colonised by reeds. Areas which were covered by reed in 1965 were, however, less likely to persist than during 1940/1944 to 1965, and were generally replaced by woody vegetation (49.6%, Table 11).

The succession which may be inferred from Carter and Rogers (1995) study is recent sedimentation in the active channels or on rock outcrop, followed by the establishment of reed and/or herbaceous cover. Reeds establish themselves on relatively stable sedimentary deposits (over bedrock or bars in the channel) and tend to persist. Ultimately, the reeds are replaced by woody vegetation. There was a significant loss of open water between 1940/4 and 1984/5, probably due to a reduction in flows, and increase in sedimentation. The persistence of the reeds and the ultimate establishment of woody vegetation shows the stabilising effect of the reeds on sedimentary deposits. Carter and Rogers (1995) study also shows that limited sedimentation occurred between 1940/4 and 1965 with major colonisation of pre-existing sedimentary deposits. Between 1965 and 1984/5, however, deposition accelerated along with reed and herbaceous vegetation colonisation. Deposits which had previously been colonised by reeds were stable and rarely inundated enough to allow the establishment of woody vegetation.

Fluvial geomorphologists recognise the importance of vegetation in controlling channel form and process (Gregory and Gurnell 1988, Thorne 1990, Rowntree 1991), but its significance has been played down, partly because it is difficult to quantify (Rowntree 1991). It is difficult to determine how much of the observed change in the channel between 1940/4 and 1984/5 is a result of reductions in flow leading to deposition and bar formation and how much is due to a positive feedback through vegetation. This latter effect occurs by 1) stabilising deposits by binding the substrate with roots and so limiting erosion (Hickin 1984, Thorne 1990); 2) enhancing deposition and/or preventing deposition through a reduction in flow velocity and bed shear stress, and dampening of turbulence (Li and Shen 1973) and 3) attenuating flood disturbances which can limit the process of vegetation development. Existing vegetation also fosters further vegetation establishment by providing a supply of new propagules (Carter and Rogers 1995).

Furthermore, vegetation has been shown to increase the channel flow resistance, with a commensurate increase in flow depth and reduction in flow velocity, thus modifying the channel processes (Kouwen *et al.* 1969). Establishment of bars and stabilisation of the bars and banks should lead to down cutting in the active channel, since the cross-sectional area is reduced and the river is prevented from widening. This is a possible direction of change for the Sabie River in the alluvial sections.

Table 11. Transition matrix for the Sabie River in the Kruger National Park based on the river states of Carter and Rogers (1995).

State change from:	State change to:					
1940/4 to 1960	Reed	Water	Sand	Rock	Herbs	Woody
Reed	80.0	0.1	0.0	0.0	0.7	19.2
Water	13.8	83.8	0.7	1.0	0.7	0.0
Sand	53.3	12.0	19.6	0.0	13.4	1.7
Rock	5.8	17.4	4.4	49.3	23.2	0.0
Herbs	13.7	1.5	0.4	0.6	82.0	1.8
Woody	3.5	0.0	0.0	0.0	0.0	96.6
1965 to 1984/5	Reed	Water	Sand	Rock	Herbs	Woody
Reed	47.5	0.7	0.8	0.0	1.4	49.6
Water	64.3	28.7	5.4	0.4	0.9	0.4
Sand	55.8	10.6	24.0	0.0	5.8	3.9
Rock	48.8	0.0	0.0	39.5	4.7	7.0
Herbs	43.3	1.7	0.9	0.6	38.7	14.9
Woody	0.5	0.0	0.0	0.0	0.0	99.5

Long term changes (greater than 50 years) in the Sabie River are more difficult to ascertain. Since the incision of the river in the late Miocene and early Pliocene, extensive sedimentation has occurred forming major macro-channel bar deposits which are covered only by the highest floods. Little is known of the rates of long term sedimentation, although augering to the depth of the water table and subsequent penetration of the saturated sediment using a 20mm diameter steel rod has revealed that such deposits are, in places, in excess of 12.5m thick over bedrock. Such morphological features are better developed in some areas than in others and it is suggested that these may be the result of infrequent pulsed sedimentation, in response to major flood events. This has resulted in a change in state from bedrock anastomosing, bedrock single thread and bedrock pool-rapid channel types towards fully alluvial, single thread, braided or anastomosing systems in some areas.

4.3 Recent changes in catchment controls

Increased development pressure on the region as a result of social, political and economic factors has resulted in changes in water and land-use patterns, which are the primary factors resulting in altered catchment hydrology and sediment production. Existing and projected water demands and land-use in the Sabie River catchment have been quantified (Birkhead and Heritage 1995), (Table 4).

The total water demand in the Sabie catchment, estimated in 1985 upstream of the Kruger National Park, accounted for 28% of the natural mean annual runoff (MAR). The projected total increase in water demand in the Sabie catchment is 84% by the year 2010 (Table 4), which places the total upstream demand at 54% of the natural MAR. This is comparable to demand in the Letaba River catchment in 1985. There is a projected 737% increase in demand for municipal industrial and domestic water use in the under-developed rural areas of the Sabie River catchment which will account for 6% of MAR in 2010 (Birkhead and Heritage 1995). At present, only 30% to 40% of rural households have ready access to an adequate drinking water supply. Trends towards more intensive agricultural land-use can be expected, with a higher assurance water supply as dry-land farming practices progress towards irrigation. Increased sediment yields have been reported in the Sabie and Letaba River catchments (van Niekerk and Heritage 1994, Heritage 1994), and this trend can be expected to continue as reduced river flows are no longer capable of transporting the sediment derived from the catchment (Table 2).

Afforestation in the Sabie River catchment has resulted in an estimated 17% reduction in the MAR (Chunnet, Fourie and Partners 1990a). The projected increase in water demand by irrigation in the Sabie River catchment will further reduce existing low base-flows, impacting on the river ecosystem during low-flow periods.

In addition to these anthropogenic influences on catchment hydrology, are the effects of natural climatic change. Within the generally random year to year rainfall variability is an apparent underlying non-random component to the rainfall record which has been shown to vary systematically since the 1920s (Tyson 1987). The transition from a wet to dry spell has followed an approximately 18-year cycle in the Lowveld over the period 1910/11 to 1985/86. There has been, however, a 38% reduction in the recorded annual rainfall and an increase in the rainfall variability over the Lowveld during the last two decades (Mason 1996), which may be partly attributed to the El-Niño/Southern Oscillation phenomenon.

Given these recent changes to the catchment controls, an analysis of annual aerial photographs for selected sections of the Sabie River in the Kruger National Park was undertaken for the years 1986 to 1992 (chapter 8). The study revealed considerable deposition of new sedimentary units, particularly in areas where bedrock influence was reduced. Such a trend is in line with the demonstrable reduction in flow duration and magnitude and the increased sediment production rate within the catchment.

4.4 A conceptual model for change on the Sabie River

Given the preliminary understanding of the structure and principal controlling variables operating on the Sabie River, it is possible to conceptualise the impact that changes in the magnitude and variability of discharge, input of sediment and channel competence (QMAG, QVAR, SEDI, COMP respectively) will have on the geomorphological structure of the river.

To explain the conceptual model of change (shown diagrammatically in Fig. 23), it is useful to begin with the assumption that the macro-channel is free of alluvium. As sediment accumulates progressively in the macro-channel, the nature of the river changes from bedrock anastomosing through successive channel types to an alluvial anastomosing system. Such a sequence of changes does not, however, take into account changes in controls other than sediment input. It is apparent that once the river has changed from bedrock anastomosing through mixed (bedrock and alluvial) anastomosing to a mixed pool-rapid character, changes follow a variety of sequences which could result in the development of one of many alluvial channel types. Depending on the relative changes in QMAG, QVAR, SEDI and COMP, the river may change from having a mixed pool-rapid character to sinuous, braided or single thread channel forms, all three of which may form entirely on alluvium.

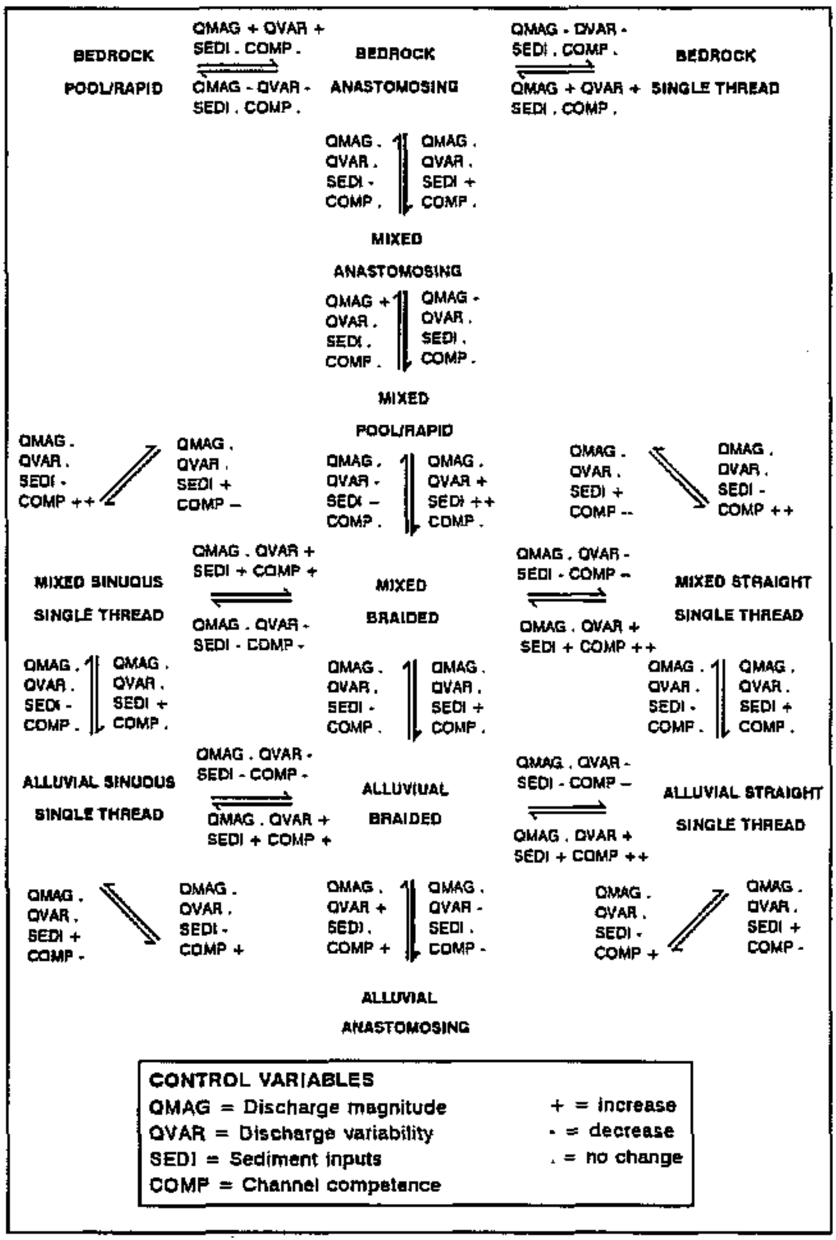


Figure 23. A conceptual model of channel change for the Sabie River.

The range of possible changes described by the conceptual model (Fig. 23) are reversible. Further, it should be appreciated that, depending upon the variability of controls, changes in the river may reflect a progression through some or all of the river types included in the model (in an order determined by the variation in controls), or changes could simply be reflected in an oscillation of a river reach between two types of channel.

The conceptual model provides the basis for predicting forms to which any particular section of river may change if there is a change in channel controls. For example, a mixed sinuous single thread channel may change to either mixed pool-rapid, mixed braided or an alluvial sinuous single thread channel. The conceptual model may be tested through studies of processes which also facilitate the determination of which conceptual change is more likely. The model also provides a theoretical insight into the geomorphological functioning of the Sabie River system and highlights the following variables which must be investigated further in order to begin to quantify channel change on the Sabie River:

Dynamic variables:

Hydrology (flow variability and magnitude)
Hydraulics
In-channel sediment dynamics
Sediment production

Static variables:

Geology

The results of intensive studies into these dynamic factors are detailed in chapters 5 to 7.

4.5 Summary

☺ The flow and sediment input trend on the Sabie River appears to be towards a reduced flow frequency and magnitude and an increased catchment derived sediment load, leading to an increase in sedimentation and a decrease in exposed bedrock in the channel. These changes are occurring on the scale of decades.

☺ The catchment control factors influence the geomorphological nature of the Sabie River. It has been demonstrated that recent changes to the balance of these factors has caused geomorphological change to many areas of the river within the Kruger National Park. It is vital to conduct more detailed investigations into the functioning of these variables in order to begin to understand the patterns of geomorphological response of the Sabie River. Previous chapters detail the spatial structuring of the geomorphological units observed on the Sabie River and following chapters detail the research conducted into the functioning and influence of the catchment control variables.

☺ There was increased reed colonisation of sedimentary deposits between the 1940s and 1960s and this accelerated between the 1960s and 1980s.

☺ The Sabie River exhibits a possible ten channel types as part of the bedrock-alluvial continuum of channel types, only five of these are common (bedrock anastomosing, mixed anastomosing, mixed pool-rapid, alluvial single thread and alluvial braided) .

☺ The principal catchment control factors responsible for channel change in the Sabie River are discharge magnitude, discharge variability, local channel sediment transport capacity and lateral sediment inputs.

☺ Geological influence on the form of the Sabie River is apparent, however this factor is static at the temporal scale of this investigation (<100 years).

☺ A number of probable channel-type evolutionary pathways are suggested by the conceptual model that are a function of the relative influence of the principal catchment control variables.

☺ Only the principal dynamic controls on channel form are considered in the conceptual model of change, other factors are also influencing, and being influenced by, geomorphological change, including riparian vegetation. Such factors have not been explicitly considered in the present study as the models proposed are too coarse to warrant their inclusion. Refinement of these models necessitates further investigation into these factors at the earliest opportunity.

☺ The conceptual model provides a theoretical framework that describes the possible geomorphological change pathways for the Sabie River in the Kruger National Park. It also qualitatively describes the changes that must occur to the principal controlling variables that prescribe a change from one geomorphic state (channel type) to another. It thus highlights the important dynamic controls on channel form that must be understood in order to begin to make more quantitative statements concerning channel change for the Sabie River. The following chapters describe detailed investigations of these controls on channel form, before qualitative and quantitative models of change are proposed.

5. HYDROLOGICAL REGIME

Detailed information on the Sabie River hydrology is required to describe the natural and anthropogenic induced variability in the flows experienced in the river. It also allows these flows to be analysed using statistical methods, producing a quantitative description of the flow regime. This information is utilised in subsequent chapters to assign probabilities of occurrence to various flow events and allows broad timescales to be attached to the likelihood of change as a result of such flows.

The hydrological regime of the Sabie is complex and hydrological data for the Sabie River in the Lowveld region is limited. Gauging stations are located at Perry's Farm, Kruger Weir, and Lower Sabie (Fig. 9). Of these only Perry's Farm has a good historical flow record, extending back to 1959, whereas Kruger Weir has operated only since 1990 and Lower Sabie since 1987.

5.1 Temporal aspects of flow in the Sabie River

The Sabie River exhibits flow variability on a number of temporal scales, namely daily, seasonally and annually, due to changing precipitation patterns.

Daily variability:

> Daily flows can vary in response to rainfall events within the catchment to anthropogenic and natural abstractions for irrigation and evapotranspiration (Fig. 24). Within the daily flows the river stage responds to individual rainfall events, generating flow events that peak and decline over timescales of only a few hours to several days. It is these event-based flow episodes that influence the geomorphology, however, quantitative modelling using flow data at this level of detail is prohibitive due to the quantity of information involved, therefore, daily average flows are used to approximate actual flow events.

Seasonal variability:

> The Sabie River catchment lies in the semi-arid Mpumalanga Province and has a well defined wet (summer) and dry season (winter). Flows during the dry season are generally constant and low, whereas wet season discharges are higher and more variable (Fig. 24).

Annual variability:

> Annual flow variability is very marked for the Sabie River catchment (Fig. 25) and is a function of longer term fluctuation in the climate. Time series analysis of the regional rainfall records reveal distinct wet and dry periods (Tyson 1987). These are reflected in the flow gauging records at Perry's Farm when a three point running mean is calculated from the annual daily flow data (Fig. 25).

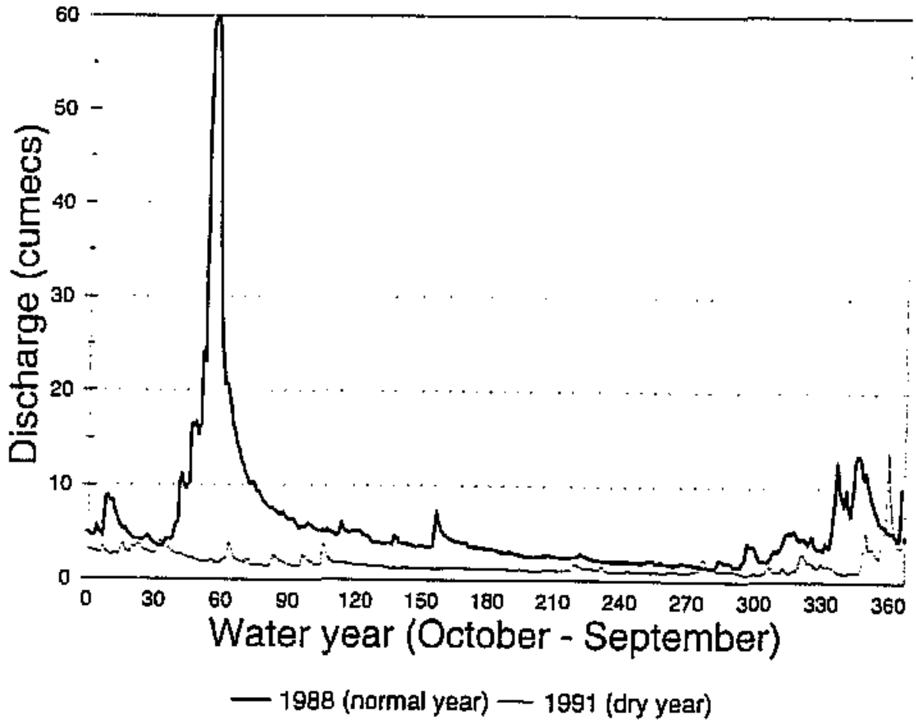


Figure 24. Daily flow variability on the Sabie River.

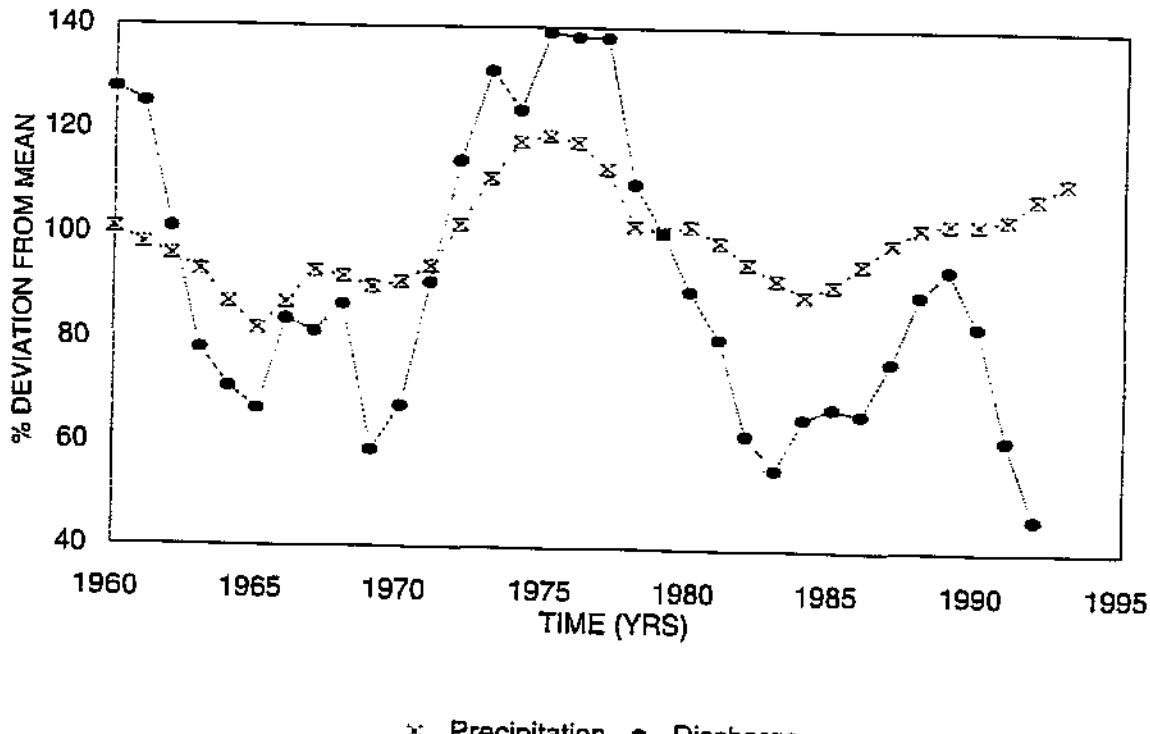


Figure 25. Climatic influence on annual flow volumes for the Sabie River in the Lowveld (wet and dry years defined by Tyson 1987).

5.2 Statistical analysis of temporal patterns in the hydrology

Statistical analysis of the flow records on the Sabie River allows the extremely variable discharge regime to be rationalised with respect to the climatic variation observed in the rainfall record. At the time of writing no daily rainfall runoff simulations were available through the Kruger National Park Rivers Research Programme. Annual flow volume simulations (Chunnet, Fourie and Partners 1990b) have been used in dam design, but have limited utility in predicting dynamic geomorphological adjustment. Data from the gauging weirs thus form the basis of the subsequent probability analysis. The data were available in the form of average daily flows from the Department of Water Affairs and Forestry archives, Pretoria. Additional data on peak flows and events that exceeded the reliable measuring limits of the gauge structures were manually abstracted from the pen traces and calibrated using the extended rating curves for each station. Perry's Farm weir, proved to be the most appropriate gauge to use in the study, as it has a relatively long record (35 years), contains few gauge interruptions, and the recorded flow pattern is similar to that seen on the main channel of the river (Fig. 26). Daily flow analysis was split based on climatic variability, while annual flow totals were combined for the whole flow record. The flow frequency information was then related directly to inundation level at monitored cross-sections through stage-discharge determination.

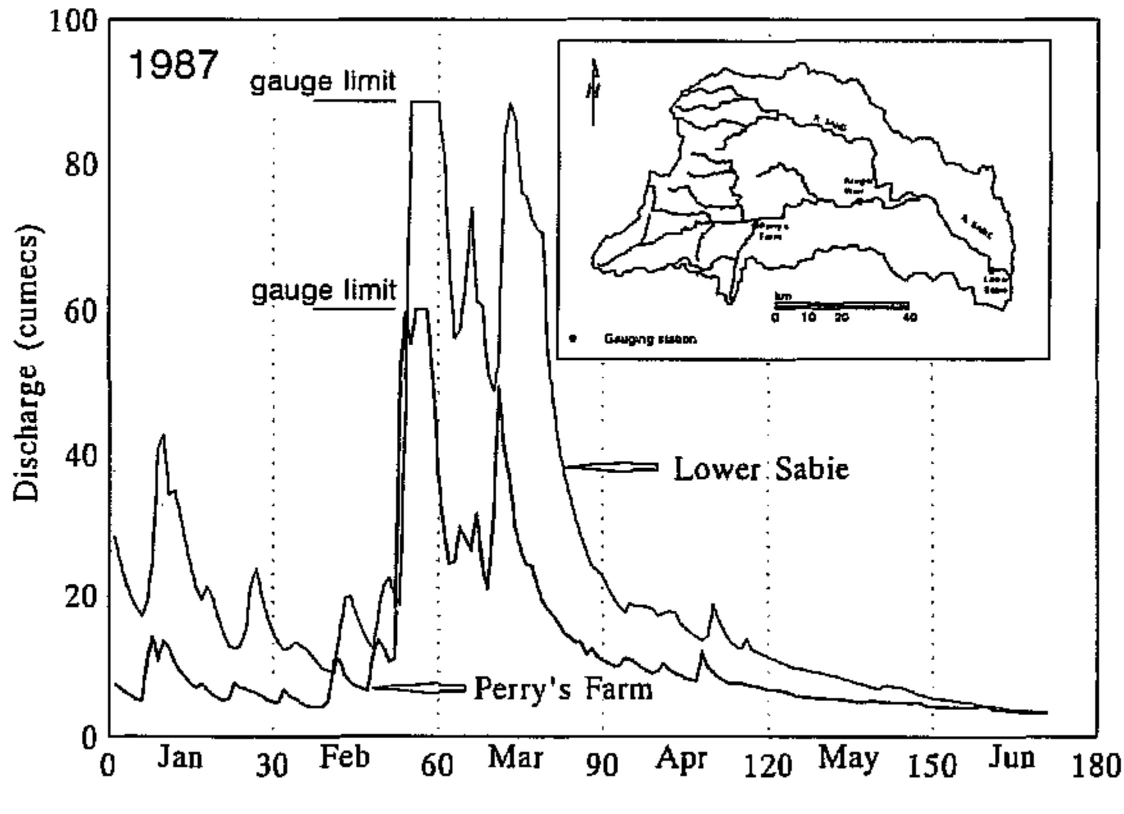


Figure 26. Flow similarity between Perry's Farm and Lower Sabie gauging structures.

5.3 Determination of periods of average wet and dry period flow data

The Sabie River displays a highly variable flow regime, however, analysis of the long term flow trends for the Sabie River at Perry's Farm gauging station (Fig. 25) indicate that there are natural periods of higher and lower annual flow volumes. Such wet and dry periods are important in prescribing the natural variability in the geomorphological response of the Sabie River, which can then be compared to the magnitude of change predicted for anthropogenic effects. Average or regime conditions were defined using the average annual flow value for a single wet-dry cycle (1965-1983). Flows were then categorised into wet, dry and average conditions according to the ± 20% cutoff values advocated by Tyson (1987). Using this discrimination, average flow years for the Sabie River at Perry's farm (Table 12) were used to define the average daily flow data set. All 35 years of record were used in the annual maximum flow series analysis.

Table 12. Daily streamflow discrimination based on annual flow volumes.

Annual streamflow volume categorisation		
Wet	Average	Dry
1960, 1961, 1972-1977	1962, 1966-1968, 1971, 1978-1981, 1988-1990	1963-1965, 1969, 1970, 1982-1987, 1991-present

5.4 Local stage-discharge relationships

Direct measurement of flow levels and calibration with measured discharges at the gauging weirs allowed generation of rating curves for each monitored site on the Sabie River. Strand lines were correlated directly to peak flows and instantaneous stage measurement was linked to discharge by lagging the flow record by the appropriate flood wave travel time (Fig. 27 and chapter 6). Such data are vital for determining inundation levels of the variety of morphological units that exist on the Sabie River and for determining the local channel hydraulic and sediment transport character as a function of the discharge regime.

5.5 Flow frequency relationships for the monitoring sites on the Sabie River

Stage-discharge relationships were related to the frequency of occurrence of flows for the regional study sites along the river. Downstream flow increase between sites was accounted for by applying the gauge relation technique of Linsley *et al.* (1958) to the longer record at Perry's Farm, transforming it into a 35 year simulated record for the gauge at Lower Sabie. While it is acknowledged that this technique is limited by the short comparable record lengths on which the relationships are based, the Sabie River does satisfy the criteria of inflow between the weirs being much less than the upstream discharge required for the use of the technique.

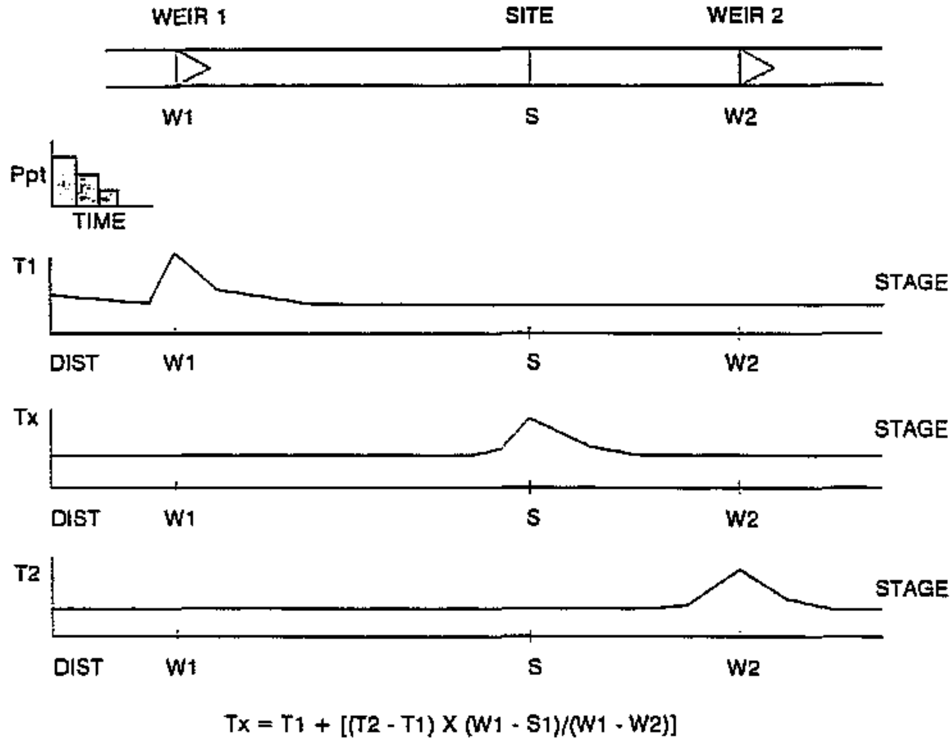


Figure 27. Model of lag time calculation for flood flows between Perry's Farm and Lower Sabie gauging structures.

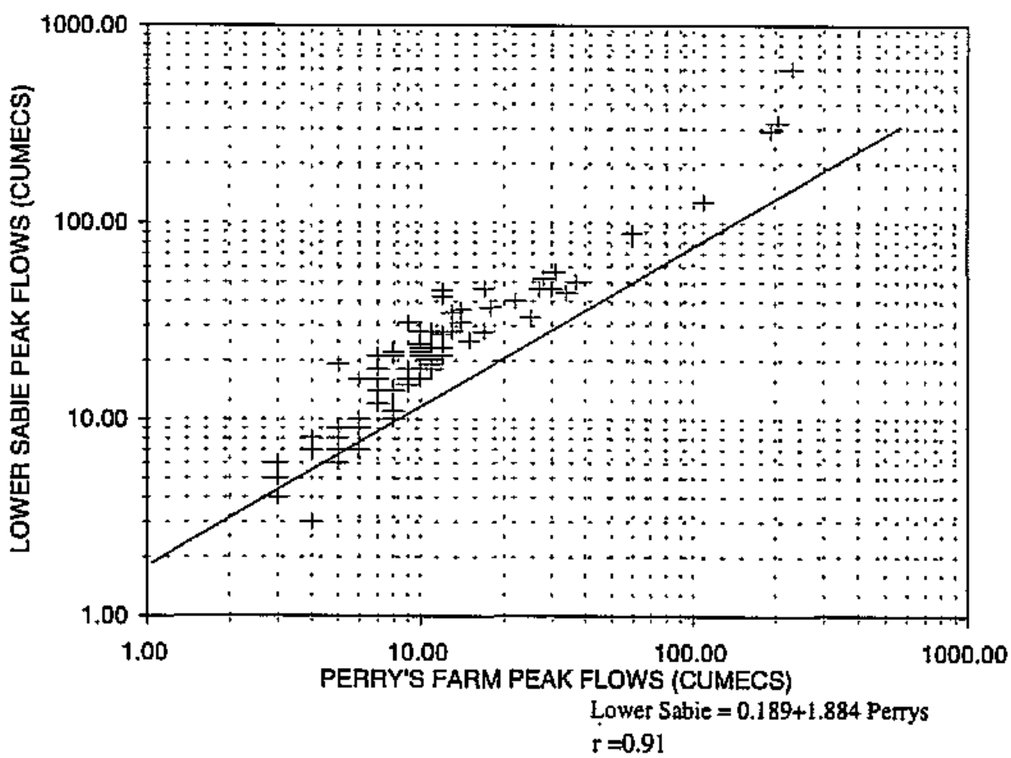


Figure 28. Statistical link between peak flows at Perry's Farm and Lower Sabie.

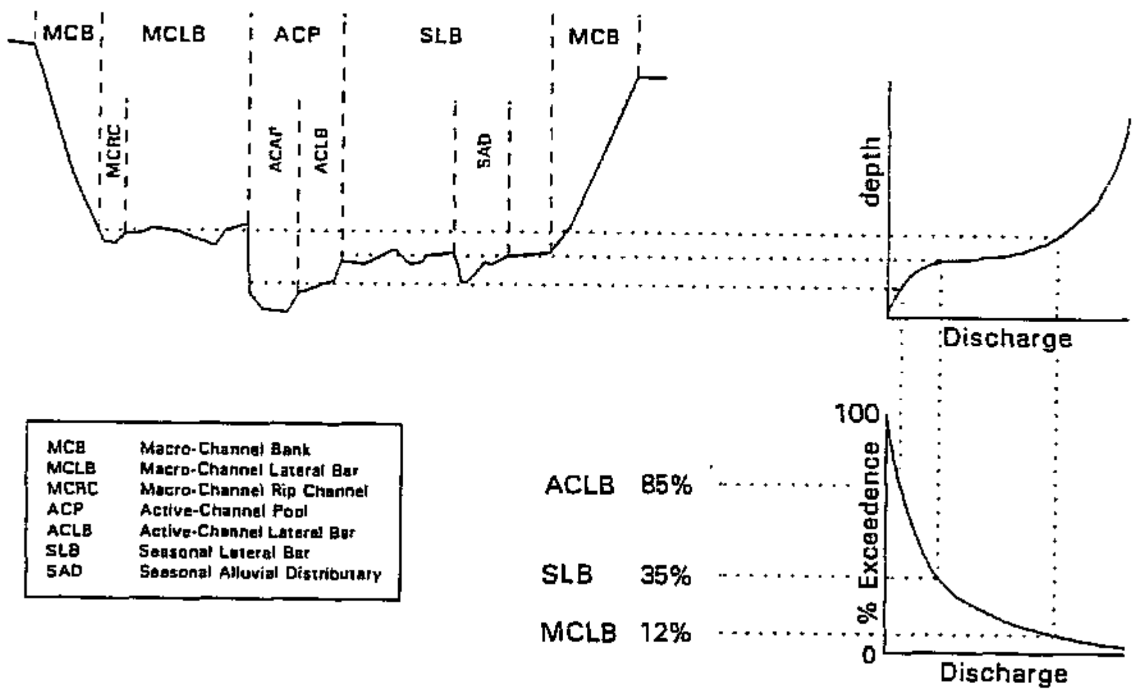


Figure 29. Model of the links between flow levels, morphological units and frequency of inundation.

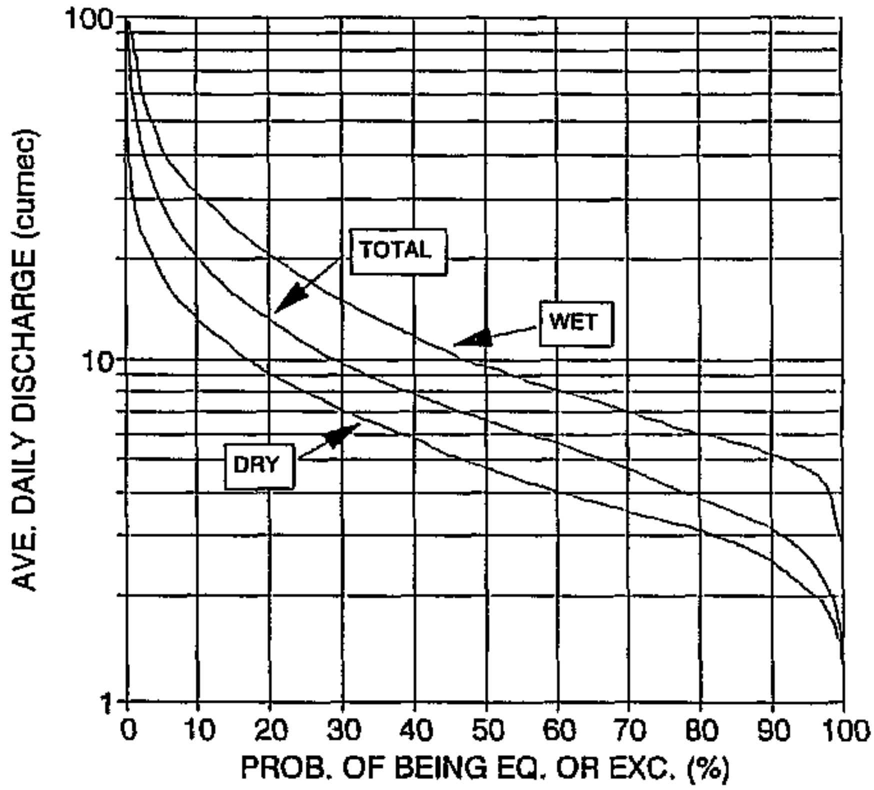


Figure 30. Differences in the recorded flow regime for wet and dry climatic periods.

Co-incident flow peaks were initially used as the basis for determining inter-gauge relationships and these were compared with an extended data set that lagged the downstream gauge site flows so that the general flow trends coincided. Estimated peak flows above the normal recording limits of the weirs were derived from the extended rating curves developed by the Department of Water Affairs and Forestry. The results for the limited data set display a very good correlation between associated peaks (Fig. 28). This association between peak flows was used to construct flow frequency relationships for each of the cross-sections using a linear interpolation between the monitored sites and the two weirs. The simulated daily flows for each monitoring site were then ranked, to generate a set of probability of exceedence (P) and average recurrence intervals (T) using the Weibull formulae (equations 1 and 2).

$$P = \frac{m}{N+1} \tag{1}$$

and

$$T = \frac{N+1}{m} \tag{2}$$

where m is the rank of the event and N is the number of records.

Combining the local stage-discharge and flow frequency information and assuming that the water surface remained horizontal across the macro-channel for all flows, enables the generation of frequency of inundation data for each cross-section (Fig. 29). Two sets of results were calculated based on the annual maximum flood series data and the daily average flow data.

Inspection of the daily average exceedence probability results (Fig. 30) reveal considerable variation in the flow regime between wet and dry years. This is particularly marked for the lower range flows between 1 and $10m^3s^{-1}$, where the probability of a flow being equalled or exceeded is reduced by 30 to 40%. Higher flows are impacted far less, with flows in excess of $40m^3s^{-1}$ being reduced from 4 to 1% of the time.

5.6 Summary

☺ The flow regime of the Sabie River is highly variable on a daily, seasonal, annual and inter-annual basis. Individual flow events occur in response to rainfall and generate a series of flow peaks that are superimposed on the more constant baseflow. This situation is most noticeable during the wet season, particularly where the annual precipitation is above average due to climatic conditions.

- ☺ The limited flow records available for the Sabie River in the Kruger National Park have been extended using a gauge relation technique applied to the data recorded at the Perry's Farm flow monitoring station.

- ☺ Flow frequency analysis has been used to statistically rationalise the data into wet, dry and average flow regimes, with the distinction between the three categories based on the climatic discrimination of Tyson (1987). Of the data available from the gauging station at Perry's Farm, 8 years are classed as wet, displaying flow volumes 20% above the average for the record, 12 are average (± 20% of the mean discharge volume) and 15 years were dry, displaying flow volumes below 80% of the record average.

- ☺ The results reveal a very marked difference in the flow regime between wet and dry periods, particularly at the lower end of the flow range, where the probability of exceedence of flows between 1 and $10m^3s^{-1}$ is reduced by 30 to 40%. Higher flows show less impact; discharges in excess of $40m^3s^{-1}$ display only a 4 to 1% reduction.

- ☺ There is a definite correlation between rainfall reduction and reduced flows in the Sabie River.

6. SEDIMENT PRODUCTION

Catchment sediment production has been identified as a principal factor determining channel form and dynamics in the Sabie River. Evidence of channel change from various authors all report an increase in the sediment visible in the river (Chunnet, Fourie and Partners 1990a, Vogt 1992, Carter and Rogers 1995), which is a consequence of the increased degradation of the catchment. Quantification of the catchment sediment production rates was thus imperative and the predicted sub-catchment lateral sediment production figures have formed the basis of annual tributary inputs to the dynamic channel change model.

6.1 The use of GIS techniques to determine potential catchment sediment yields

GIS was used to generate maximum potential sediment yields for the Sabie catchment for existing and undisturbed land-use patterns. The results indicate that limited amounts of sediment are entering the main channel in the upper catchment, but there are significant inputs from the Sand River which drains a rural area with soils of above average erodibility. GIS has also been used to investigate the competence of the rivers to transport this sediment using simulated mean annual runoff (MAR) records and sub-catchment sediment yields. Combining the MAR and sediment yields generates a spatial picture of sedimentation within the Sabie River system. A close agreement is obtained when comparing this with actual patterns of sediment accumulation derived from recent (1986) 1:10000 scale aerial photography.

A detailed study of development potential and management of water resources in the Sabie River catchment was commissioned by the South African Department of Water Affairs (Chunnet, Fourie and Partners 1990a). In this study, a soil/slope class map was produced and the detailed data on land usage in the catchment were used to produce a land-use map (Fig. 31). These data have been analysed using ArcInfo GIS.

The portion of the catchment downstream of Sabie town is underlain by granite and gneiss of the Basement Complex and sediments in the river are characteristic of the soils generated on these rock types. The soil/slope class map along with estimates of soil erodibility from Chunnet, Fourie and Partners (1990a) and P. Cheshire (pers. comm.) were used to define six slope/soil erodibility classes (Fig. 32) according to broad slope and soil type criteria as follows:

Class 1 :- Moderate to gentle slopes and low erodibility.

Class 2 :- Steep slopes and below average erodibility.

Class 3 :- Moderate slopes and below average erodibility.

Class 4 :- Moderate to flat slopes and average to above average erodibility.

Class 5 :- Moderate to steep slopes and above average erodibility.

Class 6 :- Moderate slopes and above average erodibility.

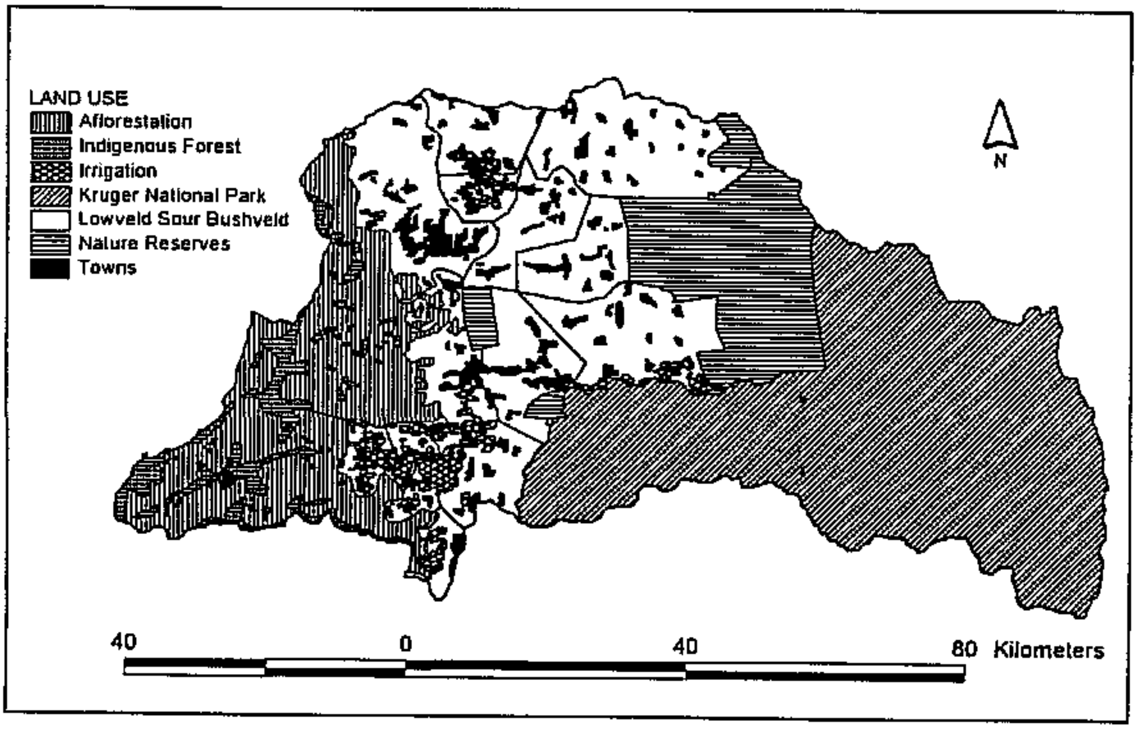


Figure 31. Land-use map of the Sabie River catchment (after van Niekerk and Heritage 1994).

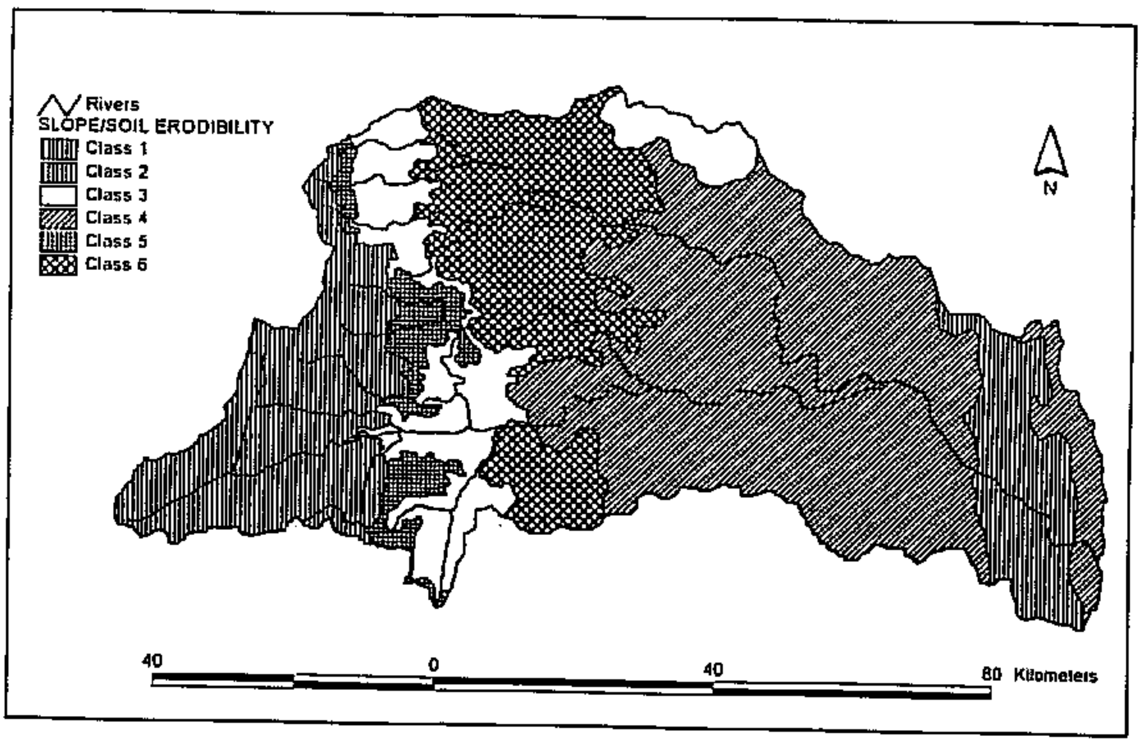


Figure 32. Slope-soil erodibility map for the Sabie River catchment (after van Niekerk and Heritage 1994).

Monthly runoff volumes for different sub-catchments in the Sabie River catchment under a variety of development scenarios (for example, natural undisturbed conditions, existing conditions, maximum afforestation) for the period 1922 to 1986 were simulated using the Pitman (1973) model (Chunnet, Fourie and Partners 1990a and 1990b). The Pitman model uses meteorological data (monthly rainfall and mean monthly evaporation) and catchment parameters to simulate monthly runoff volumes at specified points in a catchment and is calibrated using existing flow data. The mean annual runoff (MAR) for the different development conditions is calculated from these data.

Afforestation in the upper catchment has led to a significant reduction in the natural runoff (approximately 17%) (Chunnet, Fourie and Partners 1990a). Increased water abstraction for agriculture has also caused a decrease in the natural runoff in the Sabie River (Chunnet Fourie and Partners 1990a). Soil erosion and its associated problems in the former homeland areas is a consequence of severe overgrazing, poor soils, the removal of natural vegetative cover and in some areas, poor agricultural practices. Drought years are common, thus exacerbating the problem. During drought years, overgrazing occurs in the Lowveld nature reserves since natural game migration routes have been severed.

The application of the American Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) for southern African conditions is problematic as the American factor values are not necessarily applicable to local conditions and locally applicable values have yet to be determined (Elwell 1984). Furthermore, river sediment sampling and reservoir sedimentation data, necessary for calibration and verification of the model, are limited in southern Africa and are non-existent in the lower Sabie River catchment.

Degrees of relative land degradation have been estimated using the classification of Viljoen *et al.* (1993) and a study of Landsat TM imagery in conjunction with ground truthing. Three classes are clearly distinguishable:

Class 1 :- Forested areas.

Class 2 :- Game reserves showing an intermediate degree of vegetation denudation.

Class 3 :- Former homeland areas showing a high degree of vegetation denudation.

The land-use, slope/soil erodibility and political boundary maps were combined using the ArcInfo GIS to delineate zones with different slope/soil erodibility, land-use and vegetation degradation characteristics. Chunnet, Fourie and Partners (1990a) recommend the delineation of zones with equal sediment yield potential based on dominant combinations of slope, soil erodibility and land-use in the Sabie River catchment (Table 13). They obtained local sediment yields by adapting values derived from a regionalised sediment yield map, established from data collected throughout South Africa (Rooseboom 1974), to local conditions. Their adaptation of the regionalised data was done in collaboration with Professor Rooseboom and discussions with personnel from the South Africa Department of Agriculture. The soil/slope erodibility, land-use and vegetation degradation characteristics map and the Chunnet, Fourie and Partners (1990a) estimates of sediment yields (Table 13) were then combined to produce a spatial picture of the maximum potential sediment yield zones for the catchment (Fig. 33). The results indicate a maximum sediment yield potential of 300 to $400 t km^{-2} a^{-1}$, for the whole catchment under undisturbed conditions, except for the area in the Kruger National Park which has a low yield potential of 150tkm^{-2}a^{-1}. These values are based on the assumption that there would be a low degree of vegetation denudation throughout the catchment under natural, undisturbed conditions.

Table 13. Estimated sediment yields for different dominant combinations of slope, soil erodibility and land-use in the Sabie River catchment.

Description	Estimated yield tkm^{-2}a^{-1}
Forests on steep slopes; soils with below average erodibility; low degree of vegetation denudation.	300
Forests on steep and moderate slopes; soils with above average erodibility; low degree of vegetation denudation.	400
Other land-use activities (settlements, subsistence farming and cattle) on moderate slopes, soils with below average erodibility, high degree of vegetation denudation.	400
Other land-use activities on moderate slopes; soils with above average erodibility; high degree of vegetation denudation.	500
Irrigated crops on moderate to steep slopes; soils with above average erodibility; intermediate degree of land degradation.	500
Game reserves on moderate to flat slopes; soils with moderate to above average erodibility; intermediate degree of vegetation denudation.	300
Game reserves on moderate to flat slopes; soils with low erodibility; intermediate degree of land denudation.	150

Rooseboom *et al.* (1992) collated all available information relevant to sediment yields in South Africa and developed a new yield map for the region. Their early attempts to quantify maximum sediment yield potential revealed that sediment availability is the determining factor in sediment yield processes throughout southern Africa. They used a statistical approach that generated regional sediment yield estimates which incorporated the variation in observed local sediment yields. These figures were used to generate regionalised sediment yield potentials, weighted for different areas according to soil erodibility and the size of the area.

The approach of Rooseboom *et al.* (1992) results in values of 155tkm^{-2}a^{-1}, with 50% confidence; 350tkm^{-2}a^{-1}, with 80% confidence and 620tkm^{-2}a^{-1}, with 95% confidence for the Sabie River catchment, which forms a small portion of one of nine sediment regions in South Africa. The conservation areas are not included in any of the regions since no data are available and the value of 155tkm^{-2}a^{-1} (the same as the surrounding region) was applied to these areas. This regional approach does not quantify the impact of specific variables such as land-use, rainfall intensity, slopes and vegetation in a meaningful way, since there was extremely limited data from the Sabie River catchment for use in the statistical analysis.

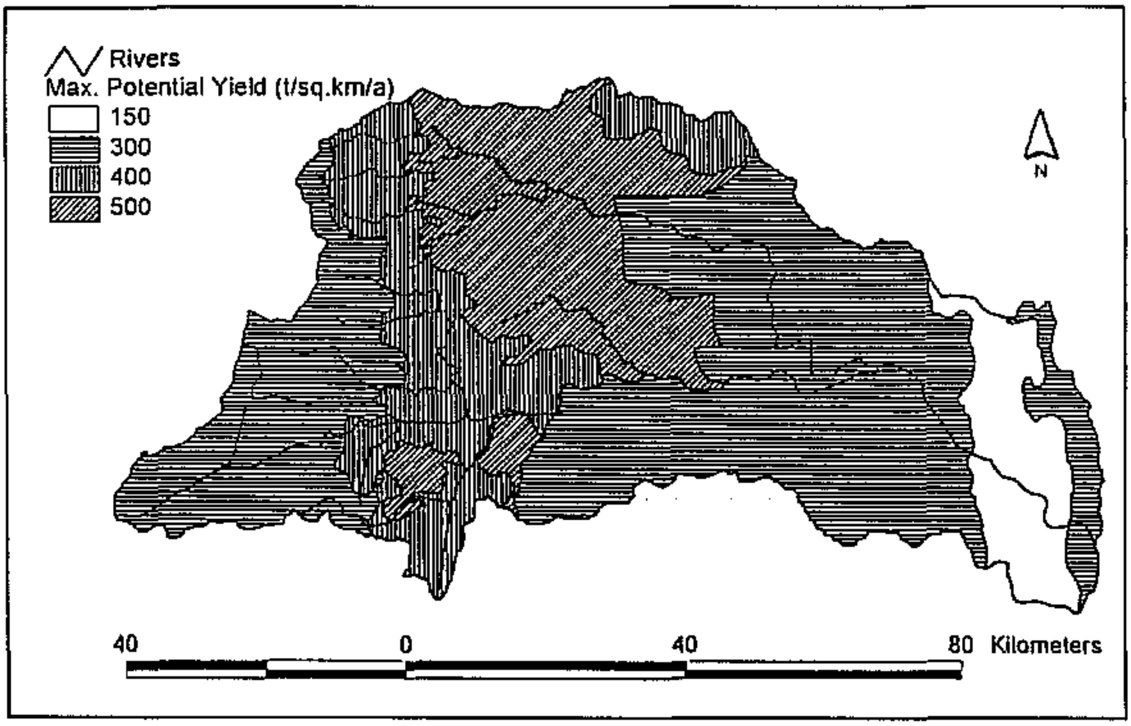


Figure 33. Sediment yield map for the Sabie River catchment (after van Niekerk and Heritage 1994).

GIS was used to overlay the sub-catchment and maximum sediment yield potential maps and calculate the total area within each sub-catchment with a specific yield potential. The products of the areas and yields were summed in the GIS to calculate annual sediment tonnages generated in each of the important sub-catchments (Table 14) for existing land-use (present) and undisturbed (natural) conditions. The tonnage yielded by the different sub-catchments under undisturbed conditions has increased by up to 26% for conditions existing today (Table 14), with the major increases occurring in the rural areas where there has been a significant increase in population and major land-use change with increased land degradation. Replacing indigenous forest with exotic plantations has not had a major effect in the upper catchment. Associated with change in land-use, is a reduction of MAR simulated by Chunnet, Fourie and Partners (1990a and 1990b) ranging from 13% to approximately 30% at different key points on the rivers.

Table 14. Estimated sediment yields for major sub-catchments in the Sabie River catchment (after van Niekerk and Heritage 1994).

River Catchment	Area (km^2)	Present Annual Yield[1] (t)	Natural Annual Yield[1] (t)	Rooseboom Annual Yield[2] (t)	Present % Annual Yield[1]	Natural % Annual Yield[1]	Rooseboom % Annual Yield[2]	Difference (%) (1)	(2)
Upper Sabie	770	252209	231000	119271	12	13	12	-8	-53
Maritsane	472	162929	141300	73084	7	8	8	-13	-55
Noord Sand	254	102359	75600	39430	5	4	4	-26	-62
Sand	1910	766943	573300	296073	35	32	31	-25	-61
Middle Sabie	1466	554873	438900	227151	25	24	23	-21	-59
Lower Sabie	1389	342633	342633	215315	16	19	22	0	-37

[1] Calculated using this approach.
[2] 50 % confidence values calculated using the approach established by Rooseboom *et al.* (1992).
(1) Difference between present annual yield and natural annual yield.
(2) Difference between present annual yield and Rooseboom *et al.* (1992) annual yield.

Simulated existing and natural MAR (Chunnet, Fourie and Partners 1990a and 1990b) show that the bulk of the sediment (80%) is produced in the dry sub-catchments (35% of natural MAR) downstream of the Maritsane confluence. Large sediment loads will thus be introduced into the Sabie River episodically (during seasonal and ephemeral floods) and subsequently reworked. Sedimentation indices are calculated as the ratio of annual sediment tonnage generated upstream of the considered river section, to the MAR at that point. This provides a relative measure of the amount of water available for transporting sediments to specific points and subsequently reworking them.

There is an increase in the sedimentation indices throughout the catchment from natural, undisturbed conditions to present day, implying a progressive increase in sedimentation from the 1920s, when the catchment was essentially undisturbed, to the present. The high sediment yield and low runoff from the Sand River catchment, which is predominately occupied by the former homeland areas of Gazankulu and Lebowa, is clearly reflected in the high sedimentation indices here (Fig. 34). The indices in the Upper Sabie sub-catchment (Fig. 34) are similar, indicating that increased sedimentation is not to be expected downstream of the Maritsane and Noord Sand River confluences. There is a large increase in indices as the river enters the Middle Sabie sub-catchment (Fig. 34), indicating that increased sedimentation is to be expected in this reach. The dramatic increase in indices from the Sand River sub-catchment (Fig. 34) indicate that a further increase in sedimentation is expected in the Sabie River reaches downstream of the Sabie/Sand River confluence.

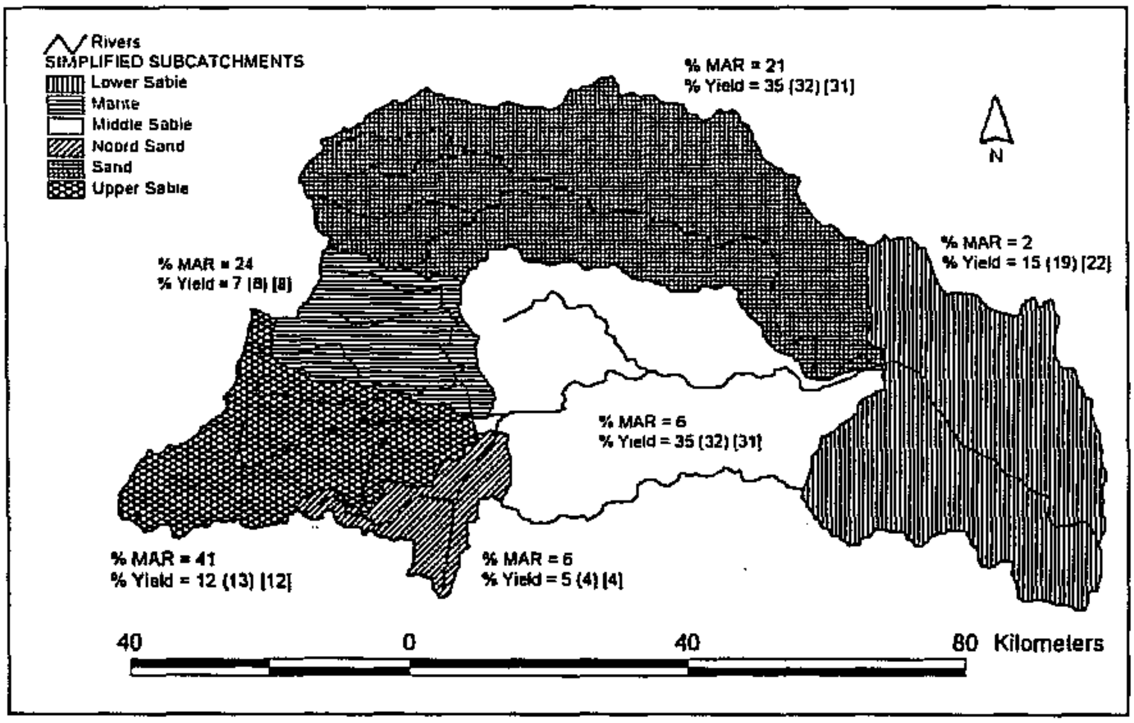


Figure 34. Sub-catchment potential sediment yield map for the Sabie River catchment (after van Niekerk and Heritage 1994).

Close agreement was found when comparing the picture emerging from the sedimentation indices with actual patterns of sediment accumulation derived from recent (1986) 1:10000 scale aerial photographs and extensive ground truthing. The Sabie River and its tributaries in the Upper Sabie, Marite and Noord Sand sub-catchments (Fig. 34) display predominately bedrock features with localised sediment accumulations upstream of major bedrock controls. Aerial photograph interpretation indicates a progressive increase in valley fill and alluvial features in the Middle Sabie (Fig. 34), although bedrock features are present in the form of rapids and bedrock distributary channels (van Niekerk and Heritage 1993). The Sand River contributes large quantities of sediment to the Sabie River, resulting in a significant increase in the accumulation of sediment at the confluence of the two rivers (van Niekerk and Heritage 1993). There are large accumulations of alluvium in the lower reaches of the Sand River with a progressive increase in bedrock features in an upstream direction. The Sabie River widens downstream of the Sand River confluence and there is a dramatic increase in valley infill in both extent and thickness here (Fig. 34). Bedrock features observed upstream are largely buried, although rapids do occur in the active channel where it has cut down to unweathered bedrock (van Niekerk and Heritage 1993). The Sabie River steepens, where it cuts through the Lebombo mountains to the coastal plains in Mozambique. Sediments are flushed through this well defined valley and the valley floor consists predominately of unweathered bedrock.

6.2 Summary

☺ Land degradation in the Sabie River catchment is severe and is increasing.

☺ The use of GIS techniques has predicted that most sediment production is occurring in the middle of the catchment, close to the Kruger National Park boundary.

☺ Increased sedimentation in the Sabie River is predicted downstream of Skukuza Rest camp and particularly downstream of the Sand confluence, where contributions of large volumes of sediment from the Sand River have resulted in the build up of large scale sedimentary deposits within the macro-channel of the Sabie River.

☺ The data generated can be subdivided according to sub-catchment area to predict annual bulk sediment inputs to the main channel of the Sabie River at each of its tributary junctions. The predicted sub-catchment sediment yields are used as lateral inputs in the dynamic bulk sediment transport channel change model (chapter 9).

7. HYDRAULICS AND IN-CHANNEL SEDIMENT DYNAMICS

This chapter details the results of the hydraulic and sediment transport assessment of the Sabie River. Two spatial scales are investigated, a regional or whole river scale where information on large scale long term change can be generated and a local scale that operates within a representative example of each of the channel types described in chapter 2. Here information on detailed hydraulics and sediment dynamics that are characteristic of each channel type is generated. Data are provided on hydraulic parameters such as flow depth, flow velocity and channel width which are later utilised to predict the sediment transport characteristics of the river.

To achieve the aims outlined for each spatial scale, a regional monitoring network was set up to assess large scale long term changes in the hydraulics and sediment dynamics of the river. This was used to predict broad zones along the river that are functioning as sediment sinks and hence would be more prone to change as a result of increased sedimentation than other areas. Local scale studies were also initiated to generate date on channel hydraulics, sediment dynamics and channel flow resistance that are characteristic of the principal channel types identified for the Sabie River in chapter 3.

The data are also used to construct and validate a bulk sediment transport model for the Sabie River that can route daily flows and lateral sediment inputs along a sequence of channel types over a number of years to predict local channel change as a result of erosion or deposition (chapter 9).

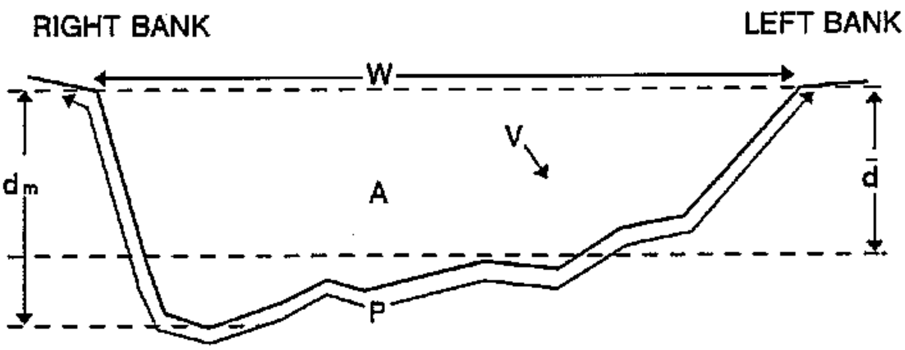
Using the framework of the conceptual model (chapter 4), a comprehensive field monitoring programme was initiated on the Sabie River. The data generated are detailed below for both the regional and local studies.

7.1 Sabie River regional monitoring

It is possible to determine channel hydraulics by monitoring the flow elevation with respect to channel discharge at a surveyed cross-section. Average flow parameters for any discharge within the measured range can then be calculated (Fig. 35). Details of the monitoring techniques employed are given in Appendix A.

7.1.1 Monitoring network

A total of 24 sites were monitored along the 110km of river within the Kruger National Park (Fig. 36). The sites were chosen to cover the full range of channel types and to reflect major changes in the channel slope or energy gradient of the river. Detailed cross-sections were surveyed perpendicular to the macro-channel at each site (Appendix B) and bed sediment samples were collected and later sieved to determine the size frequency distribution of sediment across the river. All sites were co-ordinated to generate regional slope values.



$$R = \frac{A}{P} \qquad Q = W \bar{d} V = A V \qquad \bar{d} = \frac{A}{W}$$

Figure 35. Definition diagram of channel geometric parameters (d= average flow depth, A= channel flow area, P= channel wetted perimeter, W= channel flow topwidth).

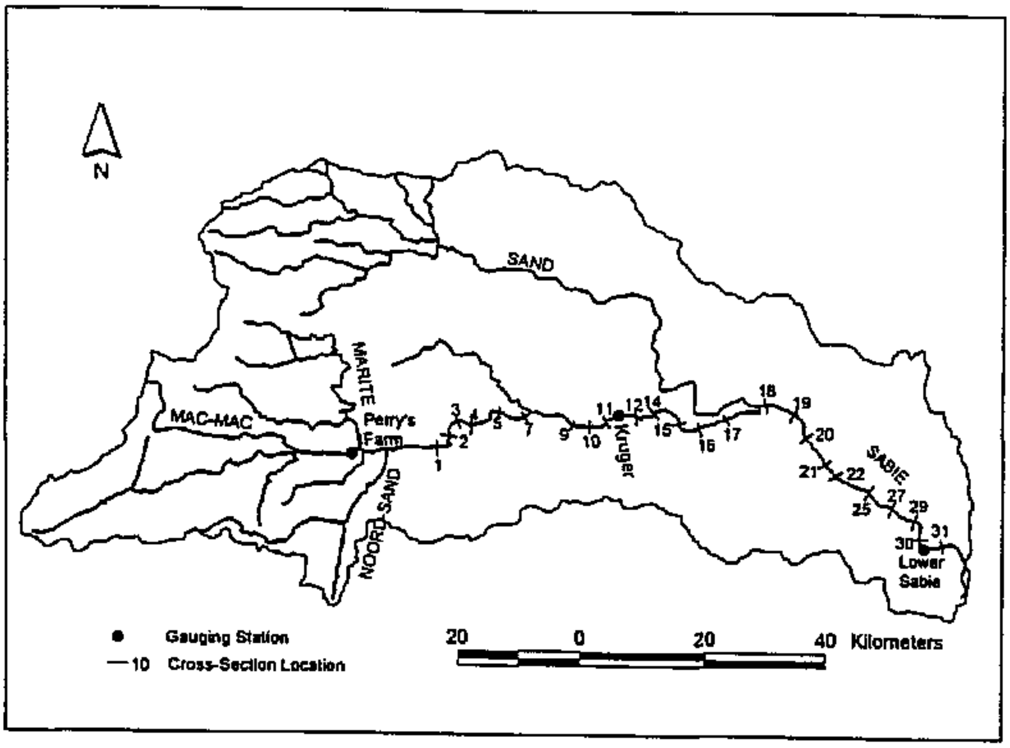


Figure 36. Regional monitoring sites for flow and sediment dynamics on the Sabie River.

Stage monitoring was achieved by direct measurement of stage or inferred maximum stage using mechanical stage recorders. Stages were related to the discharge recorded by the appropriate gauging structure, lagged by the flood wave travel time where necessary. For example, if a flood wave took 24 hours to travel between the two gauges, an instantaneous reading taken at a point half way between the two must be lagged backwards in time by half the travel time (12 hours) to the upstream weir, or forwards by half the travel time (12 hours) to the downstream weir (see Fig. 27).

7.1.2 Data rationalisation

Stage-discharge relationships have been developed for each of the regional cross-sections (Fig. 37). In general, flows between 1 and $100 m^3 s^{-1}$ are well represented on the graphs, with fewer flows being recorded up to a maximum flow of between 1600 and $2300 m^3 s^{-1}$ (Appendix C). Cross-sectionally averaged channel hydraulics were computed for the range of flows experienced at each cross-section (Appendix D). These are used in chapter 9 to predict regional river dynamics.

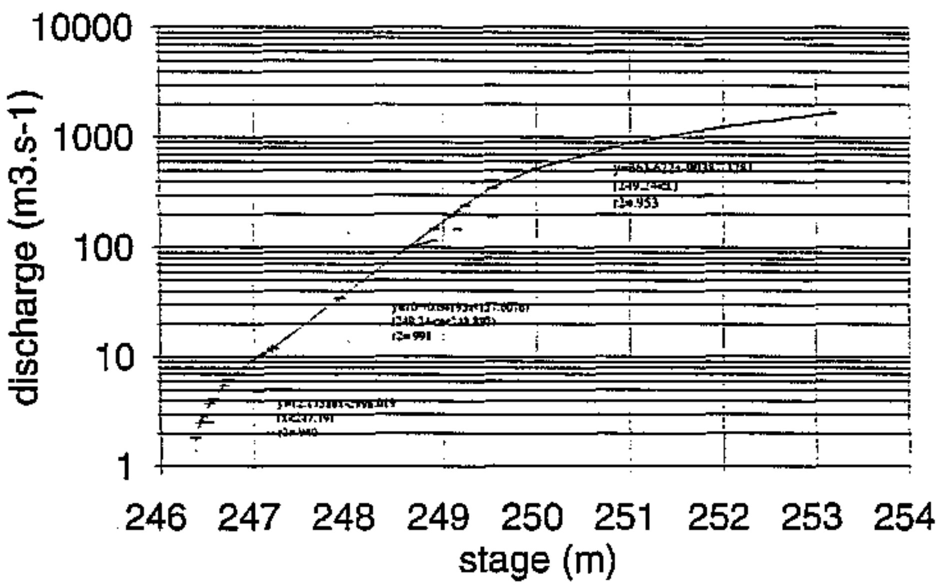


Figure 37. Example stage-discharge curve for regional monitoring site 16 on the Sabie River near Skukuza Rest Camp.

7.2 Sabie River local monitoring

In order to investigate the local channel dynamics that operate in the various channel types that characterise the Sabie River in the Lowveld, sites were selected for intensive spatial monitoring. The study generated two products. The first determines the flow resistance characteristics of each channel type, which may be transferred to similar unstudied stretches of the river to predict their hydraulic character. The second quantifies the local hydraulic regime, in a similar procedure as that used for the regional study (chapter 6).

7.2.1 Monitoring network

Five reaches of the Sabie River were chosen to represent the variety of channel types found on the river within the Kruger National Park boundaries (Fig. 38). The channel types covered were: bedrock anastomosing, alluvial braided, alluvial single thread, mixed pool-rapid and mixed anastomosing (Figs. 15 to 19).

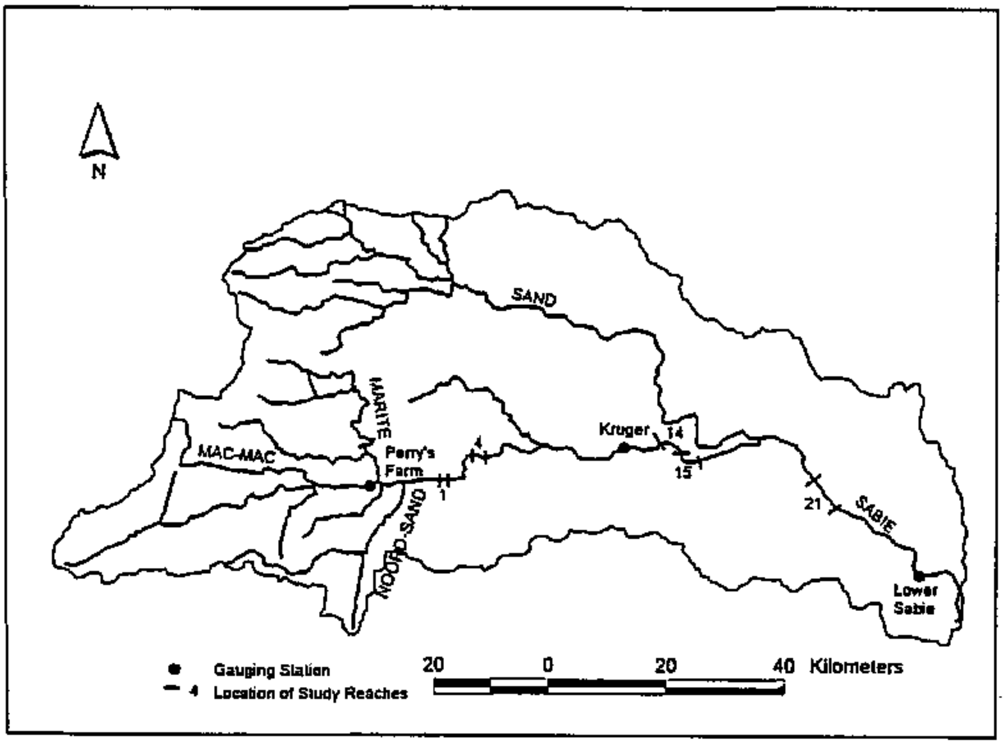


Figure 38. Representative reach monitoring locations on the Sabie River.

To identify all of the flow resistance components at each channel type and to correlate their occurrence to observed local hydraulic conditions, between eight to ten cross-sections per channel type were surveyed by conventional surveying techniques and flow resistance components were mapped. The longitudinal spacing of the cross-sections was designed to incorporate the presence of low flow hydraulic controls, and thus to define accurately water surface slope along a reach (a principal reflector of local channel energy conditions). These controls included bedrock outcrops, major alluvial bars or tributary confluences and major channel features, such as mid-channel or braid bars, meander apexes, channel constrictions or changes in the vegetation community found (Broadhurst *et al.* 1996).

Flow stage for a range of low and medium discharges was recorded at several hydraulically relevant points along each representative channel type, so as to define the water surface slopes. Flood flows, estimated at $650m^3s^{-1}$ (Kruger Weir) and $1000m^3s^{-1}$ (Lower Sabie Weir) (van Bladren pers. comm.), were recorded at several sites within and adjacent to the channel flow resistance investigation reaches. These recorded high flow levels were used to extend the rating curves for three of the five study sites, to increase the range of flows to be used to estimate flow resistance.

The network of cross-sections surveyed and hydraulic data collection stations enables flow resistance to be quantified over a range of physical spatial scales. Figure 39 describes the variety of scales for flow resistance analysis for two of the channel types studied. The bedrock anastomosing channel type allows flow resistance calculation over a whole channel type reach, at a multiple distributary cross-section (A to B, Fig. 39), or for an individual bedrock distributary channel (C, Fig. 39). The pool-rapid channel type can also be analysed as a whole reach, or as a morphological unit sub-reach, or at a cross-section (Y to Z, Fig. 39). The Barnes (1967) methodology averages flow resistance for a multi-cross-section reach and was used to quantify flow resistance at the scale of channel type (Broadhurst *et al.* 1996). Total flow resistance at a cross-section or at an individual distributary was calculated from equations 3 to 5.

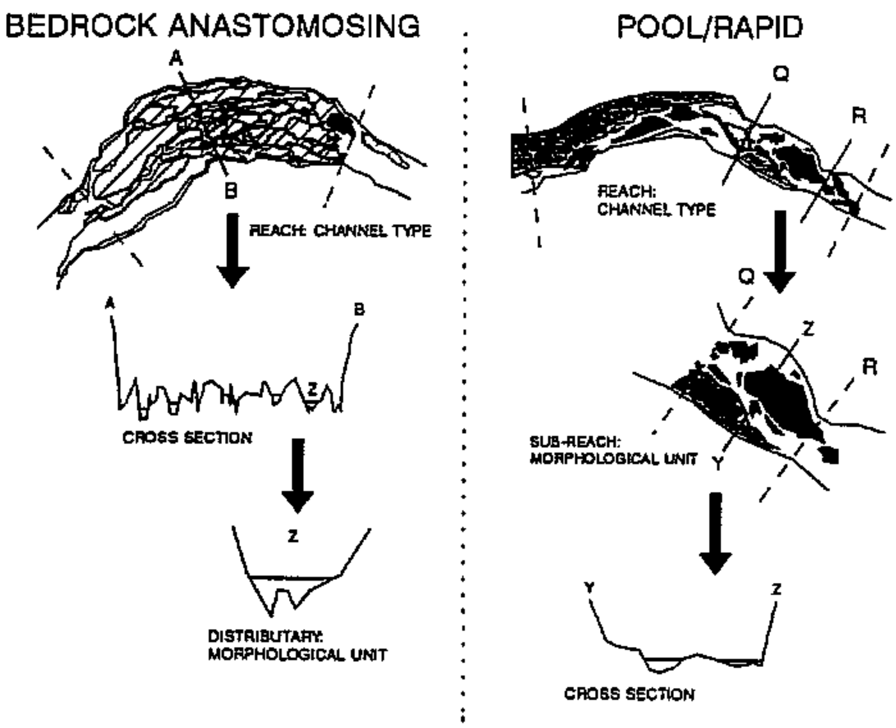


Figure 39. Scales at which the frictional characteristics of the Sabie River were investigated.

All of the channel types studied, with the exception of the single thread channel, had multiple distributary channels active at low or medium flows. In alluvial sections, where there is good water connectivity through the sediments, the water level in multiple channels was found to be the same and a single stage-discharge relationship characterises the whole section. In bedrock dominated sections however, the water level in one channel is dependent on the upstream conditions in that channel, so that a cross-section may contain channels with differing water surface elevations.

Where the water level across a cross-section is horizontal, traditional methods for calculating hydraulic and channel geometry parameters apply and a single rating relationship can be used (Fig. 40). Under these conditions, channel geometry is said to be defined by 'Horizontal' parameters (Broadhurst *et al.* 1996). Bedrock influenced reaches produce a non-horizontal water surface in multiple active distributaries across a cross-section (Fig. 40). This is particularly pertinent for the bedrock and mixed anastomosing reaches, where the observed low flow water surface elevation differed by up to 1.5m in separate channels. Therefore, the assumption of a horizontal water surface elevation for a bedrock influenced cross-section is not realistic. A multiple channel, non-horizontal water surface overspill model ('Non-Horizontal') was devised for use in bedrock influenced reaches. Individual channels will have different flow depth to total cross-section discharge relationships (Fig. 41).

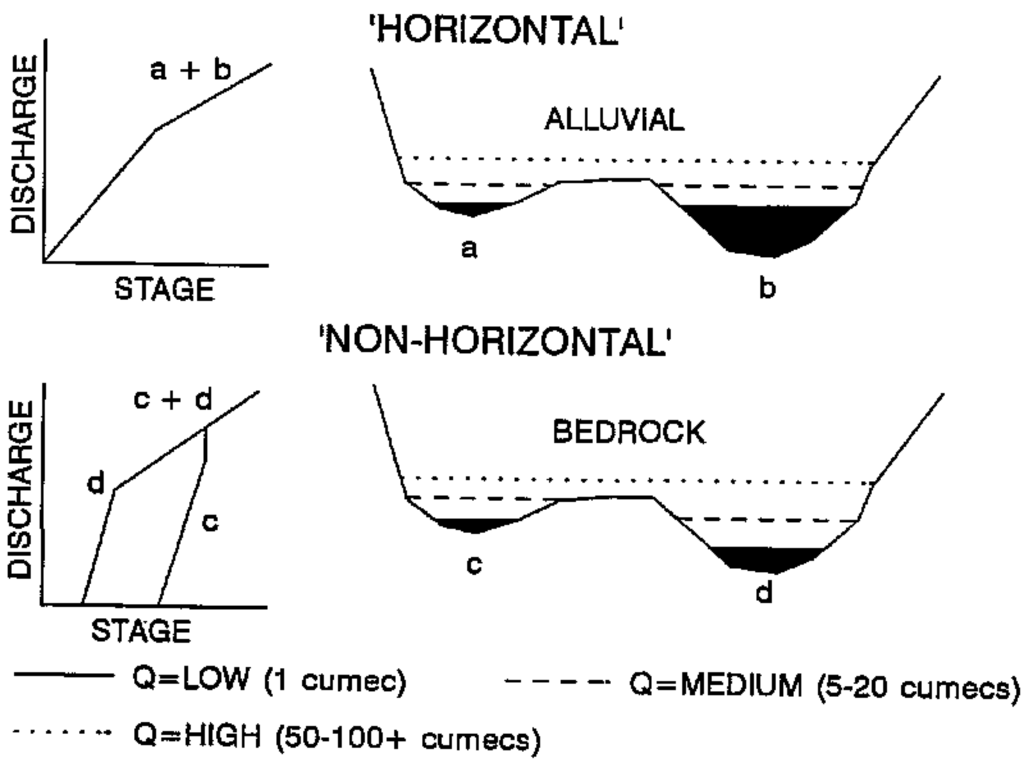


Figure 40. Approaches to modelling channel geometry in alluvial and bedrock sections: the 'horizontal' and 'non-horizontal' models (after Broadhurst *et al.* 1996).

The water level in each active channel was surveyed at low, dry season flow and the flow depth:total cross-section discharge relationship(s) obtained for the accessible channels at that cross-section were applied to all of the remaining channels in that section. The assumption that the single rating curve was applicable to the multiple channels was justified by plotting all the available rating curves for bedrock anastomosing channel types on the same graph axis. They generally overlap, and display similar trends (Fig. 42). In this way, although the initial water levels of the different channels in a cross-section will vary, their rate of change with discharge will be similar. Clearly, this model will only function for deep, unconnected channels; yet cross-section profiles for the Sabie River show that the multiple channels coalesce at medium to high flows, eventually forming a single channel across the whole macro-channel in very high flow events. Observations of bedrock distributaries at medium flows have shown that once a channel reaches the elevation 'threshold' dividing it from the next, it overspills into that channel until they are at the same elevation and become one channel.

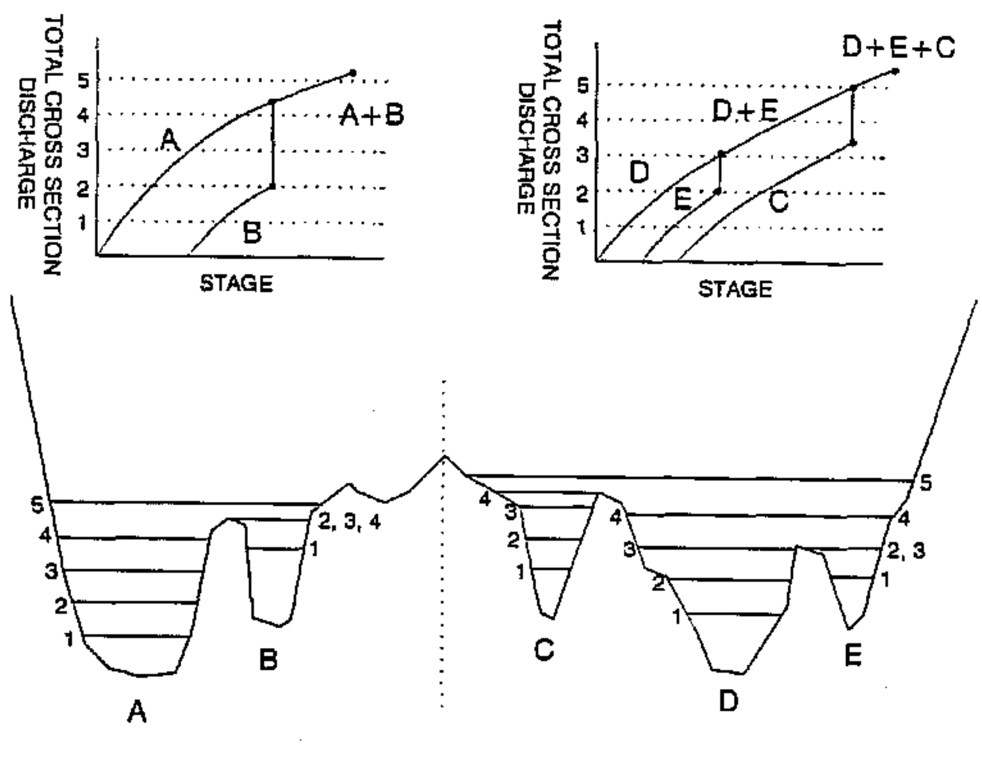


Figure 41. Diagrammatic example of the 'Non-Horizontal' Overspill Model (after Broadhurst *et al.* 1996).

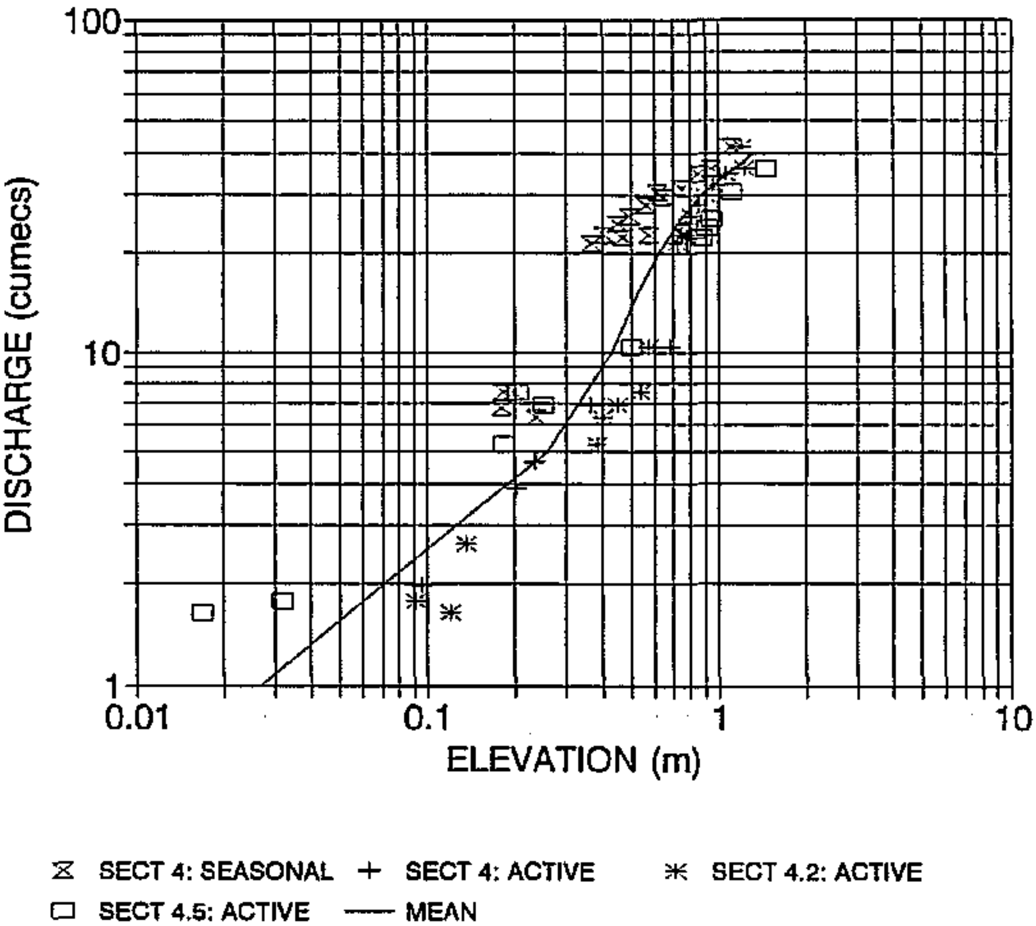


Figure 42. Rating curve similarity between individual bedrock distributaries in a bedrock anastomosing channel type.

With reference to Figure 41, at an arbitrary discharge, 1, the initial water levels in the five distributary channels vary. The rate of change with increasing discharge, to 2, is constant, but channel B has reached the overspill threshold to channel A. Therefore, its level remains constant while it contributes its share of the increase in discharge to channel A via overspill until the water levels are equal. The resultant rating curves may be derived, with the channel containing the lowest initial water elevation controlling the change in stage with discharge (Fig. 41).

A variety of channel geometry and hydraulic parameters were calculated using the 'Horizontal' model or 'Non-Horizontal' model in bedrock influenced sections. At a cross-section these parameters for a given discharge were: average stage S , width W, average depth d, wetted perimeter P, hydraulic radius R, channel area A and average velocity V (Fog. 35). A width weighted average elevation was computed to give average stage for multi-channel bedrock sections, as it was thought that wide distributaries would influence the total energy slope for a multiple channel section proportionally more than a small, narrow distributary. The cross sectional wetted perimeter, channel area and width values were simply the sum of the individual distributary parameters. Therefore, single values of these parameters were determined for the range of measured discharges for each cross-section monitored.

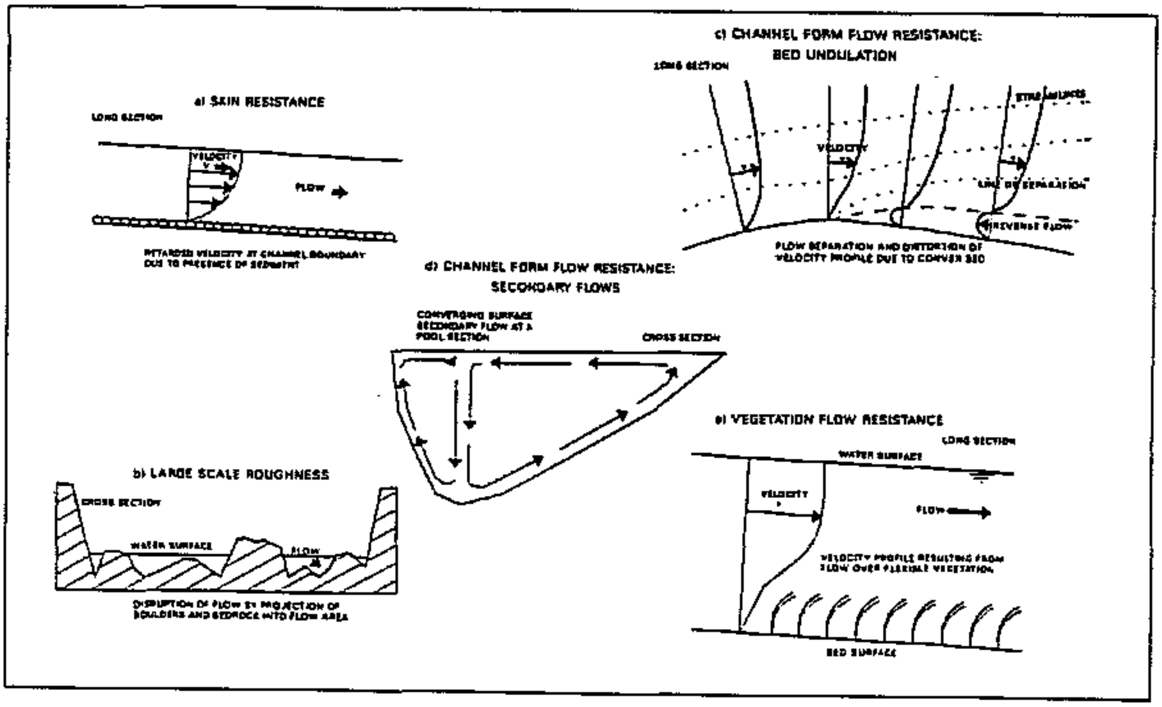


Figure 43. Components of flow resistance in open channels (after Broadhurst *et al.* 1996).

The data collected at each section along the representative reaches can be used to generate frictional characteristics and hydraulic information on scales ranging from whole channel type through morphological unit to cross-section.

7.2.2 Frictional characteristics

There are several forms of flow resistance in natural open channel flow which all contribute to the total resistance. These are: skin resistance, channel resistance, vegetational resistance and free surface resistance (Fig. 43). Most natural channels are too small for significant wind generated waves to develop and standing waves caused by supercritical flow are extreme and often ephemeral phenomena restricted to small distributary channels. Certain sections of the Sabie River do, however, exhibit frictional losses due to these phenomena.

Three standard equations have been used by engineers for at least a century, to quantify mean flow velocity, using the premise that velocity, V is proportional to a power of the friction slope, S_f (often approximated by the water surface slope) and the hydraulic radius, R (as defined in Fig. 35).

These Equations are:

Chezy

$$V = C(RS_f)^{1/2} \tag{3}$$

Manning

$$V = \frac{R^{2/3} S_f^{\ 1/2}}{n} \tag{4}$$

Darcy-Weisbach

$$V = \left(\frac{8gRS_f}{f} \right)^{1/2} \tag{5}$$

where g is the acceleration due to gravity.

The evaluation of the resistance coefficients, namely C, n and f in the above equations, gives a quantification of total flow resistance. These coefficients are interrelated, in the following way:

$$C = \frac{R^{1/6}}{n}; f = \frac{8gn^2}{R^{1/3}}; f^{1/2} = \frac{(8g)^{1/2}}{C} \tag{6}$$

The Manning's equation is partially empirical and both the equations of Chezy and Manning give dimensional coefficients. The Darcy-Weisbach equation gives a dimensionless friction coefficient which is based on boundary layer and pipe flow theory and its use is recommended by The American Society of Civil Engineers Task Force (1963). The advantage of this method is that it is related to the processes of fluid mechanics which actually determines the flow resistance.

Following the geomorphological hierarchy outlined in chapter 3, it is possible to characterise the Sabie River at a variety of relevant physical scales (Section 7.2.1), namely at a channel type, morphological unit or cross-section scale. All of these scales must be analysed and the multi-section Barnes (1967) approach is most commonly used to estimate total flow resistance over a (sub)reach.

A value of the friction slope, to be used in total resistance equations, such as Manning's or Darcy-Weisbach (equations 4 and 5) is available only between sections, as it is defined by:

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta hv - k(\Delta hv)}{L} \qquad (7)$$

where L is the reach length, h_f is the friction head, Δh is the change in elevation of the water surface between the upstream and downstream cross-sections, Δhv is the change in velocity head between the upstream and downstream cross-sections and k(Δhv) approximates the energy loss due to acceleration or deceleration in a contracting or expanding reach (Fig. 44). Following convention, k is assumed to be 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 was assumed for the purpose of this study 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). Several studies have shown however, that values for α can far exceed unity, with values of greater than 2 attributed to expanding sections displaying flow separation (Streeter 1942). Such a situation has been observed for the Sabie River.

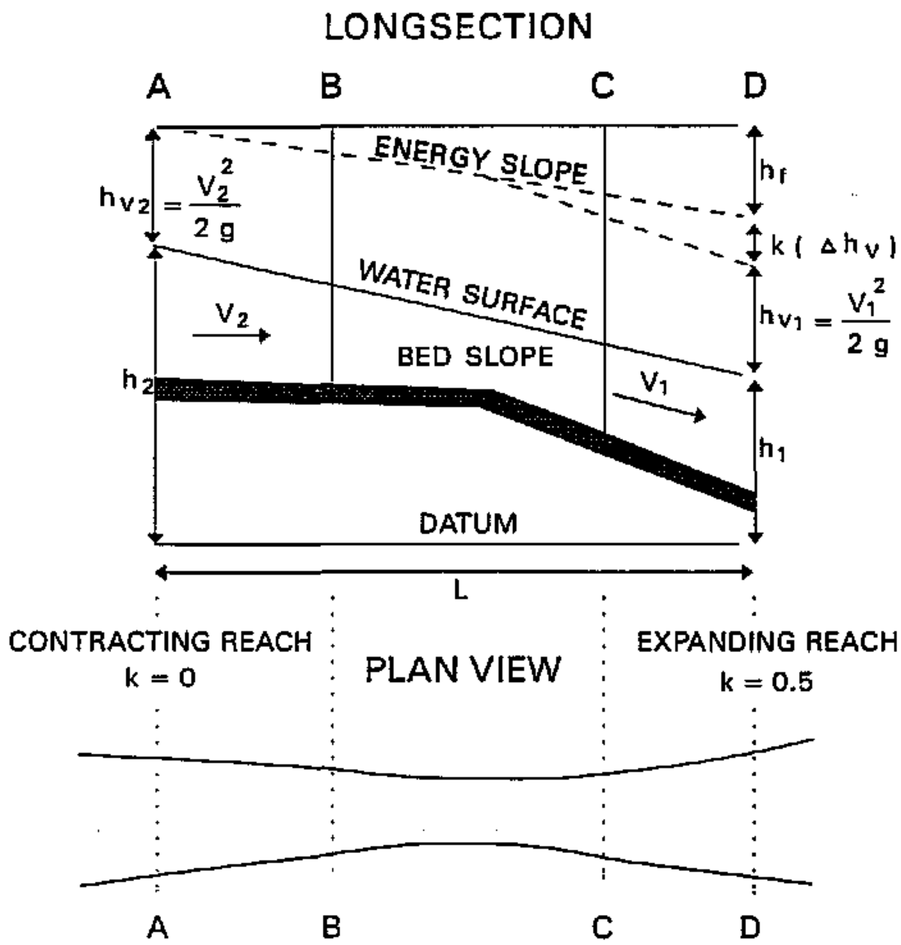


Figure 44. Reach energy slope estimation (modified from Barnes 1967).

A representative value of Manning's n for a multiple section reach at a given discharge can be obtained by equating the friction head loss calculated from the friction slope with the friction head loss. This follows the method adopted by Barnes (1967) and followed by Jarrett (1984) and Hicks and Mason (1991) (Fig. 44). Therefore,

$$h_f = h_{f_{1.2}} + h_{f_{2.3}} + h_{f_{(m-1).m}} \tag{8}$$

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

$$h_f = n^2 Q^2 \left(\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \ldots \frac{L_{(m-1).m}}{Z_{(m-1)} Z_m} \right) \tag{9}$$

where m is the number of cross-sections (with the m^{th} cross-section being furthest upstream), m-1.m represents the difference in value of the parameter in question between cross-section m-1 and m, $Z = AR^{2/3}$, and a representative value of Z for the reach between two adjacent cross-sections is $(Z_1Z_2)^{1/2}$.

From equations 7 and 8:

$$h_f = (h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + k_{(m-1).m}\Delta h_{v_{(m-1).m}} \tag{10}$$

and therefor from equation 8:

$$n = \frac{1}{Q}\left(\frac{h_f = (h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + k_{(m-1).m}\Delta h_{v_{(m-1).m}}}{\frac{L_{1.2}}{Z_1 Z_2} + \frac{L_{2.3}}{Z_2 Z_3} + \frac{L_{(m-1).m}}{Z_{(m-1)} Z_m}} \right)^{1/2} \tag{11}$$

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

$$C = Q\left(\frac{\frac{L_{1.2}}{X_1 X_2} + \frac{L_{2.3}}{X_2 X_3} + \frac{L_{(m-1).m}}{X_{(m-1)} X_m}}{h_f = (h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + k_{(m-1).m}\Delta h_{v_{(m-1).m}}} \right)^{1/2} \tag{12}$$

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

An equivalent expression for Darcy-Weisbach friction factor has been derived for use in this study (Broadhurst *et al.* 1996):

$$f = \frac{8g}{Q^2}\left(\frac{h_f = (h_m - h_1) + (h_{v_m} - h_{v_1}) - (k_{1.2}\Delta h_{v_{1.2}} + k_{2.3}\Delta h_{v_{2.3}} + k_{(m-1).m}\Delta h_{v_{(m-1).m}}}{\frac{L_{1.2}}{(Y_1 Y_2)^{1/2}} + \frac{L_{2.3}}{(Y_2 Y_3)^{1/2}} + \frac{L_{(m-1).m}}{(Y_{(m-1)} Y_m)^{1/2}}} \right)^{1/2} \tag{13}$$

where $Y = A^2R$

In this way, using equations 11, 12 or 13, total flow resistance can be quantified over a variety of scales, from a two section 'sub-reach', which could encompass a morphological unit, to a multi-section channel type 'reach'.

Following the Barnes (1967) methodology, and using the hydraulic and channel geometry parameters derived from either the 'Horizontal' or 'Non-Horizontal' model, reach flow resistance was quantified for the five channel types, over the range of flows encountered on the Sabie River during the period of study (Figs. 45 to 47). The high magnitude flow levels were recorded only at one or two cross-sections per channel type at three out of the five channel types. Where only one estimate of high discharge stage was recorded within the study reach, equations 3 to 5 were used to calculate at a cross-section flow resistance. In these cases, local water surface slope was not available, so the energy slope was assumed to equal the regional bed slope (this assumes that the flow is uniform at high discharges). Therefore, these high discharge flow resistance estimates are less reliable than the multi-cross-section derived estimates of the low and medium discharges. Where two records of high discharge stage were recorded within a study reach, local slope, and hence true energy slope, was available and the Barnes (1967) methodology was used to quantify flow resistance.

For this report the results at the scale of channel type were used to generate friction factor estimates for use in computing sediment transport rates along the Sabie River. More detailed analysis of the frictional characteristics of the Sabie River at smaller spatial scales may be found in the companion volume (Broadhurst *et al.* 1996).

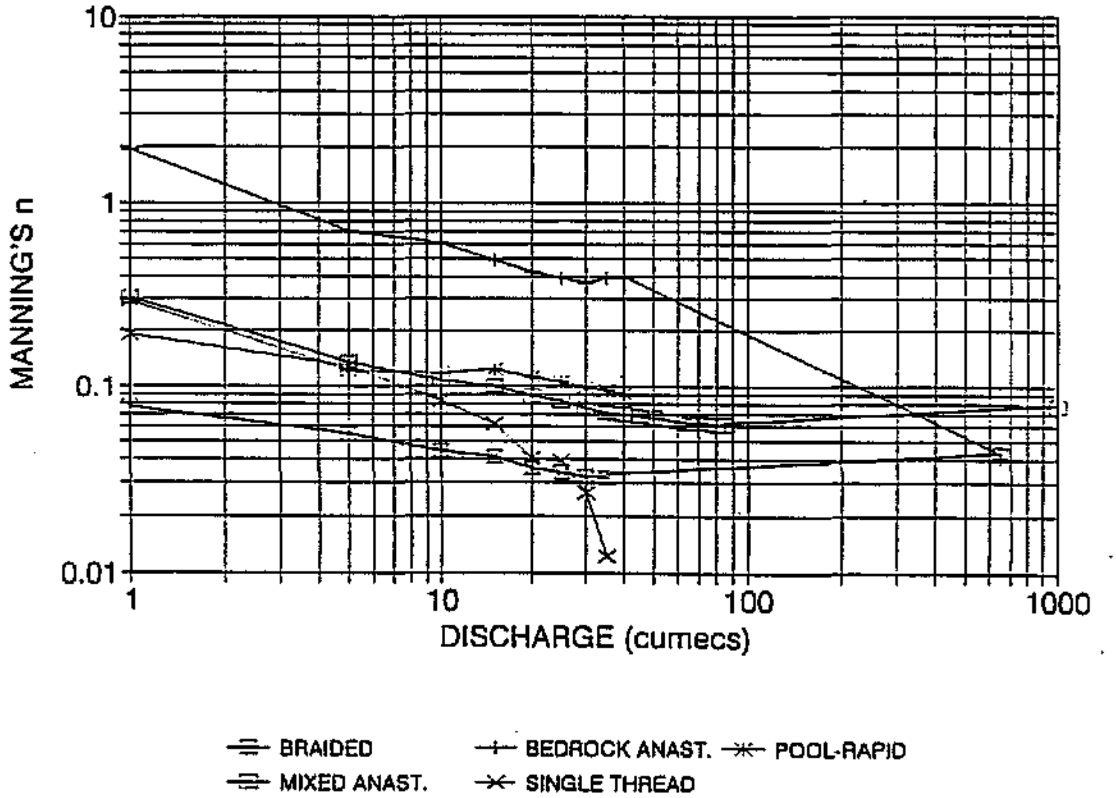


Figure 45. Characteristic Manning's n flow resistance values at the channel type scale (after Broadhurst *et al.* 1996).

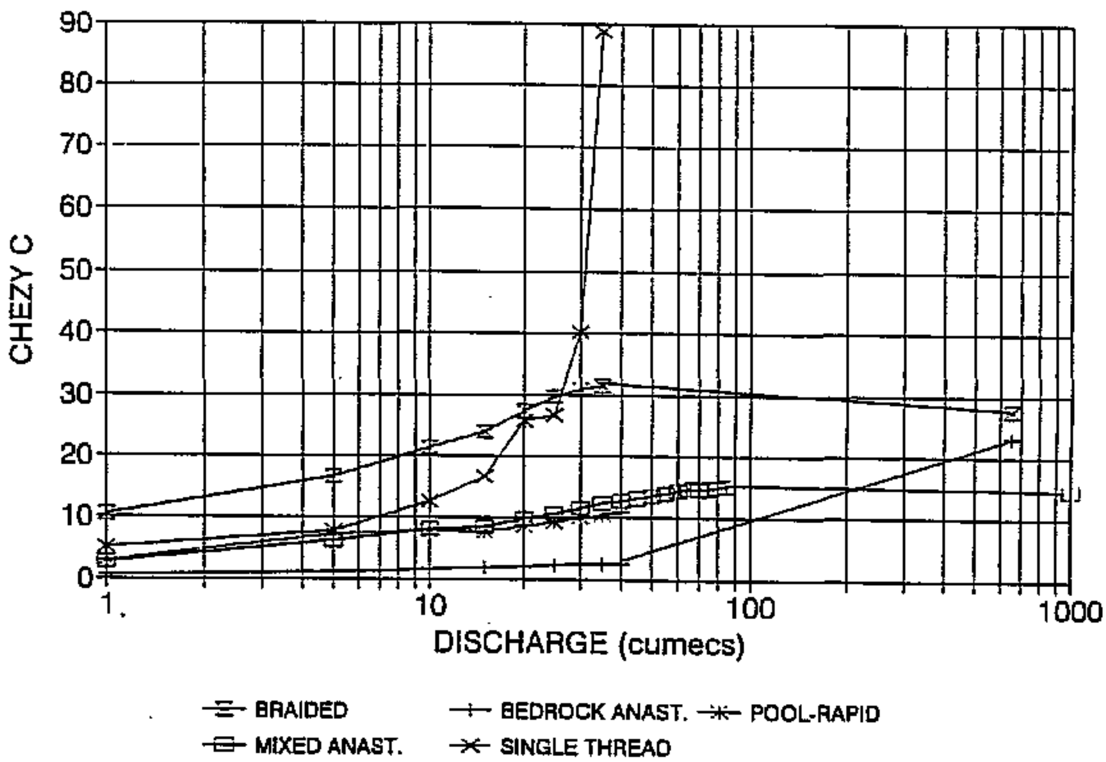


Figure 46. Characteristic Chezy C flow resistance values at the channel type scale (after Broadhurst *et al.* 1996).

Table 15. Comparison of a variety of river channel flow resistance values reported by various authors (after Broadhurst *et al.* 1996).

Author	Description	Manning's n	Darcy f
Chow 1959	Vegetation infested	0.1	-
	Dense brush and willows	0.16(max)	-
	Cobble bottom	0.05(max)	-
Barnes 1967	Bedrock base with boulders. High slope, low depth	0.075	-
Bathurst 1978	Mountain stream, low flow	-	3.12(max)
Bathurst *et al.* 1981	Flume study, large scale roughness	-	4.79(max)
Richards 1982	Clean natural channel	0.03	0.072
	Weedy natural channel	0.07	0.4
	Mountain stream with boulders	0.05	0.196
Thorne and Zevenbergen 1985	Mountain stream, large boulders	0.11(max)	1.55(max)
Bathurst 1985	Mountain river, high slope	-	0.65 5.46(max)
Hicks and Mason 1991	Boulder bed, low flow	0.27	-
	Large boulder and bedrock, high flow	0.2	-
Whittaker and Jaeggi 1982	Steep-pool mountain streams	-	44.9(max)
Beven *et al.* 1979	Waterfalls and plunge pools; low flow	-	1328(max)
	Straight, pools and cobbled riffles	-	48
Bridge and Gabel 1992	Low sinuosity, braided	-	0.07 0.13(max)
Bakry *et al.* 1992	Vegetation infested canals	0.05 0.074(max)	-
Hall and Freeman 1994	Flume study, dense vegetation	0.27 0.7(max)	-

The highest flow resistance coefficients measured at the reach scale were found over the bedrock anastomosing channel type (Figs. 45-47). The extreme reach flow resistance occurs at a low discharge, where the flow is shallow and numerous protruding boulders on a 97% bedrock base generate a tortuous wetted perimeter. Comparable environments, with water surface slopes of greater than 0.0165 and a high incidence of bedrock and boulders in channel have yielded high Manning's n values (Table 15), for example, 0.27 (Hicks and Mason 1991) and Darcy-Weisbach f values in excess of 40 (Beven *et al.* 1979, Whittaker and Jaeggi 1982). The large scale roughness and energy dissipation effect of the irregular bed becomes drowned out as discharge increases. During flood flows, the bedrock anastomosing reach flow resistance values decline markedly, to values indicative of more uniform channels (Richards 1982).

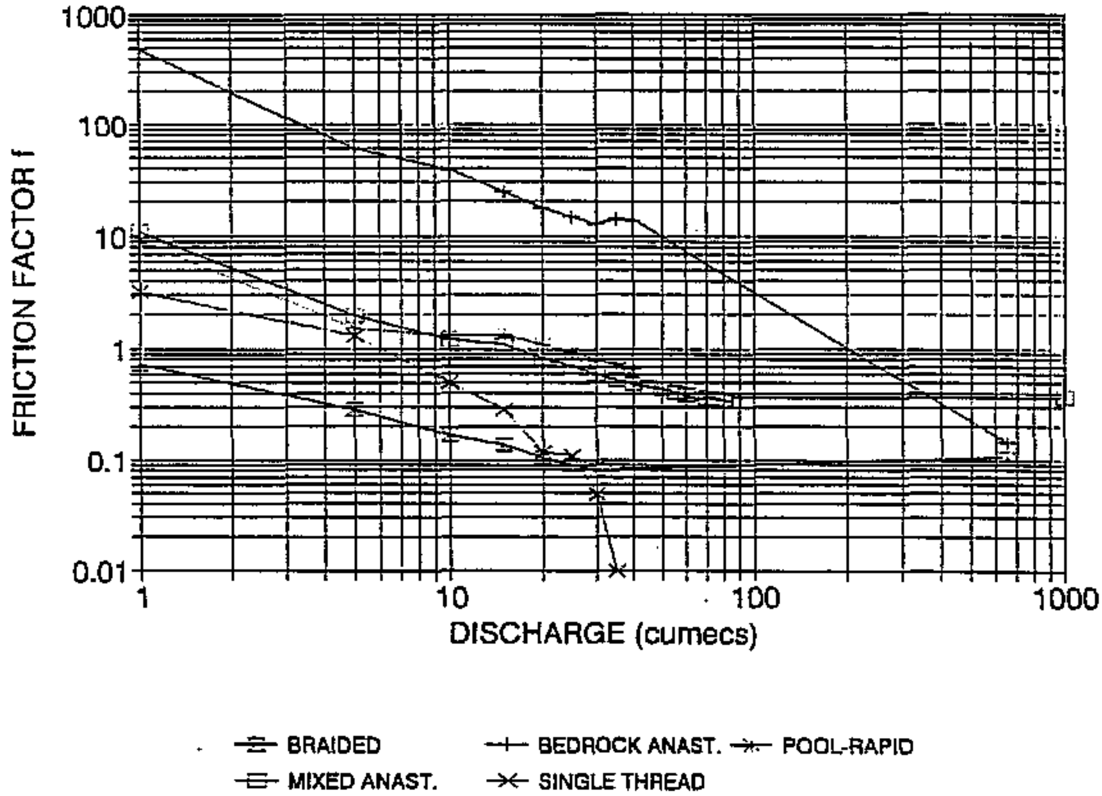


Figure 47. Characteristic Darcy-Weisbach f flow resistance values at channel type scale (after Broadhurst *et al.* 1996).

The alluvial channel types, namely braided and single thread, generate the lowest flow resistance values and tend, with medium range discharges, to values identical to those reported by authors investigating "clean natural channels" (Richards 1982). In particular, the braided reach compares favourably to other alluvial "low sinuosity braided channels" (Bridge and Gabel 1992). At low discharges of less than $10m^3s^{-1}$, the flow resistance values resemble the lower range of values reported from cobble and some boulder bed channel environments (Chow 1959, Barnes 1967, Richards 1982, Thorne and Zevenbergen 1985). The median grain diameter of the active channel sediments at this channel type was just over 1mm and therefore, not cobble sized. Although this reach is predominantly alluvial, isolated bedrock outcrops and boulders constitute about 5% of the wetted perimeter in this channel type, which results in increased flow resistance at low discharges and flow depths. High discharge ($650m^3s^{-1}$) stage data was collected at the braided reach generating a flow resistance value of 0.103, due to the influence of bars covered by dense reeds.

The increase in flow resistance at $20m^3s^{-1}$ at the single thread channel type can partly be attributed to vegetational resistance of the fringing river cliff reeds and shrubs. However, it is thought to be largely the result of channel narrowing at mid-range flows, that causes a noticeable backing up of the water surface slope over the top half of the reach.

Mixed anastomosing and pool-rapid flow resistance coefficients show a decline with discharge and the low flow recorded values are similar to those measured in mountain streams (Bathurst 1978, Thorne and Zevenbergen 1985, Bathurst 1985). These higher flow resistance values are a result of the greater presence of bedrock and boulders at these channel types. Large scale roughness is manifest at rapids within the pool-rapid channel type and throughout the mixed anastomosing channel type, where active distributaries comprise more than 70% bedrock or large boulders.

7.2.3 Local channel hydraulics

A detailed evaluation of local channel hydraulics is necessary for this study, in order to characterise the effects of flow on the channel types defined in the hierarchical classification and to provide input data to the semi-quantitative bulk sediment transport model, which is used to predict channel change on the Sabie River (chapter 9). Detail on the estimation procedures used to derive the hydraulic variables follows.

Flow depth monitored at a number of sites and related to discharge on different channel types along the Sabie River in the Lowveld has enabled the development of stage-discharge relationships for the 24 sites. Using these relationships and the geometry of the measured cross-sections, a number of flow parameters were calculated. Manning's flow resistance coefficients, determined for detailed studies of various channel types (Broadhurst *et al.* 1995) were used to calculate friction slopes and hence bed shear stresses, shear velocities and ultimately sediment transport rates for a range of particle sizes for any particular discharge at each cross-section.

Breaks in the stage-discharge curves were identified through visual inspection of discharge vs stage and log(discharge) vs stage plots of the data. Regression equations were determined for discharge and log(discharge) vs stage for the different portions of the stage-discharge curves and the ones with the lowest r^2 values were selected. Typical values of r^2 range from 0.73 - 0.999, with the majority in excess of 0.95. The stage-discharge relationships were extrapolated beyond the range of measured data using the assumption that the ratio of friction slope to Manning's flow resistance is constant for high discharges (equation 14).

$$\frac{S_f^{1/2}}{n} = k \qquad (14)$$

where k is a constant calculated for the upper limit of the measured data from:

$$k = \frac{Q_{max}}{AR^{2/3}} \qquad (15)$$

where Q_{max} is the maximum discharge for which stage was measured, A is the flow area, R is the hydraulic radius (A/P) and P is the wetted perimeter. The assumption that stage-discharge relationships can be extrapolated beyond the range of measured data is a reasonable one since first, channel shape is more regular for high discharges and second, local controls in the channel are drowned out at high discharge and hence have limited effect on the water surface slope. One problem is that Manning's n values vary with discharge in the different channel types (Broadhurst *et al.* 1996), but, they are generally asymptotic to a constant value at high discharges for all channel types (Fig. 45). Assuming a constant high flow value for k, discharge (Q_{ext}) may be estimated for flows in excess of those measured using

$$Q_{ext} = kAR^{2/3} \qquad (16)$$

Flow resistance results determined from detailed studies on single thread, braided, pool-rapid, and bedrock and mixed anastomosing channel types (Broadhurst *et al.* 1995), were then used to estimate representative Manning's flow resistance coefficients for each of the cross-sections (bedrock anastomosing, n = 0.25, mixed pool-rapid, n = 0.08, mixed anastomosing, n = 0.08, alluvial single thread, n = 0.08 and alluvial braided, n = 0.035).

Friction slopes S_f were then calculated for the different discharges from the Manning equation

$$Sf = \left(\frac{nQP^{2/3}}{A^{5/3}}\right)^2 \qquad (17)$$

Shear velocity was then calculated from

$$u_* = \sqrt{gRS_f} \qquad (18)$$

Since the chosen values of n are underestimated for braided, pool-rapid and mixed anastomosing channel types for low flows, the shear velocity and hence sediment transport rates will also be underestimated.

Sediment transport rates are calculated using the total load equation of Ackers and White (1973). The dimensionless Grain size D_{gr} is given by

$$D_{gr} = \left(\frac{g(s-1)}{v^2} \right)^{1/3} D \tag{19}$$

where s is the relative density of the sediment, v is the kinematic viscosity of the fluid and D is the sediment diameter. Coarse particals are transported mainly as bedload and fine ones mainly as suspended load. For transitional particle sizes 1< Dgr >60.

$$a = 1.00 - \log D_{gr} \tag{20}$$

$$b = \frac{9.66}{D_{gr}} + 1.34 \tag{21}$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 2.53 \tag{22}$$

$$E = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{23}$$

where a and b are exponents, C a coefficient in the sediment transport function and E is the value of Froude number at nominal initial motion.

The sediment mobility number F_{gr} is given by

$$F_{gr} = \frac{u_*^a}{\sqrt{gD(s-1)}} \left[\frac{V}{\sqrt{32} \log\left(\frac{10d}{D} \right)} \right]^{1-a} \tag{24}$$

where d is the average flow depth. This allows the dimensionless sediment transport rate G_{gr} to be calculated

$$G_{gr} = \left(\frac{F_{gr}}{E} - 1\right)^{b} \tag{25}$$

This may then be converted to a sediment transport rate Q_s in m^3/s

$$Q_s = Q\frac{G_{gr} SD}{d}\left(\frac{V}{u_*}\right)^{n} \tag{26}$$

This formula has been applied to a range of field data with reasonable success, most predictions being within the range:

$$\frac{1}{2} < \left(\frac{estimated Q_s}{measured Q_s}\right) < 2 \tag{27}$$

Yang (1984) found that dimensionless stream power Pd provided a better indication of the bedload or gravel transporting capacity and this was calculated from

$$P_d = \frac{VS_f}{\omega} \tag{28}$$

where ω is the particle fall velocity as calculated from Dietrich (1982)

$$\begin{aligned} \log W_* = &-376715 + 1.92944\left(\log D_{gr}{}^{1/3}\right) - 0.09815\left(\log D_{gr}{}^{1/3}\right)^2 \\ &-0.00575\left(\log D_{gr}{}^{1/3}\right)^3 + 0.00056\left(\log D_{gr}{}^{1/3}\right)^4 \end{aligned} \tag{29}$$

$$W_* = \frac{\rho\omega^3}{(s-1)g\nu} \tag{30}$$

where W. is the dimensionless settling velocity

Flow depth, width, area, wetted perimeter, hydraulic radius, average flow velocity, friction slope, unit stream power, dimensionless unit stream power, average bed shear stress, average shear velocity and transport rates of 0.5 mm, 1 mm and 2 mm size fractions were calculated for all average daily flows over the entire length of record at each cross-section (Appendix D).

The bulk annual sediment transport results (Figs. 48a and 48b) indicate that the bedrock anastomosing channel type is extremely competent to transport suspended and bed-material delivered to it. This accounts for its remarkably robust nature, despite the reduction in flows and increase in sediment experienced by the Sabie River in recent years. This channel type is also unique in that it is competent to transport sediment even at very low flows. In contrast, the other principal channel types all have a much lower bulk sediment transport capacity (Fig. 48b). Deposition of delivered material is thus likely, particularly for the mixed anastomosing channel type. Aerial photographic analysis supports these predictions with all of the remaining channel types exhibiting increased sedimentation particularly during dry years.

The pool-rapid and single thread channel types show similar bulk sediment transport characteristics (Fig. 48b). This is because the site used to establish the pool-rapid characteristics was at a pool, within a pool-rapid channel type and would be expected to display similar characteristics to a single thread channel type. Although rapids would have a high transport capacity, it is expected that the pools, within a pool-rapid channel type, due to the higher potential to trap sediment, would control the overall transport characteristics of a pool-rapid channel type.

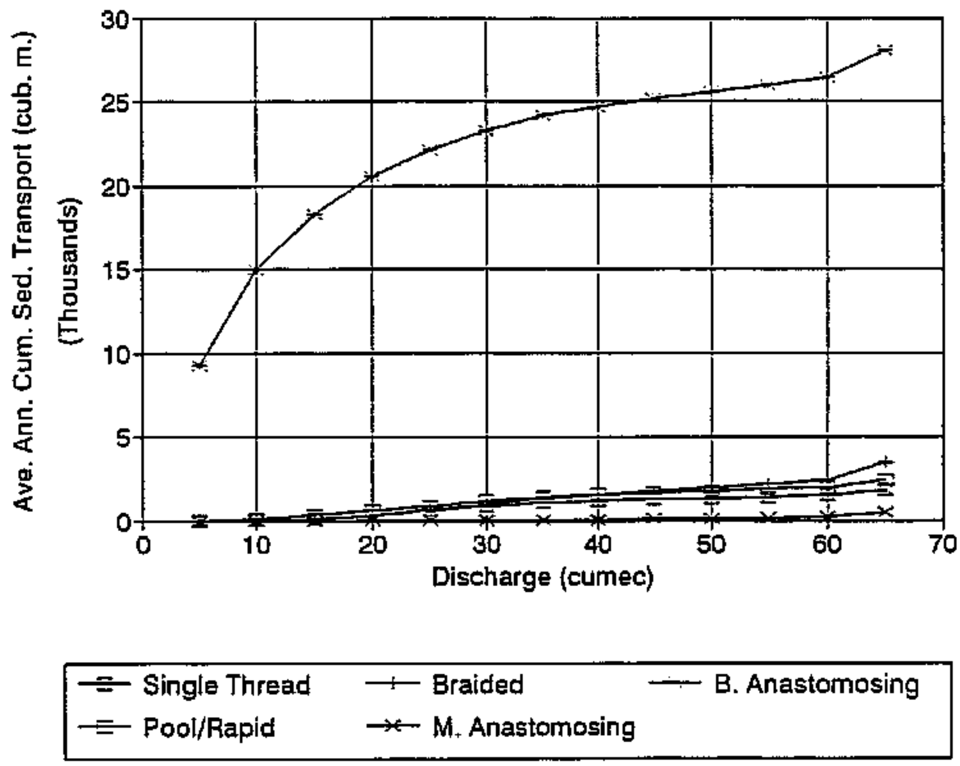


Figure 48a. Cumulative bulk potential sediment transport for the different channel types 1959-1993.

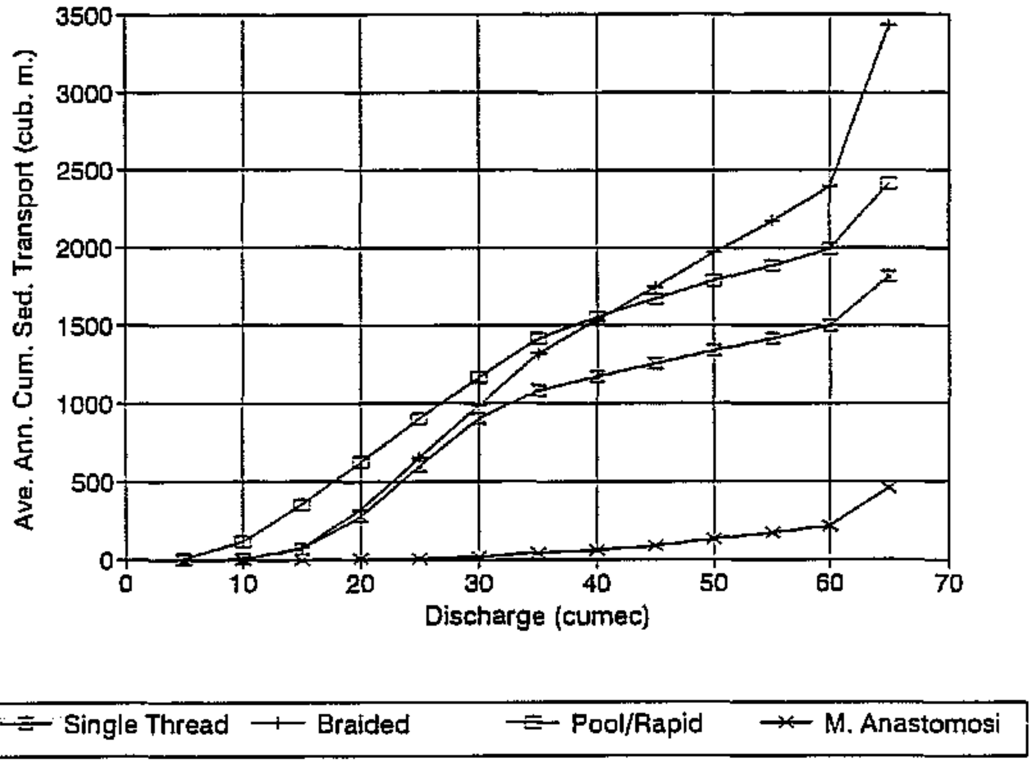


Figure 48b. Cumulative bulk potential sediment transport for the different channel types 1959-1993.

7.3 Summary

☺ The major in-channel controls on geomorphological form are hydraulics and sediment dynamics. These are viewed on a regional (Sabie River in the Lowveld) and local (channel type and morphological unit) scale in order to generate information on large scale, long term channel change, together with the detailed hydraulic and sediment dynamics that influence geomorphological change at the scale of morphological unit.

☺ Regional scale studies yield information on coarse channel dynamics and can be used to identify areas along the river that are prone to large scale, long term change as a result of erosion or sedimentation. The results reveal three distinct zones of lower channel energy (as measured by a reduction in channel sediment transport capacity), which correspond well with the large scale build up of deep sedimentary deposits along the river.

☺ Local scale studies generate data on the hydraulics and hydrodynamics for cross-sections in representative examples of each channel type. The data have been used to simulate bulk sediment transport capacities for each channel type generating a coarse measure of the degree to which they are resistant to sedimentation. The predictions correspond well with the sedimentary situation observed for each channel type from aerial photographs.

- ☺ The multiple cross-section technique of Barnes (1967) was used to quantify channel flow resistance at a variety of spatial scales (Broadhurst *et al.* 1996). The 'reach' channel type results presented in this report, were used to evaluate a variety of hydrodynamic parameters for transference to other, geomorphically similar areas and to construct a detailed regional picture of channel dynamics for use in the dynamic modelling.

- ☺ Individual channel types display unique hydraulic and channel flow resistance characteristics. The Manning's n flow resistance coefficients appear to become asymptotic with increasing discharge, generating the following characteristic values for each channel type: bedrock anastomosing, n = 0.25, mixed pool-rapid, n = 0.09, mixed anastomosing, n = 0.06, alluvial single thread, n = 0.035 and alluvial braided, n = 0.035.

- ☺ A 'Non-Horizontal' water surface channel overspill model is proposed to deal with the channel dynamics in bedrock influenced channel types (Broadhurst *et al.* 1996).

- ☺ The data generated from the channel hydraulics and flow resistance research exercises, combined with information on sediment inputs to the river channel (chapter 6), provides the quantitative basis for the construction of a semi-quantitative dynamic model of geomorphological change on the Sabie River. The detail of the data collected enables the model to run on a daily flow time step and generates prediction of geomorphological change at the scales of channel type and morphological unit.

8. QUALITATIVE MODELLING OF CHANNEL CHANGE IN THE SABIE RIVER

8.1 Observed change

Channel response to alterations in catchment controls provides valuable evidence of the sensitivity of the river system to imposed change. Details of the geomorphological changes on the Sabie River can be derived from aerial photographic interpretation at the morphological unit scale. This chapter presents these changes with respect to short term (annual) and long term (> 50 years) pathways of change. Finally, qualitative pathways of likely directions of change are proposed for each channel type and these are built into an overall model of channel type change for the Sabie River within the Kruger National Park.

Detailed analysis of aerial photographs at the morphological unit scale has shown that annual patterns of erosion and deposition are highly variable along the length of the Sabie River, with more significant sedimentary build up below the confluence of the Sand River tributary. However, when the system is viewed in the light of the channel types defined by the morphological hierarchy (Fig. 13), it is clear that each channel type is exhibiting locally consistent changes to its morphological units. For example, pool-rapid areas upstream of bedrock anastomosing sections have shown progressive sedimentation, beginning with deposition in bedrock pools to form braid bars, followed by more extensive accumulations at the active channel margins in the form of lateral bars. Occasionally, lateral and braid bars merge and the bedrock influence in the section may be lost (Fig. 49). Braiding and sinuosity are increasing through braid and lateral bars formation as sediment accumulates (Fig. 50).

Aerial photographs were used to study channel change at the level of morphological unit on an annual basis for selected reaches in the Kruger National Park. Change was evaluated in terms of the number and area of new sedimentary features between 1986 and 1989, a period of average runoff, and between 1989 and 1992, a period of reduced runoff. Some 400 changes in morphological unit presence or extent were recorded across the five channel types covered by the aerial photographs. Change between 1986 and 1989 was limited; new features did form but similar features were also removed (Table 16). Mixed pool-rapid and bedrock pool-rapid channel types show some net deposition, followed by mixed anastomosing and braided. The bedrock anastomosing channel type remained stable (Table 17). The years in which a flow reduction was experienced (1989-1992) showed a more dramatic change at the scale of morphological unit; mixed anastomosing and mixed pool-rapid channel types displayed large scale sediment build up with more moderate accumulations appearing in bedrock pool-rapids. Generally, the braided channel type behaved in a similar fashion to the period 1986-1989, displaying limited deposition and the bedrock anastomosing areas also showed a very slight increase in sedimentary deposits.

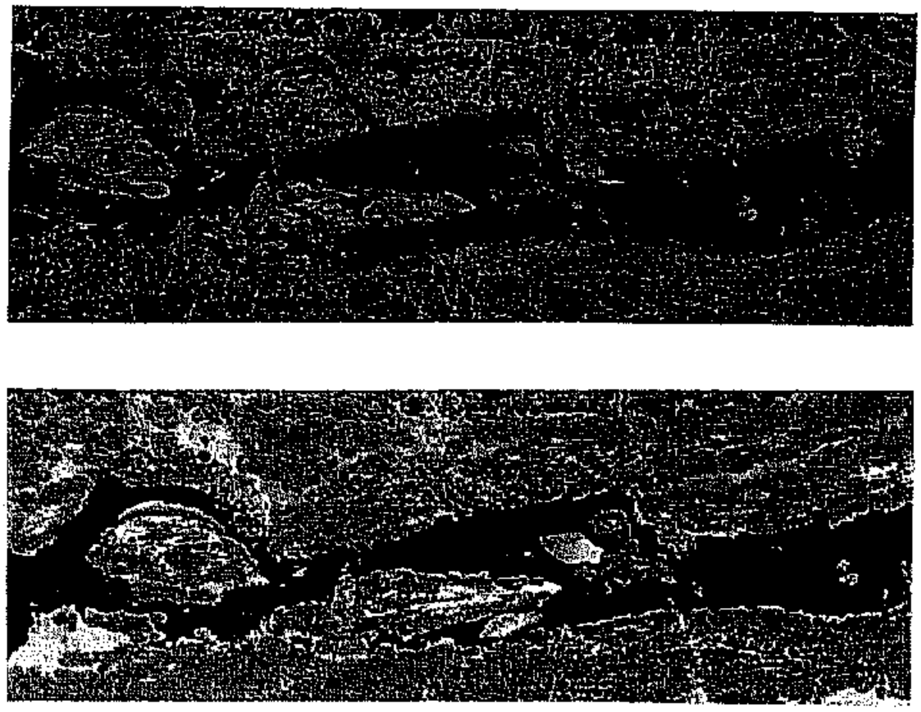


Figure 49. Observed change in a pool-rapid channel type on the Sabie River in the Kruger National Park (1989 - 1992).

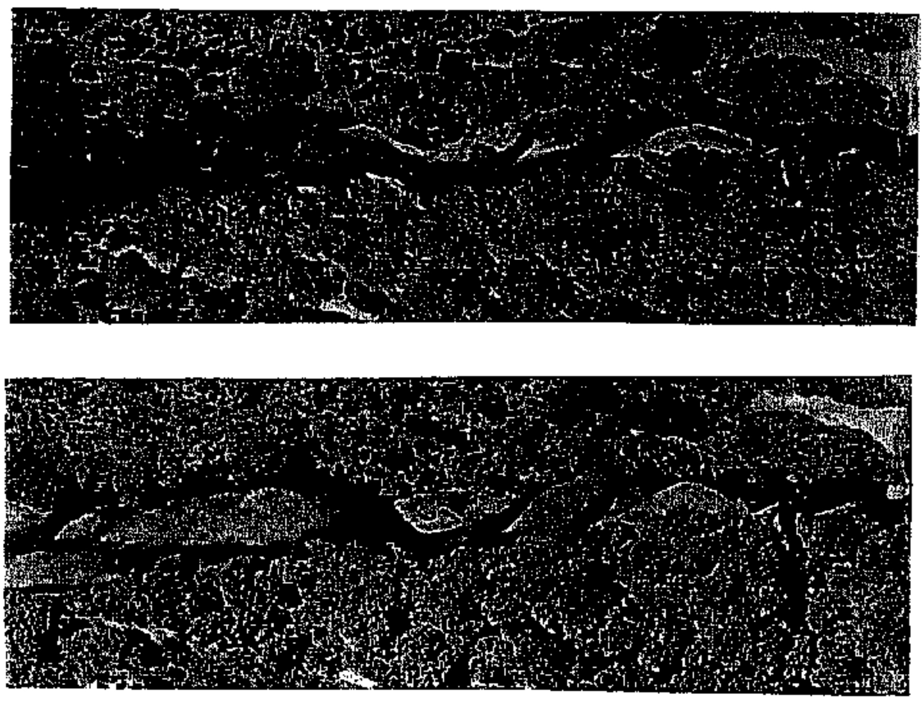


Figure 50. Observed change of an alluvial single thread/braided channel type on the Sabie River in the Kruger National Park (1989 - 1992).

Table 16. Change in the morphological unit structure of the channel types recorded on the Sabie River between 1986-1989 (a wetter period) and 1989-1992 (a drier period).

Channel type	Change	Morphological unit 1989	Morphological unit 1992
Bedrock pool-rapid	Increase	leb → pb → lb → mcb	lb → leb → mcb → bcb → pb
	Decrease	mcb → pb → leb → lb	mcb → pb
Mixed pool-rapid	Increase	lb → rc → mcb → leb → bcb	lb → rc → mcb → bcb
	Decrease	mcb → bcb → leb → lb → tb	lb → mcb → bcb → leb
Bedrock anastomosing	Increase	lb → leb → mcb	mcb → leb → lb
	Decrease		
Mixed anastomosing	Increase	mcb → lb → leb → bcb	lb → mcb → rc → leb → bcb
	Decrease	lb → mcb → bcb → bb → leb → I → pb → tb	bcb → lb → mcb → leb
Alluvial braided	Increase	mcb → leb → lb	mcb → leb → lb
	Decrease	mcb	rc → mcb → leb

lb= lateral bar, leb= lee bar, bcb= bedrock core bar, mcb= mid-channel bar/braid bar, rc= rip channel or chute, pb= point bar, tb= tributary bar, I= island
→= magnitude of change decreases left to right

Table 17. Quantitative change in the area of morphological units for the channel types recorded on the Sabie River between 1986-1989 (a wetter period and 1989-1992 (a drier period).

Channel type	Morphological unit change	
	1986-1989	1989-1992
Bedrock pool-rapid	lee bar ↑↑ point bar ↑ mid-channel bar ↓	lee bar ↑↑ lateral bar ↑↑↑ mid-channel bar ↑ bedrock core bar ↓ point bar ↓
Mixed pool-rapid	lateral bar ↑↑ rip channel ↑↑ mid-channel bar ↓ lee bar ↓ bedrock core bar ↓ tributary bar ↓	lateral bar ↑↑↑ rip channel ↑↑ mid channel bar ↑↑ bedrock core bar ↑↑ lee bar ↓
Bedrock anastomosing	lateral bar ↑	mid-channel bar ↑ lateral bar ↑
Mixed anastomosing	mid channel bar ↑↑↑ lateral bar ↑ lee bar ↓	lateral bar ↑↑↑ bb ↑↑↑ mid-channel bar ↑↑ rip channel ↑↑ lee bar ↑↑ bedrock core bar ↓
Alluvial braided	mid-channel bar ↑↑ lee bar ↑ lateral bar ↑	mid-channel bar ↑↑ lee bar ↑ lateral bar ↑ rip channel ↓
↑↑↑ Major increase, ↑↑ Marked increase, ↑ Increase ↓↓↓ Major decrease, ↓↓ Marked decrease, ↓ Decrease		

8.2 Inferred long term change and qualitative change models

Leopold and Wolman (1957) noted that channels existed as a continuum between single thread and braided systems. However, their classification was restricted to alluvial rivers where they recognised three major channel forms: straight, meandering and braided, dependent upon sinuosity and number of distributary channels. These channel types have formed the basis of much subsequent research into alluvial systems and many attempts have been made to modify and extend this classification (Mollard 1973, Rust 1978, Brice 1984, Knighton and Nanson 1993). Anabranching and anastomosing systems have been recognised and 'mixed' systems, such as the sinuous braided channels of Brice (1984), have been classified. Thus the original three channel types have been dissected and extended to include a large variety of alluvial channel patterns.

Similarly, much emphasis has been placed on determining the controls on channel form. The continuum concept of Leopold and Wolman (1957) recognised that channel pattern was controlled by a set of continually varying factors (channel gradient, measures of discharge, sediment inputs, sediment transport ability and bank cohesion). Subsequent work (Langbein and Leopold 1966, Knighton 1984, Brakenridge 1985, Ashley *et al.* 1988) has highlighted and attempted to quantify these factors and defined thresholds of change based upon them.

The continuum concept has thus proved valuable in understanding alluvial river systems, allowing a wider variety of channel types to be proposed after it was realised that the three division classification was limiting (Knighton 1984) and that straight channels rarely existed in nature for more than about 10 channel widths (Langbein and Leopold 1966). The modified continuum concept (Brakenridge 1985, Ashley *et al.* 1988) recognises that bedrock and alluvial systems exist as opposing ends of a large range of channel types, controlled by the balance between sediment supply and channel transport capacity. It may thus be applied directly to the Sabie River to infer long term patterns of channel change.

Channel types on the Sabie River have been identified and described based on their morphological components and include both bedrock and alluvial systems (chapter 3). Transition, or the switching between different fluvial states, is a function of the force:resistance balance (Richards 1982) and the variety of channel types observed on the Sabie River reflect the rapidly varying energy conditions that influence the system (Figs. 14a-d).

Observation of morphological change on the Sabie River, together with a recognition of the common principal channel types and the intermediate secondary channel states from the aerial photographic record, allows for tentative qualitative pathways of channel change to be proposed. The rational linkage of the various channel types as a continuum assumes that any change in channel state is the result of variation in the catchment control factors that alter the local balance between sediment inputs and channel transport capacity. The pathways suggested are as a result of progressive sedimentation, linked to vegetative feedback mechanisms within the confines of the Sabie River macro-channel boundary. The 1986 aerial photographs were investigated and potential pathways of change are suggested, based on the concept of 'space for time substitution'. This concept is in turn based on the assumption that if there is a continuum between channel types and sedimentation is known to be increasing in the Sabie River, then a study of channel sections of the same channel type at different stages on the continuum will reveal the likely evolutionary pathways.

Anastomosing sections have been identified on the Sabie River with varying degrees of bedrock influence (Fig. 51). These range from multiple channel sections dominated by bedrock both in the channel and on the interfluves, through increasing degrees of sedimentation on the interfluves, to sections with interfluves inundated with sediment and bedrock dominated distributaries with localised sedimentary deposits (Fig. 51). These observations then lead to the following proposed evolutionary pathways for bedrock anastomosing channel types.

Bedrock anastomosing channel types exhibit a sediment throughput potential greater than the supply and as such, display no alluvial features across the entire macro-channel. These sections are dominated by bedrock distributary channels and bedrock pavements. In other sections, flows that inundate areas away from the active channels display rapid energy dissipation and develop bedrock core bars through the deposition of sand and later finer sediments over bedrock (Figs. 51a and 52a). Deposition of still larger sedimentary deposits, as the result of very infrequent high magnitude flow events, has completely inundated bedrock anastomosing areas, including former bedrock distributaries (as inferred from the presence of mature *Breonadia salicina* which are known to establish in sediment-starved bedrock areas only). These large scale depositional units appear to have some relationship with the macro-channel planform, accumulating on the inside of bends and as islands and lateral bars. These former bedrock anastomosing sections are now transitional towards mixed pool-rapid sequences (Figs. 51b and 52b).

A second mechanism whereby bedrock areas evolve into alluvial systems occurs in lower gradient bedrock anastomosing areas. Deposition outside of the active channels occurs in the form of bedrock core bars. A reduction in the rivers efficiency to transport introduced sediment in the active channels, as a result of reduced flow magnitudes and/or an increase in the amount of sediment coming into the reach, results in the build-up of deposits in the active channels. Eventually, both the active channel and macro-channel bedrock exposures are covered to form a mixed anastomosing system. The active channels remain anastomosing between the vegetated bedrock core bars (Figs. 51c and 52c).

Sedimentation in pool-rapid channel types has also been inferred from the aerial photographs taken of the Sabie River. Aggradation appears to occur through the build up of coarse sand deposits in the form of mid-channel bars behind the rapid and lee bars downstream of the bedrock obstruction. Progressive sedimentation appears to result in the formation of lateral bars and the subsequent amalgamation of these with the mid-channel and lee bar deposits. Eventually, the influence of the bedrock rapid on channel flow becomes reduced as it is buried under progressively more sediment. In this way the bedrock influence on the channel is lost and an alluvial system begins to dominate (Figs. 53 and 54).

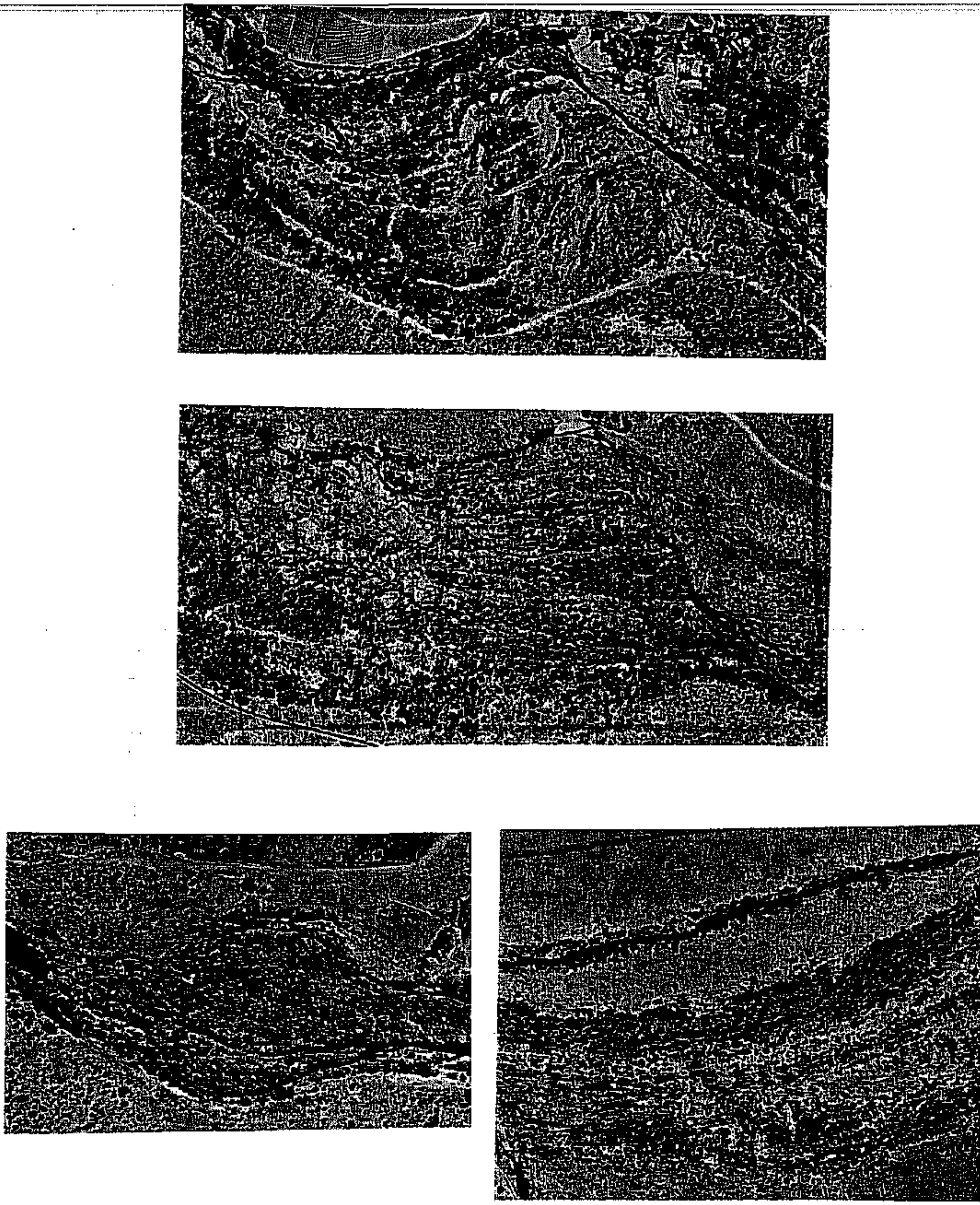


Figure 51. 'Space for time' evolution of a bedrock anastomosing channel type on the Sabie River in the Kruger National Park.

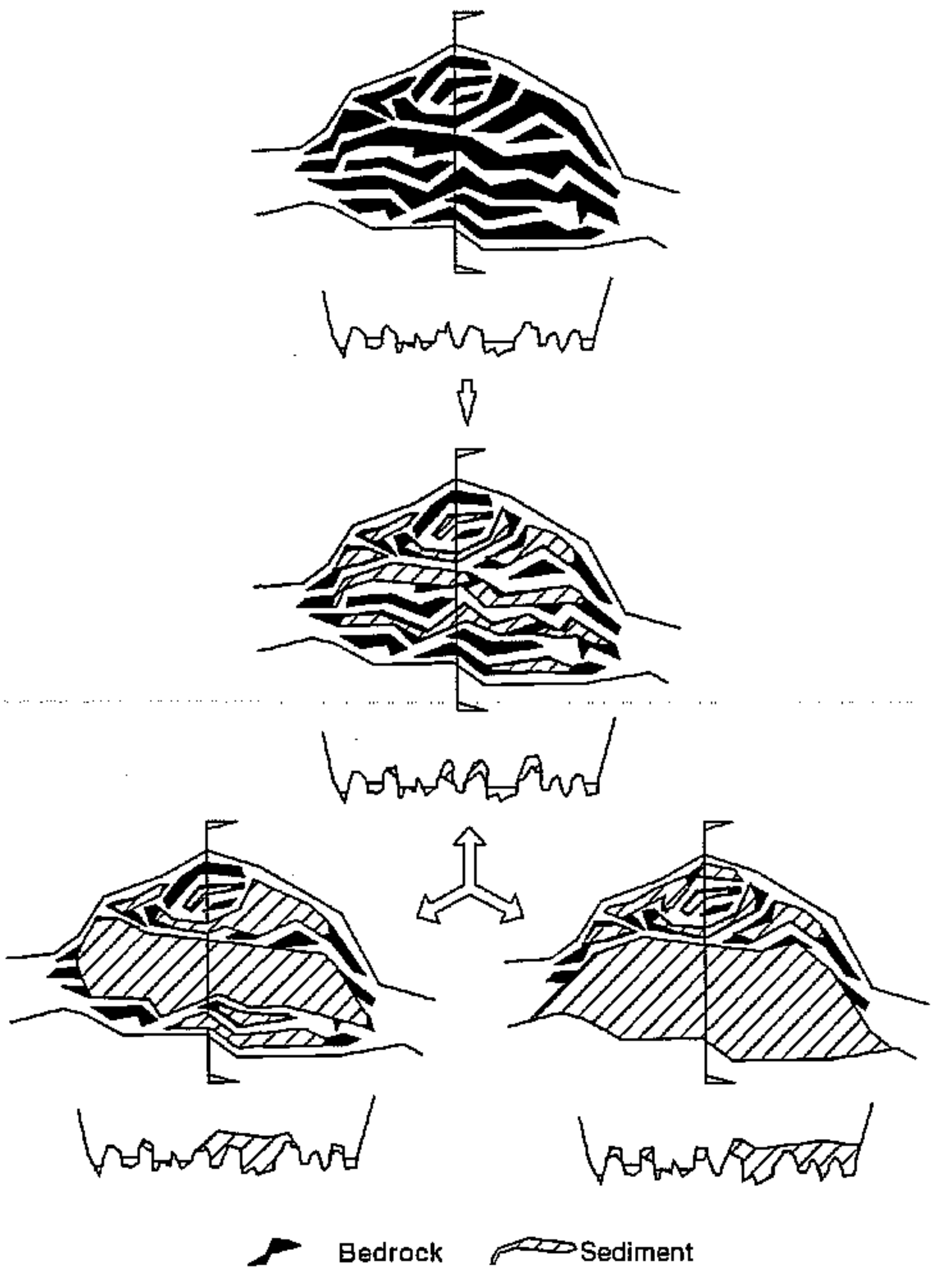


Figure 52. Inferred evolutionary pathway for a bedrock anastomosing channel type on the Sabie River in the Kruger National Park, given increased sedimentation.

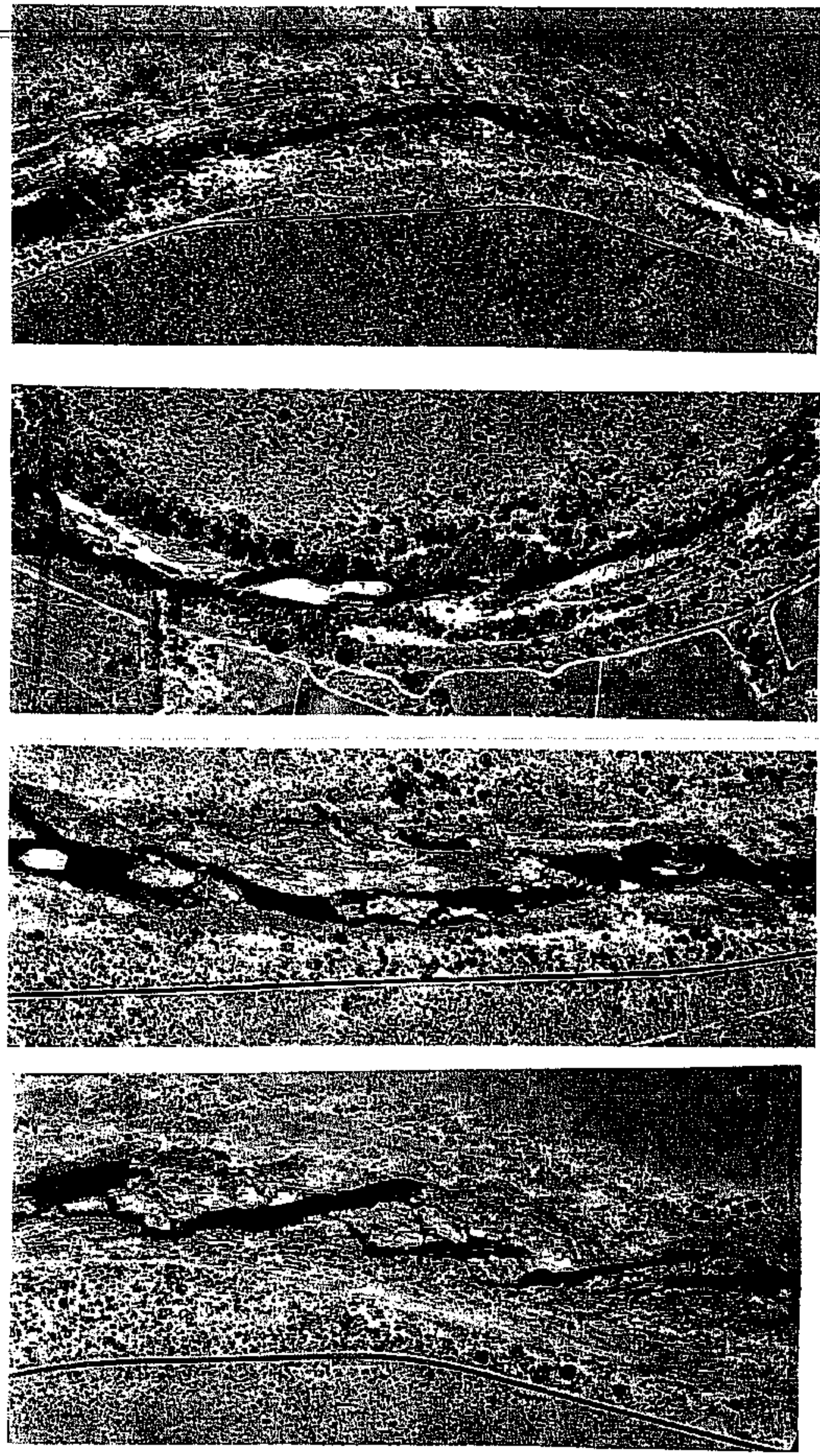


Figure 53. 'Space for time' evolution of a pool-rapid channel type on the Sabie River in the Kruger National Park.

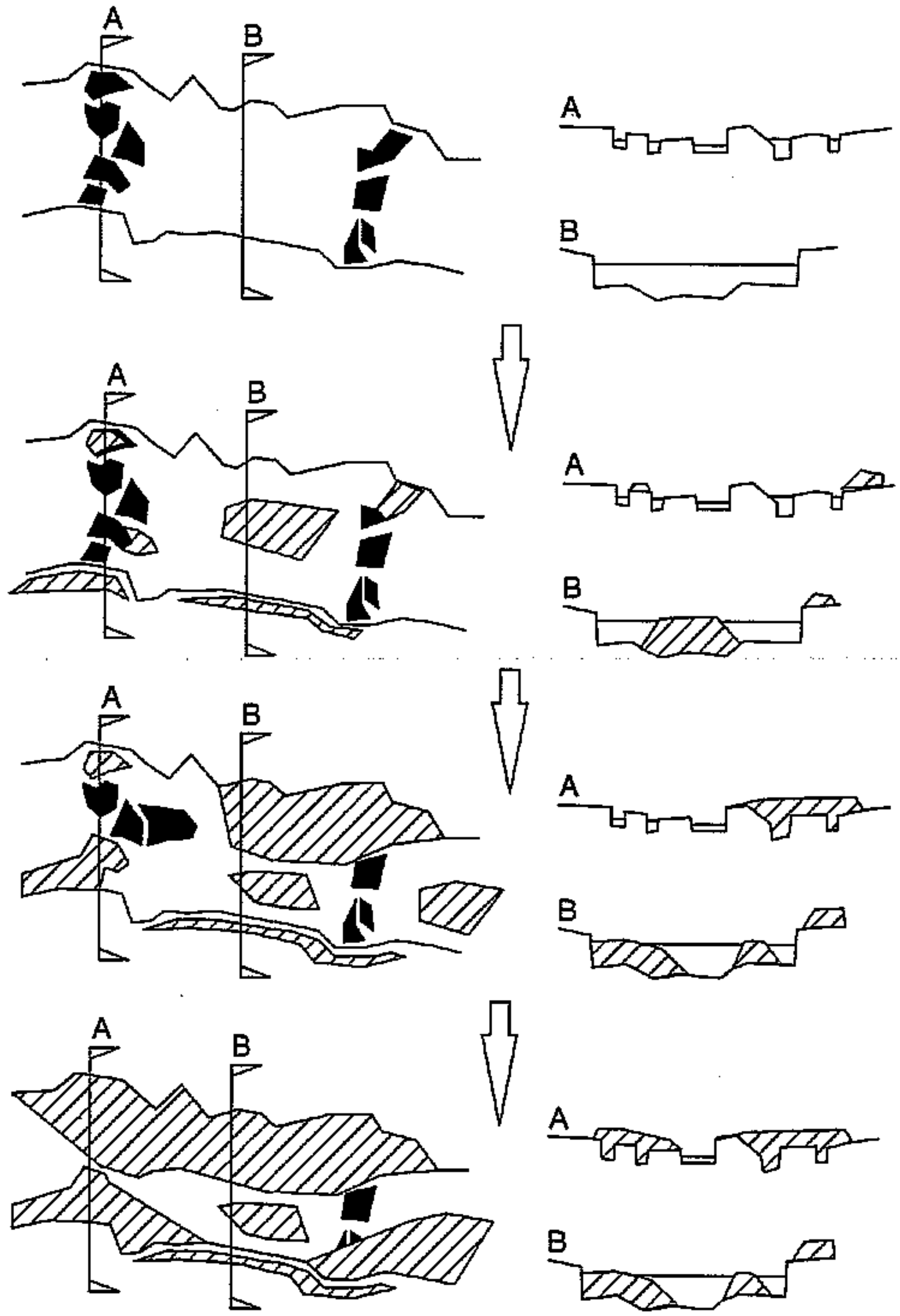


Figure 54. Inferred evolutionary pathway for a pool-rapid channel type on the Sabie River in the Kruger National Park, given increased sedimentation.

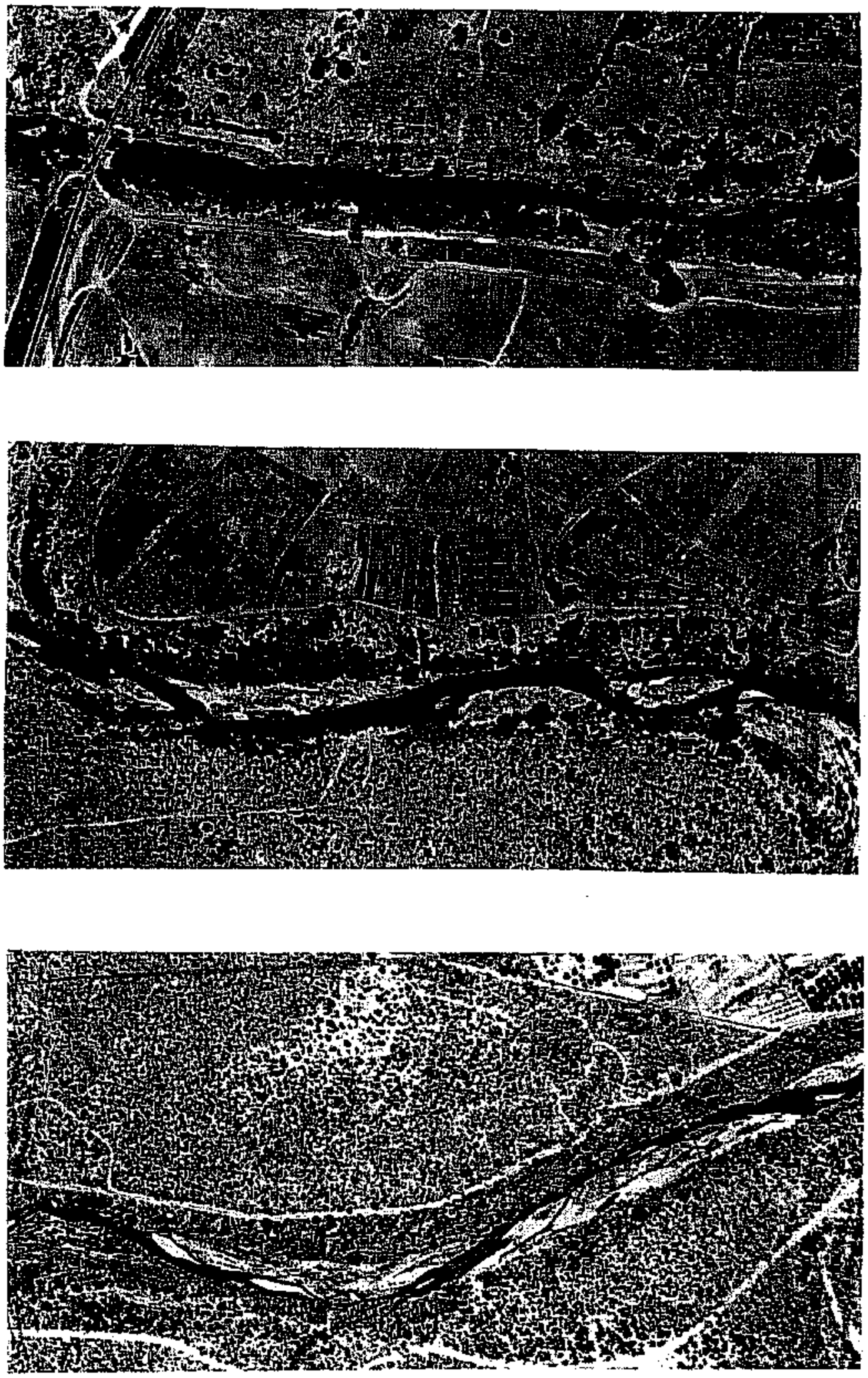


Figure 55. 'Space for time' evolution of an alluvial single thread and braided channel type on the Sabie River in the Kruger National Park.

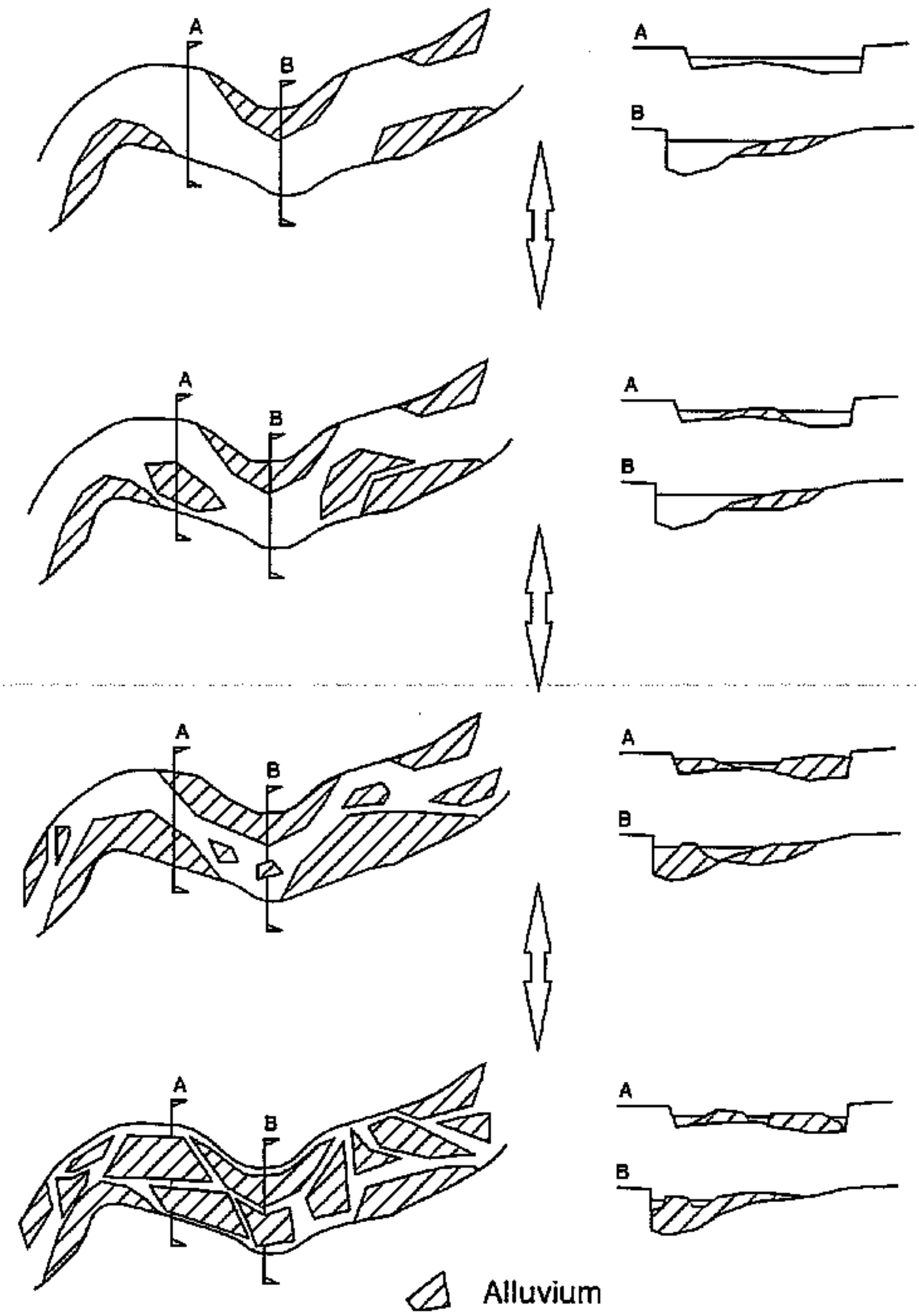


Figure 56. Inferred evolutionary pathway for alluvial single thread and braided channel types on the Sabie River in the Kruger National Park, given increased sedimentation.

Fully alluvial single thread or braided channel types are uncommon on the Sabie River. This suggests that the sediment delivery/channel transport capacity balance is generally dominated by transport factors. Where deposition has largely obliterated the influence of bedrock, single thread channels dominate. Lateral and alternate bar deposition has increased the active channel sinuosity and occasional mid-channel bar deposits have led to limited braiding (Figs. 55 and 56). Stabilisation of such sedimentary features has occurred due to vegetative growth during the drier periods of the climatic cycle, where flow magnitude and variability are reduced. Channel switching between braided and single thread appears to occur quite regularly, as it is noticeable on the decade scale of the 50 year aerial photographic record and may be a function of the climatic cycles identified for the region.

Pathways of channel change have been suggested. These changes may be gradual or catastrophic, due to the influence of one major flow or a series of minor ones. Large scale macro-channel sedimentary deposits that cause major changes of channel type operate on a long term punctuated time scale, whereas active channel deposits continuously respond to short term variations in the available energy within the system (chapter 6). Generally, observation has shown that change in channel state has occurred through the following ways:

<u>Pathway of channel type change</u>	<u>New morphological units</u>
Bedrock channel to Bedrock anastomosing	
	Primary: Macro-channel and seasonal sand sheets Macro-channel and seasonal bedrock core bars Secondary: Macro-channel, seasonal and active armoured areas
Bedrock anastomosing to Alluvial anastomosing	
	Primary: Macro-channel bedrock core bars Secondary: Macro-channel islands, macro-channel lateral bars, macro-channel point bars
Bedrock anastomosing to Pool-rapid	
	Primary: Macro-channel islands, macro-channel lateral bars, macro-channel point bars Secondary: Macro-channel bedrock core bars
Pool-rapid to Single thread	
	Primary: Seasonal bedrock core bars, active and seasonal bars Secondary: Seasonal levees

Single thread to
Braided

Primary:
Active and seasonal mid-channel bars

8.3 Summary

☺ Channel types on the Sabie River in the Kruger National Park are dynamic, with the perennial active channels responding to short term changes in catchment control variables by deposition or erosion of morphological units.

☺ Some channel types respond to changes in the control variables more readily than others. Pool-rapid and mixed anastomosing areas show a greater tendency to accumulate sediment than do bedrock anastomosing channel types. This conclusion supports the findings of the bulk sediment transport efficiency study in chapter 6, where the bedrock anastomosing channel type displayed a far greater potential transport capacity than any of the other channel types.

☺ Morphological units are continually being created and destroyed, the trend however, is for increased alluvial deposits within the river. This trend is as a result of lowering the transport efficiency in all the channel types except bedrock anastomosing, through reduction in the magnitude and duration of flows and an increase in the amount of sediment introduced to the river as a result of catchment degradation.

☺ Long term channel change can be inferred from a static picture of the river system using space for time substitution. This assumes that the range of channel types observed conforms to a continuum of channel types from bedrock to alluvial and that the degree of alluviation from the original bedrock state is defined by the local ability of the river to transport incoming sediment.

☺ Aerial photographic evidence is presented of successive stages of alluviation, from the base state bedrock anastomosing channel type, through mixed anastomosing to alluvial anastomosing and mixed pool-rapid channel types. Similar evidence is presented for the transition between bedrock pool-rapid, mixed pool-rapid and mixed single thread. An oscillatory mechanism is proposed between mixed single thread, alluvial single thread and braided channel types. Of these pathways only the final example can be seen to have occurred from the 50 year photographic record.

☺ Short term change appears to be restricted to oscillatory changes of sedimentary units within the active channels. Long term change appears to be pulsed in nature and is a function of sediment inputs and losses, as a result of infrequent high magnitude flow events.

☺ The evidence of channel change, whether observed or inferred, provides the qualitative knowledge of how the Sabie River functions geomorphologically. It provides pathways of change in response to sedimentation and applies timescales to these changes. This information has proved invaluable in formulating and validating the quantitative modelling techniques presented in the following chapter.

9. QUANTITATIVE MODELLING

The ultimate aim of this study was to develop the capacity to predict channel response to changing catchment controls. The results of three quantitative studies are presented in this chapter, namely:

1. **The return period study:** results predict the probability of occurrence of geomorphologically significant flow events and attaches a timescale to them in terms of frequency of occurrence.
2. **The regional hydraulic study:** results predict regional scale (whole river) sediment transport potential and generate a picture of sediment sinks along the river.
3. **A semi-quantitative model:** this model predicts bulk sedimentation change at the scale of channel type, based on daily flow records, local channel competence and lateral inputs. The semi-quantitative model presented in this chapter predicts channel change at the scale of channel type for any flow and sediment input scenario and can be used for effectively managing the water resources of the Sabie River, in order to reduce the impact on the riparian environment.

The three approaches outlined above were chosen in preference to detailed hydrodynamic and sediment transport modelling (for example MOBED), since such an approach is of limited use on the Sabie River at present. The principal reasoning behind this decision is that the data required to run such models effectively are not yet available. Also, the assumptions inherent in current quantitative channel change models render them inappropriate, as they were developed for temperate alluvial systems. At best they can provide only a whole river picture of likely channel response for the Sabie, similar to the simpler regional approach outlined above.

The three approaches outlined above represent various levels of semi-quantitative modelling of the Sabie River which may be achieved using statistical and mathematical analysis:

Statistical approaches:

- Potential for geomorphological change at the scale of a morphological unit may be predicted using the local hydraulic and hydrologic data. The relative elevations of individual morphological units across each cross-section may be related directly to a discharge using the local hydraulics tables generated in chapter 7. This flow can then be related to a frequency of occurrence, using the discharge-return period data generated in chapter 5. Hence, the temporal potential for flow influence can be defined and used to infer timescales of probable change to individual morphological units.

Mathematical approaches:

- Gross areas of a similar geomorphological nature can be predicted using the spatially extensive network of data collection sites and the hydrodynamic theory outlined in chapter 7.
- Semi-quantitative models of channel change at the scale of channel type can be developed utilising the river structuring procedure (chapter 3), the conceptual channel change model

(chapter 4), local channel change evidence (chapter 8) and local hydraulics and hydrodynamics (chapter 7).

Both the statistical and mathematical approaches are described below, together with details of their predictive capabilities.

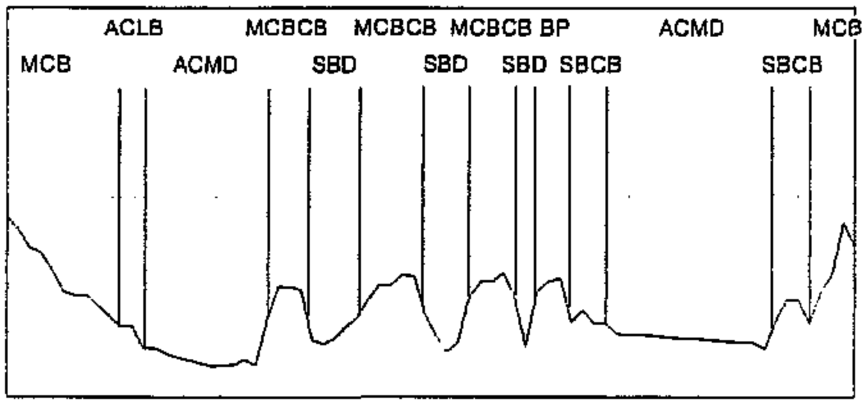
9.1 Return period and frequency of flow influence for individual morphological units

The influence of flow regime on the form of a river channel has been widely investigated on a variety of rivers. Studies on alluvial rivers in Europe and America have shown significant relationships between channel geometry and dominant or channel-forming flows (Wolman and Leopold 1957, Hey 1975, Andrews 1980). Although they noted some scatter in the data, it was possible to isolate a dominant flow which corresponded to the flow doing most work in shaping the channel. This flow corresponded to the bankfull condition in rivers that were in regime (stable and not displaying any tendency to erode or deposit material) and had a return period of between 1.5 and 2 years on the annual maximum series. Recent research conducted on semi-arid rivers, which exhibit a markedly different flow regime from the relatively invariant temperate alluvial systems, has shown that the concept of a single channel-forming or bankfull flow cannot be validated. Graf (1988) notes a tripartite division of morphological units which are influenced by different components of the flow regime. Similarly, Wohl (1992) found that the fluvial forms of the bedrock influenced Burdekin River, Australia, were also influenced, in terms of flooding and sediment transport, by a range of flows.

It would appear that semi-arid and bedrock influenced river systems are composed of a series of morphological units on different spatial scales. Smaller units may be overtopped and thus influenced by the processes operating at the lowest flows. Larger sedimentary units form but these are covered, and thus influenced only, by flows in the range of the annual flood. Finally, very large sedimentary features are changed morphologically only as a result of very infrequent, extremely large flood events. Thus a range of flows are important in maintaining the geomorphological diversity of such river systems. The influence of the various discharges that make up the flow regime of the Sabie River are considered below.

The morphological units of 24 cross-sections were mapped and local stage-discharge relationships constructed from an extensive flow monitoring field programme. Inundation discharges were then attributed to the morphological units present at each section and these were related to the probability of occurrence for each flow. This allowed evaluation of the frequency of flooding of each unit type, based on annual maximum and daily average flow data presented in chapter 5. The annual maximum data was utilised to determine the maximum flood flow for each year of record at the Perry's Farm gauging station and these were ranked using the Weibull formulae (equations 1 and 2) to generate the annual probability of occurrence for a given flood flow. Daily average flows from the same gauging station were ranked in the same manner to generate the daily probability of occurrence series, used to describe channel activation, channel overtopping and bar inundation.

The data were analysed according to whether they were channel features or bar features and these were in turn categorised into active, seasonal and macro-channel features, depending on their size and elevation relative to the cross-section (Fig. 57). Frequency of inundation figures were calculated for the sedimentary bar, terrace and island features; the results represent the probable number of times that each individual feature can be covered and thus influenced by flowing water. In addition, the frequency with which water flows through a channel or becomes activated, together with the frequency of overtopping (where the volume of water exceeds the capacity of the channel: analogous to the bankfull state in alluvial systems) was determined. The figures stated represent statistical averages. A system may be said to flow for 7 days in a year, but these 7 days of flow may not be consecutive.



	MCB	ACLB	ACMD	MCBCB	SBD	MCBCB	SBD	MCBCB	SBD	BP	SBCB	ACMD	SBCB	MCB
Q	1550	45	24	340	210	350	170	430	210	360	156	57	130	1600
FI%	.001	1.1	4.8	.02	.07	.02	.09	.01	.07	.02	.11	.8	.15	.001

MCB: Macro-channel bank, ACLB: Active channel lateral bar, ACMD: Active channel mixed distributary, MCBCB: Macro-channel bedrock core bar, SBD: Seasonal bedrock distributary, BP: Bedrock pavement, SBCB: Seasonal bedrock core bar.

Q - Innundation discharge ($m^3.s^{-1}$). FI% - Frequency of innundation (% time)

Figure 57. Example cross-section displaying morphological unit distribution and frequency of inundation figures.

Channel activation

Using the annual maximum flood frequency series derived from data at Perry's Farm gauging station, water flows in all of the active channels as a result of the annual flood. Seasonal channels are generally activated by a 1-1.3yr flood, but this may extend to 1.5yrs in a few cases. The majority of the macro-channel distributaries flow as a result of a 2-4yr flood, in rarer cases this extends to a 6yr flood (Fig. 58). On a daily average flow basis, also derived from the Perry's

Farm daily flow data, all of the active channels flow every day of the year. Seasonal channels flowed on average for a few days to a few weeks every year, although in rarer cases the model predicted flows for 3 to 4 months of the year. Macro-channel distributaries flowed for less than 1 day a year (Fig. 59).

Channel overtopping

The active channels in the Sabie River are overtopped by 1-2yr floods. This coincides with the findings of Wolman and Leopold (1957) for perennial temperate alluvial rivers. There is, however, a wide scatter within the data, with some channels, classified as active, overtopped only by flows in excess of the 3yr flood. Seasonal channel overtopping displays even greater variation; most cluster around the 1-2yr return period flood, but the range extends up to 5 years. The macro-channel distributaries overtop on average once every 2 to 6 years, but in some cases flooding is restricted to once every 13 years (Fig. 60). Overtopping of the active channels takes place for about 2 weeks a year on average, but there is a wide scatter in the data. In general, seasonal channels overtop for about 7 days a year, but this may extend to 14 days in some cases. Macro-channel features flood only rarely for a day every 2 to 3 years (Fig. 61).

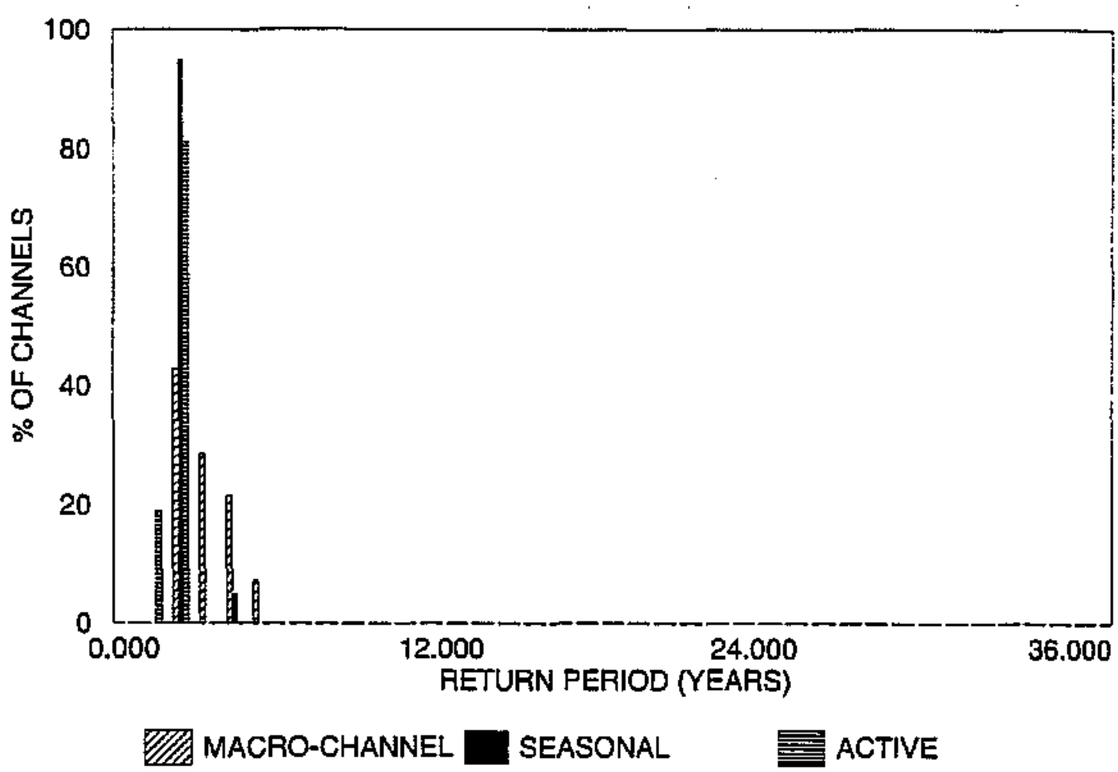


Figure 58. Frequency of channel activation based on the annual maximum flow series return period (after Heritage *et al.* 1995).

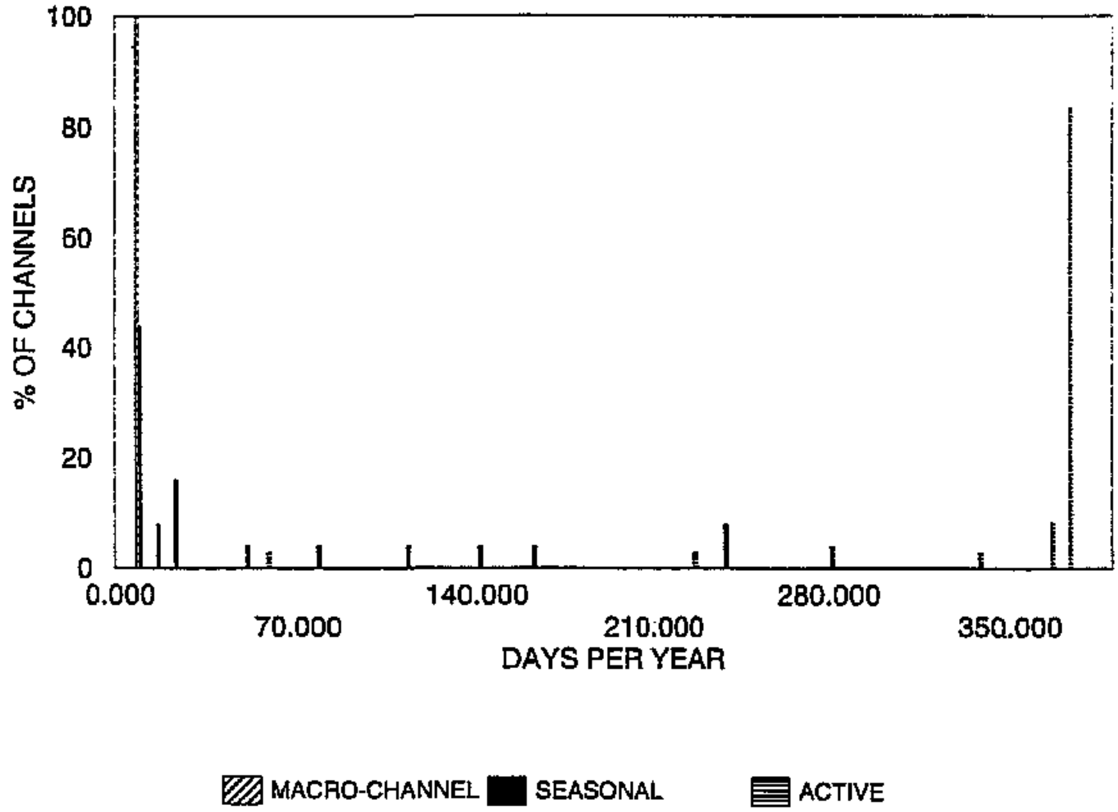


Figure 59. Frequency of channel activation based on the daily average flow series return period (after Heritage *et al.* 1995).

Sedimentary feature inundation

The sedimentary features within the Sabie River were investigated for their average inundation frequency. Defining the surface height of such features was often problematic, due to their undulating nature. The average surface height was taken to be the flattest plane over the whole sedimentary unit. Bars associated with the active channels were inundated by the 1-2yr flood on average and a few of the larger features were covered only by the 3 year flood. Seasonal sedimentary units were submerged by the 1-3yr flood, ranging up to the 5-7yr flood in a few cases. Macro-channel bars, terraces and islands were inundated only by the 3-6yr flood and in very rare cases submergence occurred on average once in 18 years (Fig. 62). Active channel sedimentary deposits are in contact with the flow all year. Inundation of the average bar surface is generally achieved by the wet season flows. Most seasonal features are covered for less than 15 days in an average year, although a few are affected for up to 80 days. Macro-channel deposits are inundated on an extremely infrequent basis (Fig. 63).

Morphological units can be divided into two categories: active features and seasonal/macro-channel features. Active channel units are influenced by the annual maximum flood and the majority display flow every day of the year. In contrast, seasonal and macro-channel features are influenced only by floods in excess of the 3 to 4 year return period and are seen to flow very rarely on a daily basis (Table 18).

Table 18. The influence of contemporary flows on the geomorphology of the Sabie River.

Flow category		Hydrological character of Sabie River morphological units: Annual maximum flow data (years)			Daily average flow data (days)		
		Channels		Bars	Channels		Bars
		Activation	Over-topping	Inundation	Activation	Over-topping	Inundation
Active	Mean Range	1	1-2	1-2 <3	Always	1-14 14-365	>350 250+
Seasonal	Mean Range	1-3	1-2 <5	1-3 5-7	1-14 100-150	1-7 7-14	<15 <80
Macro-channel	Mean Range	2-4 <6	2-6 <13	3-6 <18	<1	<<1	<<1

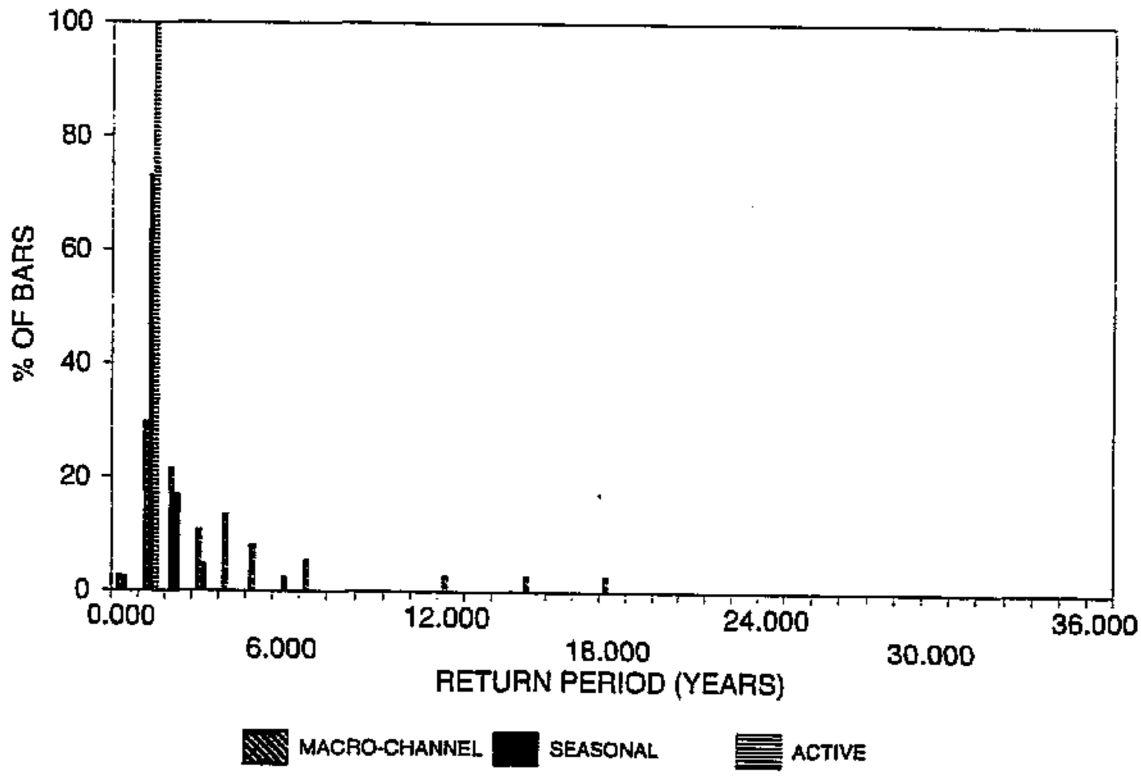


Figure 60. Frequency of channel overtopping based on the annual maximum flow series return period (after Heritage *et al.* 1995).

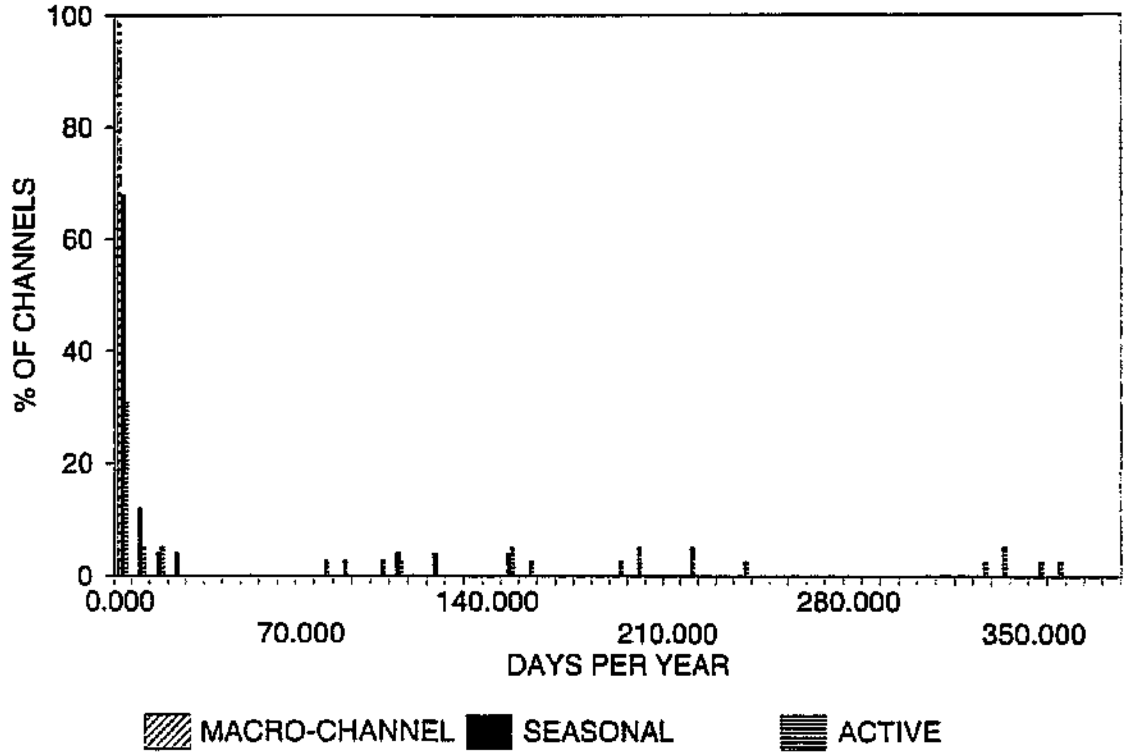


Figure 61. Frequency of channel overtopping based on the daily average flow series return period (after Heritage *et al.* 1995).

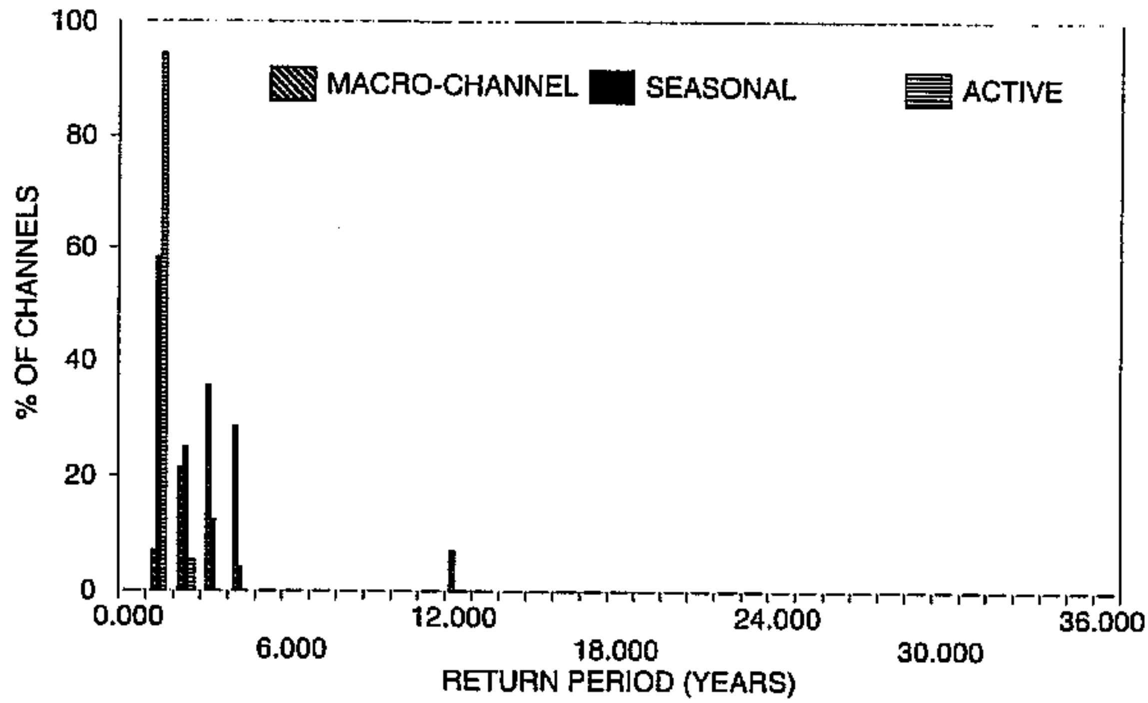


Figure 62. Frequency of bar inundation based on the annual maximum flow series return period (after Heritage *et al.* 1995).

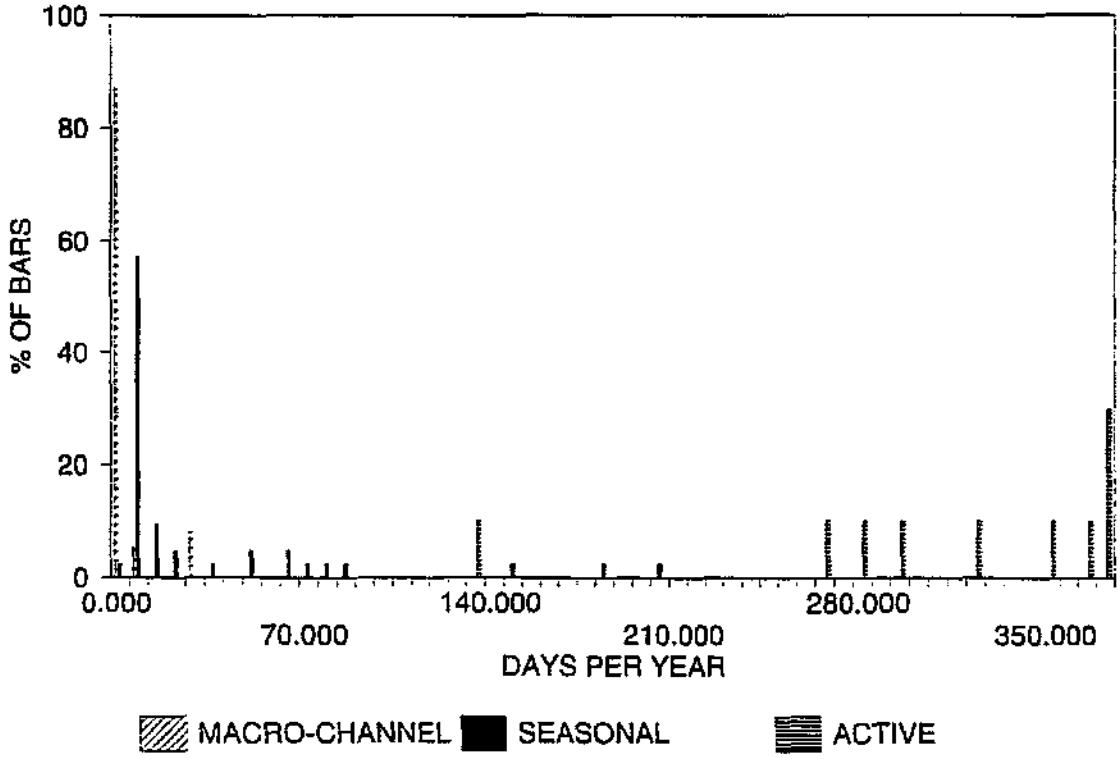


Figure 63. Frequency of bar inundation based on the daily average flow series return period (after Heritage *et al.* 1995).

No single common overtopping or 'channel forming' return period could be identified for the range of alluvial channels present in the Sabie River, although the active channels displayed annual maximum return periods for overtopping between 1 and 2 years. It is suggested that this may be a function of disequilibrium conditions within the Sabie River, where the morphological units may not have fully adjusted their morphology to the present flow regime and the influence of bedrock on the system. In contrast, the range of morphological units present experience the influence of flowing water across a very wide range of discharges (Table 18). Such findings are in general agreement with those of Graf (1988) and Wohl (1992), which were discussed earlier, indicating that semi-arid bedrock influenced rivers, such as the Sabie, respond to very different parts of the flow regime than do temperate alluvial rivers, with the geomorphologically important flows being defined by the size of geomorphological feature present.

Such conclusions on the effectiveness of a variety of flows on the geomorphology of the Sabie River have important implications for management. Many of the larger scale sedimentary features that have developed within the macro-channel are influenced only by very high magnitude low frequency flood events and as such are unlikely to be modified by anthropogenic influences in the catchment. It is the perennial and seasonally active channel features that will be most affected by alterations to the lower end of the flow regime and attention should be concentrated on these units to gain a greater understanding of their dynamics and ecological significance.

It must be stressed that the results of this study are preliminary and refinement of the results is anticipated. The assumption of a horizontal water surface slope across the macro-channel has been shown to be inapplicable in bedrock dominated areas and research is underway to address this problem in terms of detailed investigations into the dynamics of individual bedrock distributaries and the mechanisms by which they interact (Broadhurst *et al.* 1995). Also, the substitution of simulated daily runoff data in place of the extended weir flow data set should improve the accuracy of the hydrological information.

9.2 Long-stream channel sedimentation patterns

Areas susceptible to long term gross erosion and sedimentation can be identified simply by quantifying the change in channel competence along the river. Channel competence provides a measure of the rivers ability to transport sediment downstream. This index varies as a function of local channel parameters and the pattern of variability can be used to predict localised areas of erosion and deposition (chapter 8). Geometric and sedimentological data has been collected at 24 sites along the Sabie River and local hydraulic conditions have been modelled using backwater techniques. These data have been used to calculate the total sediment transport rate for each site using the sediment transport equation of Ackers and White (1973) (see chapter 7).

The results reveal a complex pattern of high and low competence along the river. Parallel studies of accumulated sediment depth from physical probing and aerial photographic identification of recent sediment accumulation areas (Fig. 64) have revealed relatively high sediment accumulations in areas of low competence and relatively low sediment accumulations in areas of high competence.

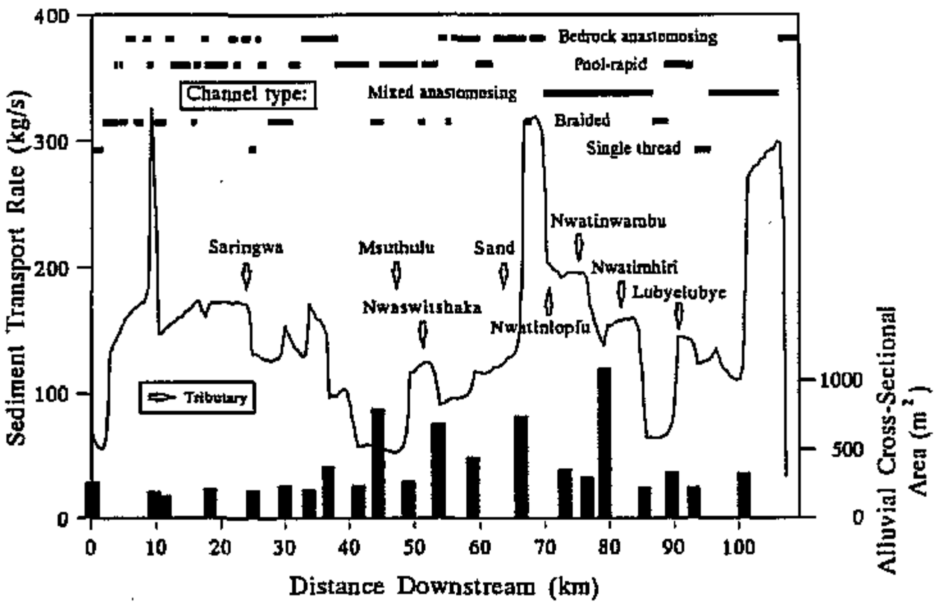


Figure 64. Regional in-channel sediment accumulation areas in the Sabie River in the Kruger National Park.

The high longitudinal variability, and the large numbers of bedrock controls, render application of traditional hydraulic and sediment routing models to the Sabie logistically prohibitive, since large datasets would be required. Cross-sectional and flow data would have to be collected at each rock outcrop, as would information on change in channel gradient and width and channel split or join. In multiple channel reaches, estimates of the proportion of the total discharge carried by each active channel would be required and the individual active channels would have to be modelled separately. The limits imposed by the available cross-sectional and flow data, coupled with difficulties involved in calibrating the step backwaters model, limited the use of sediment and flow routing models to providing semi-quantitative information for explaining coarse scale, long-term sedimentation patterns. Alternative methods were therefore required for predicting geomorphological change on the Sabie River, leading to the development of a nested hierarchy of models, ranging from models for the dynamics of individual channel types, through to a model for the length of the Sabie River in the Kruger National Park. Predictions of change at the morphological unit scale are qualitative and based on the understanding of the directions and types of change which occur in the different channel types.

9.3 Semi-quantitative modelling

Complex systems are difficult to model routinely using physically based models and data to support them are seldom available (Starfield *et al.* 1993). Approaches need to be adopted whereby potential implications inherent in a qualitative understanding can be explored, qualified and quantified (Starfield *et al.* 1993). Given the complexities of the Sabie River system, the data limitations and the impracticalities in acquiring appropriate data, it was realised that any benefit gained from a physical simulation of the system dynamics would be lost in the uncertainty and complexity of such an approach. A simplified approach was adopted in which the dynamics of individual channel types were modelled based on available theory and data. Interactions between adjacent channel type sections were based on simple rules (conservation of mass in this case). The advantages of this approach are:

1. Rapid assessments of the effects of different flow and sediment regimes (in terms of directions and rates of change) are possible despite the limitations in available data and existing theory.
2. Further refinement to models for the different channel types may be incorporated if deemed necessary and as additional data are made available.
3. The simple model can be used to drive future research and highlight areas where more complex models are required.

The conceptual model (Fig. 23) has been used as the basic predictive tool to define states and potential changes in state, in response to changes in catchment control variables (in particular, flow and sediment regimes) on the Sabie River. For example, a mixed sinuous single thread channel (Fig. 23) may change to either mixed pool-rapid, mixed braided or an alluvial sinuous single thread channel. The conceptual model may be tested, refined and the controlling variables (flow magnitude (QMAG), flow variability (QVAR), sediment production (SEDI) and local channel transport capacity (COMP)), quantified through studies of processes. Further understanding of the relationship between changes of state and the controlling variables has been gained through mathematical simulation.

The four catchment control variables (QMAG, QVAR, SEDI and COMP) can be quantified given the results of the data acquisition programme (chapters 5 to 7). A channel section has quantifiable lateral and upstream sediment inputs (SEDI) and a given sediment transport capacity for a given discharge. The probability of the occurrence of that discharge, multiplied by the transport capacity, provides the total mass of sediment which can be transported through the section over a period of time (COMP). Applying this concept over the whole of the flow regime (QMAG and QVAR) provides a distribution of the bulk sediment transport (Fig. 65). Integration under the sediment mass:discharge curve between two discharges then yields the total mass transport capacity over that range (Wolman and Miller 1960).

Consider the hypothetical case of five linked channel sections with different gross sediment transport capacities responses (COMP) (A, Fig. 65) with respect to different components of the flow regime (QMAG and QVAR). Sediment input to each of the channels (SEDI) comprises two components: 1) the lateral component from tributaries and erosion from the surrounding land (B, Fig. 65). and 2) the upstream component (C, Fig. 65), which is a function of the total sediment mass which can be transported by the upstream channel section. Assuming that the lateral sediment inputs to the channel sections are constant through time (B, Fig. 65), the capacity to transport sediment from upstream is reduced (D, Fig. 65). Any portion of the flow regime for which SEDI exceeds COMP results in sediment accumulation (E, Fig. 65) within the section, and when COMP exceeds SEDI, erosion occurs (F, Fig. 65).

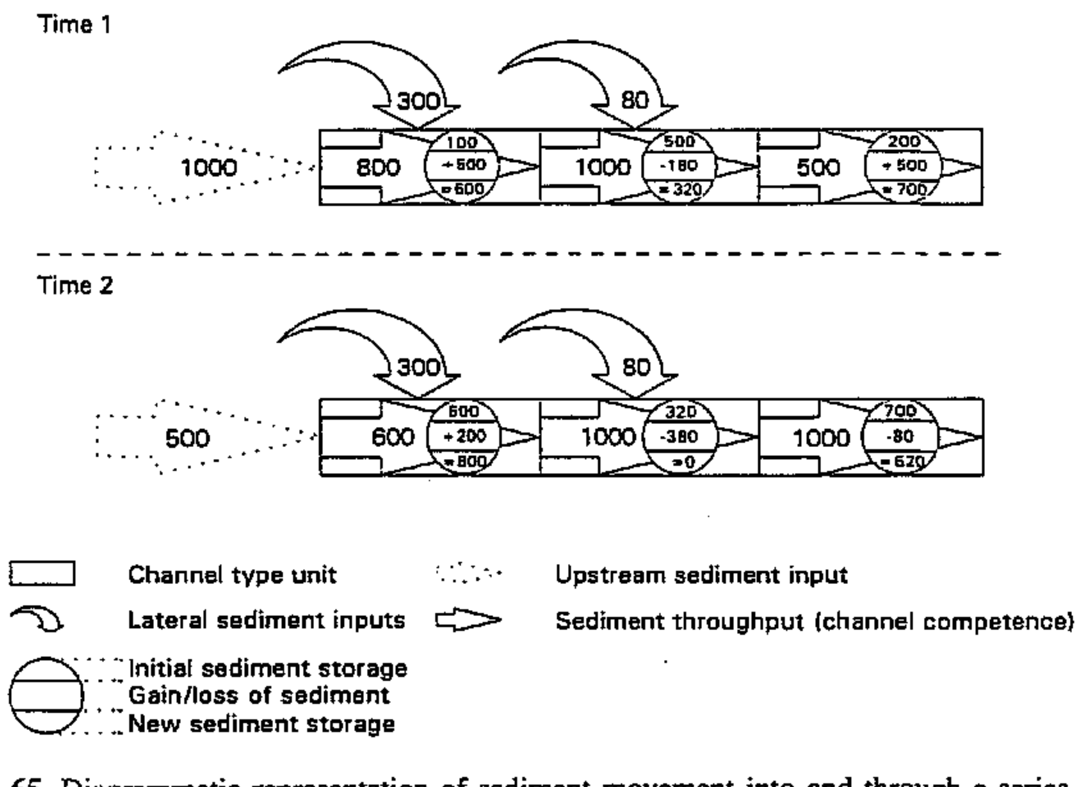


Figure 65. Diagrammatic representation of sediment movement into and through a series of spatially linked channel types.

In the case of no upstream sediment input to section 1 (for example, downstream of a dam) the excess sediment transport capacity results in erosion (Fig. 65). All of the material which can be transported through section 1 for different parts of the flow regime (skewed towards the lower flow) is passed through to section 2. Section 2 has a low excess transport capacity during low flows and a high transport capacity during intermediate flows. Thus, deposition occurs during the low flows, during which sediment input exceeds the transport capacity and erosion occurs during the intermediate flows, during which transport capacity exceeds input. The overall result is a net sediment gain in section 2. Application of this procedure through all of the linked reaches indicates which sections are susceptible to erosion or deposition for a given flow regime and the range of discharges which are significant.

Based on the above, details of the hydraulics and sediment dynamics of the Sabie River channel types were used to construct a model of sediment movement between linked channel types (Fig. 66). The ability of the river to transport sediment was evaluated for each consecutive channel type along the river, based on sediment inputs from the channel type immediately upstream and lateral inputs from the catchment. Excess inputs which exceeded the local transport capacity (chapter 7) were deposited and where the transport capacity exceeded the combined upstream and lateral sediment inputs, erosion of previously deposited material was possible (Fig. 66). The model routes daily flows through a series of channel types and generates annual bulk sediment volume change at the scale of channel type for any daily flow time series. Any period of a day or greater may be considered and the consequences of sedimentation downstream through each channel type evaluated.

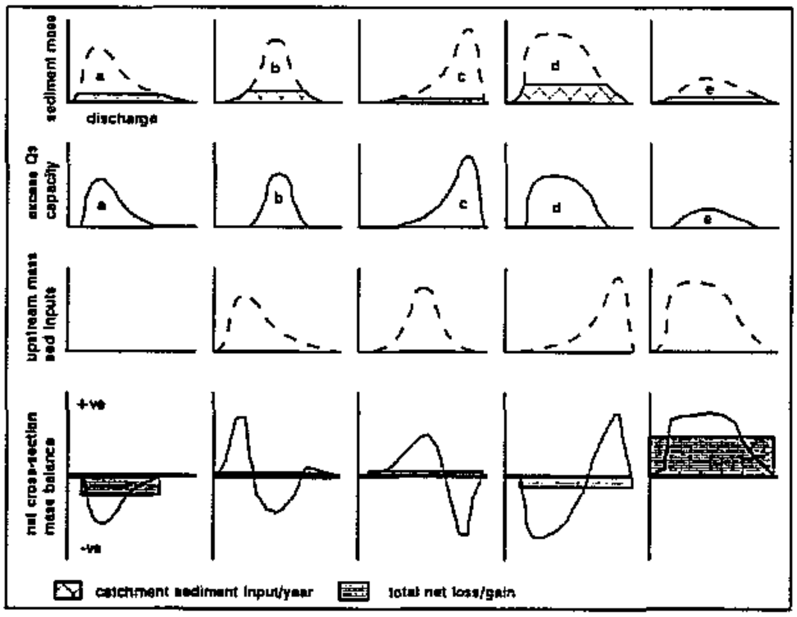


Figure 66. Diagrammatic representation of the semi-quantitative model developed to predict channel change on the Sabie River in the Kruger National Park.

The wet, dry and total average daily discharge time series were used to calculate average annual potential sediment transport volumes at all sites using the total load equation of Ackers and White (1973). The model (Figs. 65 and 66) was then used to investigate potential changes to a reach with linked pool-rapid and mixed anastomosing channel types, for which a series of annual aerial photographs exists (1986 to 1992). The hydrodynamic characteristics of the two channel types were simulated using representative pool-rapid and mixed anastomosing sections.

Cumulative average annual sediment transport volumes (Fig. 67) were calculated for the periods 1986 to 1989 (representing a wet spell) and 1990 to 1992 (representing a dry spell), using the recorded average daily discharges. Ignoring lateral sediment inputs, the total annual sediment delivery into the mixed anastomosing channel from the upstream pool-rapid channel from 1986 to 1989 is less than the potential annual transport capacity of the mixed anastomosing channel (Fig. 67). Therefore, some scour is expected in the mixed anastomosing channel. Sediment accumulates in the mixed anastomosing channel over the range of discharges up to $45m^3s^{-1}$ (the cumulative sediment transport curve is steeper for the pool-rapid channel than for the mixed anastomosing channel). Erosion occurs for the higher discharges, where the mixed anastomosing curve is steeper.

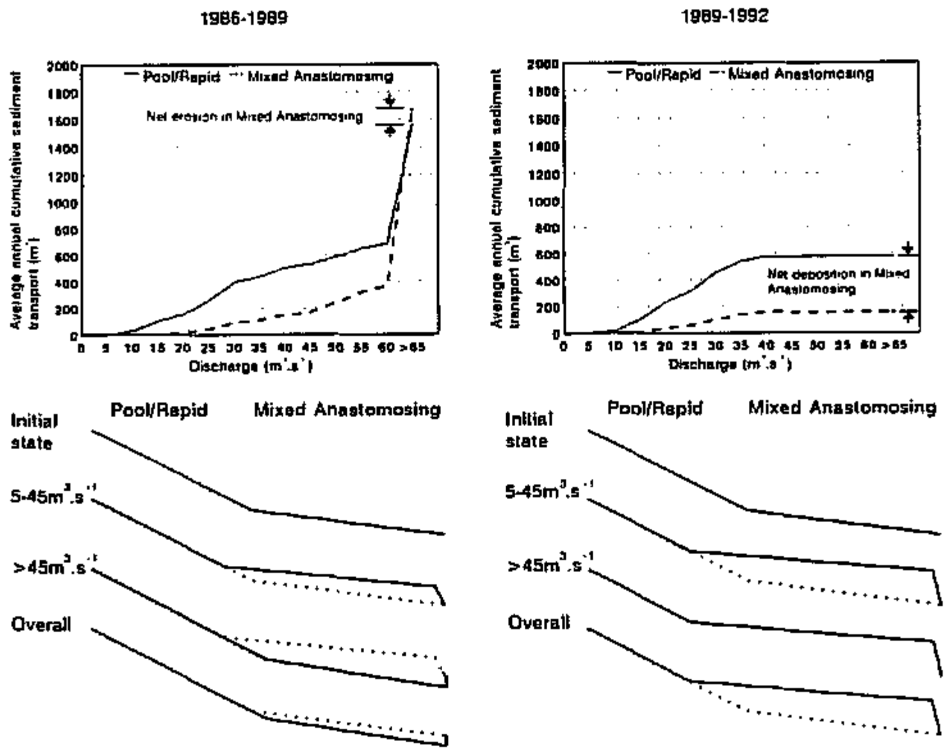


Figure 67. Results of modelling channel change for a pool-rapid mixed anastomosing combination of channel types for the flow period 1986-1989 and 1989-1992.

During the period 1989 to 1992, no flows above $40m^3s^{-1}$ were recorded and the average annual cumulative sediment transport rates for both channels remain constant above this discharge. The modelled result for this period is an accumulation of sediment in the mixed anastomosing channel, since the cumulative sediment input from the upstream pool-rapid channel is higher than the potential transport capacity of the mixed anastomosing channel (Fig. 67). Modelled results compare favourably with observations from the aerial photographs for these periods. The photographs show that the downstream mixed anastomosing section remained stable from 1986 to 1989, but showed distinct sediment accumulations in the form of lateral bars from 1989 to 1992.

In order to test application of the model over the total length of the Sabie River in the Kruger National Park, it was necessary to link all of the channel type sections along the river and to quantify lateral sediment inputs at tributary junctions.

9.3.1 Linking of channel type sections

The classification resulted in identification of 46 channel type sections along the length of the river. Sediment movement through the system is modelled by considering the existing spatial arrangement of the channel types and transporting sediment through the upstream channel type and into the next downstream one, based on the transport capacity of the individual channel types. A mass balance for each channel type section along the river is calculated based on upstream and lateral inputs and sediment availability in the channel type section, to determine net erosion or deposition for each time step.

9.3.2 Assessment of lateral sediment inputs

The map of sub-catchments, incorporating minor tributaries along the length of the Sabie River in the Lowveld (Fig. 68), was overlain on the map of maximum potential sediment yields (Fig. 33) in order to determine maximum total annual average sediment input volumes at tributary junctions. Clearly, the average annual lateral sediment inputs from tributaries calculated in this manner will not be a true reflection of actual annual tributary input volumes and will not reflect the true temporal distribution of these inputs. This is due to some of the sediment produced on the sub-catchments being stored in the sub-catchment and in the upstream tributary reaches (particularly in the Sand River which has a number of small tributaries and has a large catchment area), and the fact that the tributaries are ephemeral and contribute sediment only during high magnitude rainfall events in the appropriate sub-catchments. Averaged over long periods, however, the estimates become more realistic.

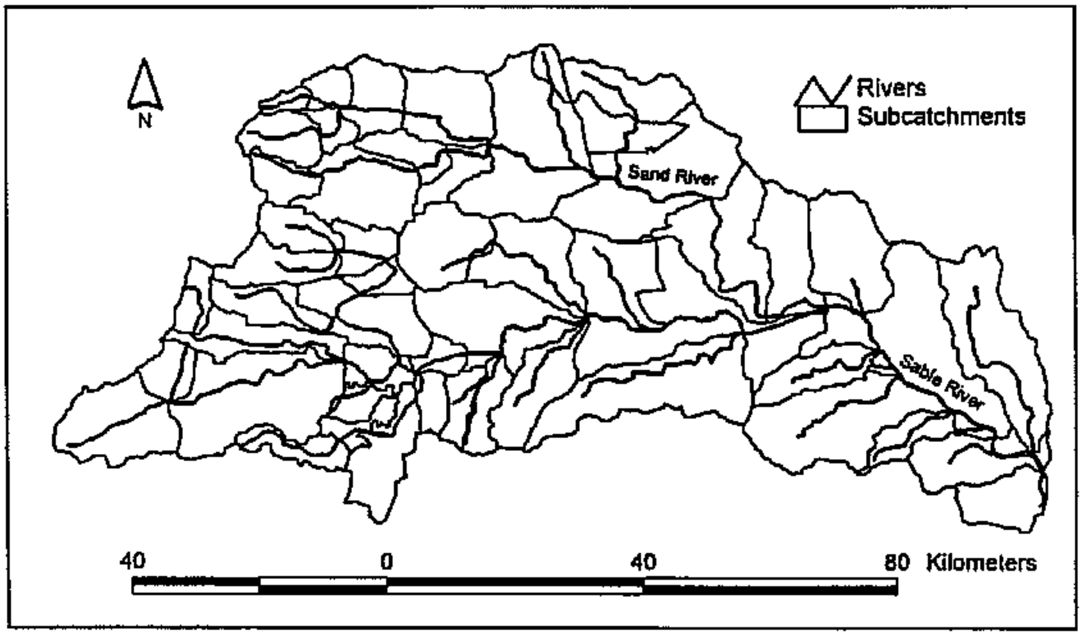


Figure 68. Sub-catchment sediment input contributing areas for the Sabie River.

9.3.3 The Sabie River sediment flux model

The 34 year daily discharge record was used to calculate daily sediment transport capacity for a range of particle sizes at each of the 24 cross-sections along the length of the Sabie in the Kruger National Park. The daily sediment transport capacities were summed for each year to provide the total annual sediment transport capacity for each year from 1959 to 1993. Total annual sediment transport capacities were assigned to channel type sections where these data were not available (since not all of the 46 channel type sections could be surveyed), by assuming that they had similar sediment transport characteristics to those of the same channel type, where data were available. This assumption is reasonable since the semi-quantitative modelling is used to provide a qualitative understanding of sediment dynamics along the Sabie River. The sediment dynamics within the same channel type are expected to be similar, resulting in similar patterns of accumulation.

Transport capacity calculations for different size fractions (Table 19) showed extremely high values for the silt fraction (< 0.02mm) for all channel type sections along the Sabie River when compared to the 0.5mm and 1mm sizes. The differences (amounting to several orders of magnitude) indicate that this former fraction would be transported through the system. Some silt has, however, been observed in the field, deposited outside of the active channels during the falling limb of a flood wave. Sediment sampling has shown 0.5 mm to be a realistic median size for sediments in the channel and this size was used for the initial bulk sediment transport modelling. For the purposes of the modelling, it was assumed that lateral inputs consist of 90% silt and 10% coarse sediments (0.5 mm median diameter). Catchment wide sediment sampling will ultimately provide more realistic assessments of size distributions of sediments provided from tributaries. It was therefore assumed that most of the silt is transported through the system or deposited on the overbanks during high flows and that it is only necessary to model transport of the coarser sizes in order to model geomorphological change in the active channel.

Table 19. Predicted sediment transport rates at different discharges for different particle size fractions for the common channel types on the Sabie River.

Single thread			
Discharge (m^3s^{-1})	Transport rate - 0.02 mm sizes (m^3day^{-1})	Transport rate - 0.5 mm sizes (m^3day^{-1})	Transport rate - 1 mm sizes (m^3day^{-1})
1	0	0	0
10	17735	0	0
50	$8.3x10^{8}$	5	2
100	$2.7x10^{9}$	12	5
650	$7.2x10^{11}$	142	68
Braided			
1	0	0	0
10	9682	0	0
50	$4.5x10^{9}$	17	8
100	$6.7x10^{10}$	36	17
650	$5.6x10^{13}$	432	193
Bedrock anastomosing			
1	$6.1x10^{24}$	195	43
10	$1.2x10^{16}$	7	1
50	$9.2x10^{17}$	23	5
100	$4.2x10^{18}$	51	11
650	$7.0x10^{20}$	469	115
Pool-rapid			
1	32	0	0
10	$1.0x10^{8}$	0	0
50	$9.9x10^{11}$	6	2
100	$1.3x10^{12}$	29	9
650	$5.3x10^{14}$	141	49
Mixed anastomosing			
1	0	0	0
10	549	0	0
50	$6.4x10^{7}$	0.4	0
100	$3.4x10^{9}$	4	0.4
650	$2.4x10^{12}$	84	32

Since the modelling was concerned with changes in sedimentation patterns (through erosion or deposition) from a base state, an arbitrary sediment volume in storage per kilometre length for 1959 (the first year of simulation) was assigned to each of the channel type sections. The amount of available sediment in storage in bedrock anastomosing channel types was set to zero, since the active channels in these channel types flow predominantly over bedrock and thus limited sediment is available for transport from within these channel types. It was further assumed that sufficient sediment was available to supply the extreme upstream channel type section.

An annual mass balance (Fig. 66) was conducted for each channel type section proceeding from upstream to downstream as follows:

1. The annual volume of sediment which could pass through any channel type section was calculated as a balance between sediment availability (upstream and lateral inputs and storage in the section) and the calculated annual sediment transport capacity.
2. Total annual upstream input to a channel type section was determined from the volume of sediment which could be moved through the upstream channel type section.
3. Where tributaries entered a channel type section, the annual lateral input of the coarse fractions was assumed to equal 10% of the maximum average potential sediment yield for that sub-catchment.
4. If the annual potential sediment transport volume in a channel type section exceeded the input volumes (upstream and from tributaries), then the excess was eroded from the bed. Conversely, if the inputs exceeded the potential transport then the excess was deposited. If no sediment was available in the bed for erosion (all sediment in storage had been eroded previously), then only the sediment which was available (coming in from upstream and from tributaries) could be passed through to the next channel type section.

Thus, the sediment flux model provides an assessment of total annual sediment accumulation or loss in each of the 46 channel type sections. Summing the accumulations and losses over a number of years provides the total sediment accumulation or loss over that period. A plot of modelled cumulative sediment build-up along the length of the Sabie within the Kruger National Park (Fig. 69), shows three distinct accumulation zones over the period 1959 to 1993. From the Kruger National Park western boundary to just upstream of the Saringwa tributary, there has been relatively minor build-up. From the Saringwa tributary, past the Nwaswitshaka tributary to the Sand confluence, there has been progressive sediment build-up resulting from inputs of a number of ephemeral tributaries, with the Sand River providing a massive injection of sediment (Fig. 69). Downstream of the Sand River confluence there has been a far more gradual build-up. The effects of the tributaries (particularly the Sand River) are potentially over-exaggerated as a result of a possible over-estimation of tributary inputs for the reasons already described.

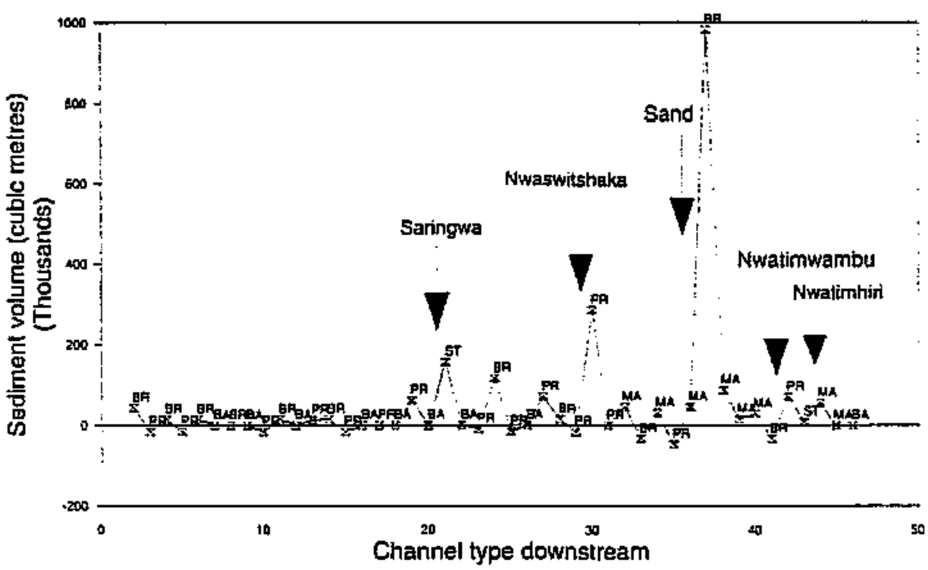


Figure 69. Predicted total sediment accumulation in each channel type along the Sabie River in the Kruger National Park between 1959 and 1993 using the Sabie Sediment Flux Model.

The model also reveals a complex spatial pattern of change between 1959 and 1992 (Figs. 70 to 77), depending on the spatial arrangement of channel types, with tributary inputs being the major controlling factor. Change upstream of channel type section 18 (Saringwa tributary) appears to have been relatively limited and there is progressive accumulation occurring downstream of channel junctions, downstream of the Saringwa confluence. There appears to have been a minor increase in sedimentation in braided channel types and a minor loss in pool-rapid channel types, between 1959 and 1992. It is interesting to note that upstream of channel type section 18, there was an increase in sedimentation between 1959 and 1971 (Fig. 71), with this trend gradually reversing, resulting in the final 1992 pattern (Fig. 70). Bedrock anastomosing channel types have remained stable with no accumulation or loss at any of these channel type sections throughout the period 1959 to 1992.

Temporal patterns of change for channel type sections are complex and variable and depend on upstream channel assemblages. Considering channel type section 13 (pool-rapid) and channel type section 14 (braided), Fig. 72 shows that the pool-rapid section accumulated sediment from 1959 to 1971, whereas the downstream braided section lost sediment over this period. Between 1971 and 1979 this trend was reversed (Fig. 72), although both sections showed a net accumulation compared with the 1959 levels (Fig. 72). Both sections showed an increase in sedimentation between 1979 and 1987 with the upstream pool-rapid channel type section 13 accumulating sediment rapidly. Conversely, the downstream braided channel type section 14 fluctuated annually between accumulation and loss, with a net overall accumulation over this period (Fig. 72). From 1987 to 1992 the model predicts opposite trends for the pool-rapid and braided sections, with the pool-rapid losing and the braided gaining sediment from 1987 to 1989 and a reversal in this direction of change for both channel type sections from 1989 to 1992 (Fig.

72). Both channel type sections show a net gain in sediment by 1992, but the difference between the overall sedimentation is smaller than in 1971, since the pool-rapid seems to have stabilised at its 1971 peak, whereas the braided channel is shown to have been steadily gaining sediment since 1971. The intricate temporal behaviour of the two adjacent channel types demonstrates the complexity of the relationship between climate, annual flow regime, channel types and their assemblages and rates and degrees of sediment accumulation or loss.

A series of aerial photographs at fixed points along the Sabie River for 1986 through to 1989 were studied in order to investigate how well the model predicts short term temporal change. For this purpose the effects of the wetter period from 1986 to 1989 and the drier period from 1989 to 1992 were explored. Total areas of accumulated and/or lost sediment were measured from the 1989 and 1992 photographs and compared with the 1986 baseline (Table 20).

The aerial photograph of section 7 corresponds to the mixed anastomosing channel type section 45 and the bedrock anastomosing channel type section 46. The measured large increase in sedimentation between 1986 and 1989, and a smaller increase in sedimentation between 1989 and 1992 (Table 20) for the mixed anastomosing section, is well predicted by the model (Fig. 73). No sedimentation was predicted in the bedrock anastomosing section (Fig. 73) for both periods and none was observed (Table 20).

The aerial photograph of section 6 corresponds to mixed pool-rapid channel type section 42. The measured slight increase in sedimentation between 1986 and 1989 and the dramatic increase in sedimentation between 1989 and 1992 is again well predicted by the model (Fig. 74).

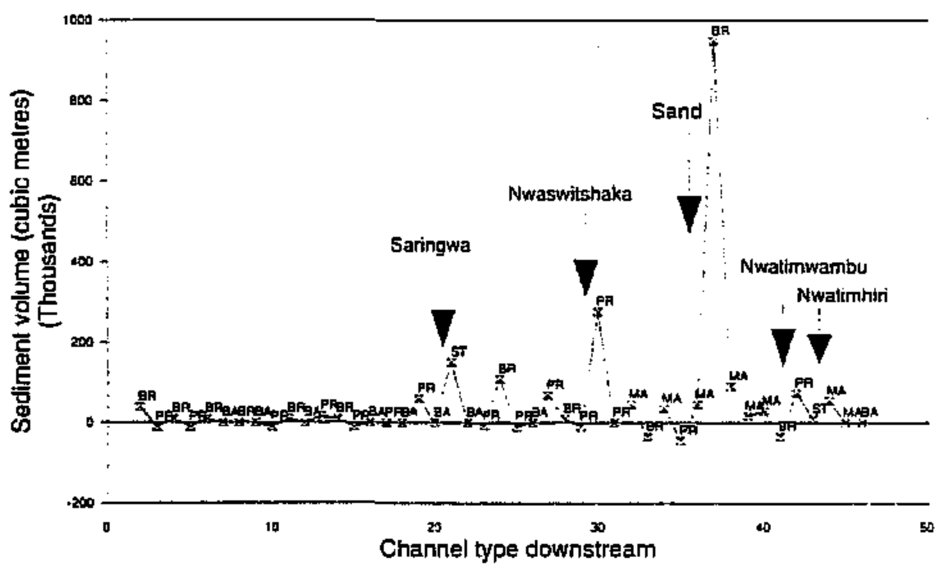


Figure 70. Predicted total sediment accumulation in each channel type along the Sabie River in the Kruger National Park between 1959 and 1992 using the Sabie Sediment Flux Model.

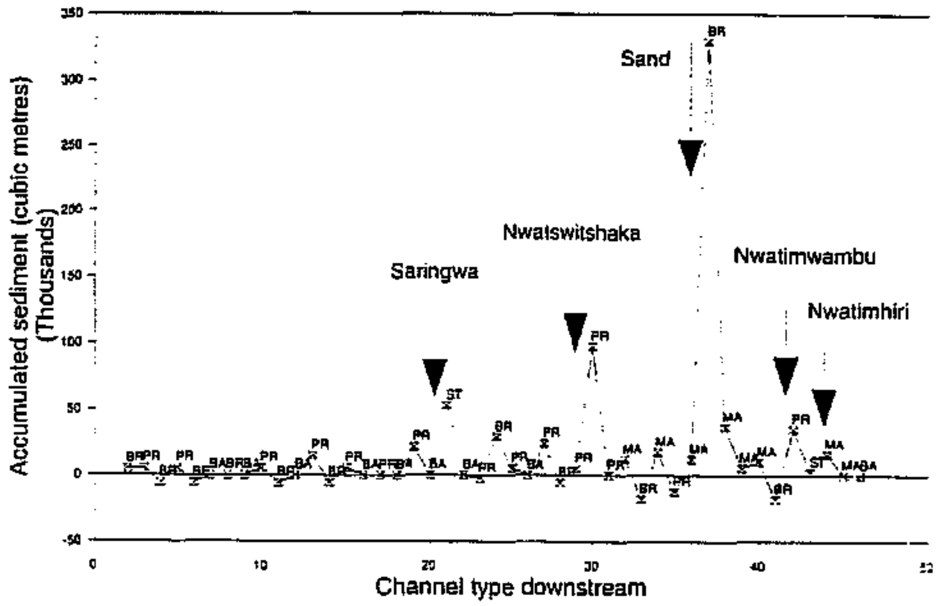


Figure 71. Predicted total sediment accumulation in each channel type along the Sabie River in the Kruger National Park between 1959 and 1971 using the Sabie Sediment Flux Model.

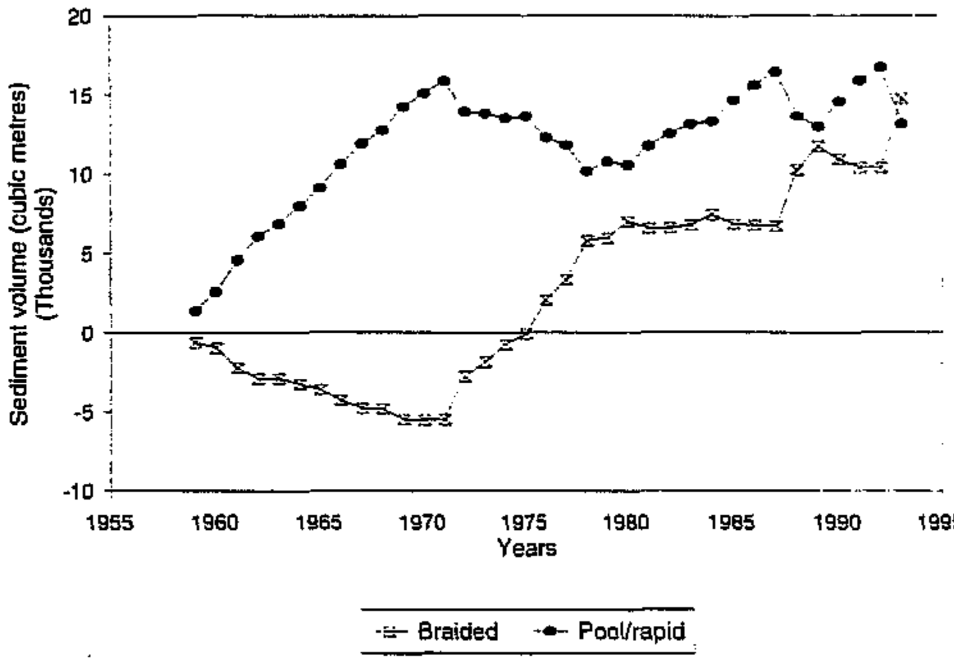


Figure 72. Predicted sediment dynamics of a pool-rapid and braided channel type for the period 1959-1993 using the Sabie River Sediment Flux Model.

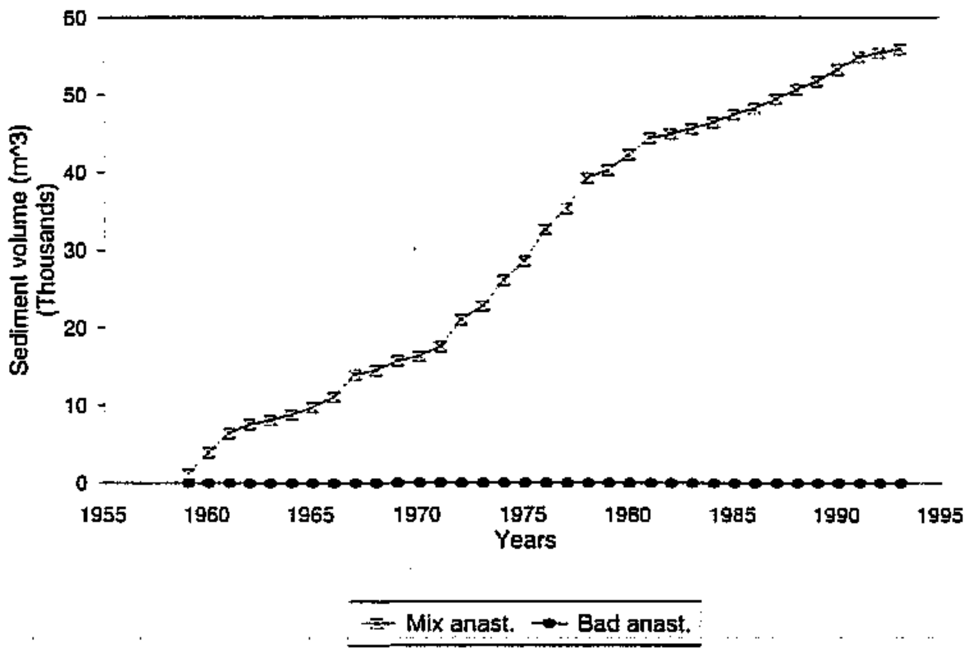


Figure 73. Predicted sediment dynamics of a bedrock anastomosing and a mixed anastomosing channel type for the period 1959-1993 in Kruger Park aerial photograph area 7 using the Sabie River Sediment Flux Model.

The aerial photograph of section 5 corresponds to channel type section 39 (mixed anastomosing). The model predicts a steady increase in sedimentation (Fig. 75), reflecting a tributary effect. A slight increase in sedimentation between 1986 and 1989 was measured and a major increase between 1989 and 1992. The model predicts the overall long term trend well. The model, however, assumes a constant average lateral input from tributaries, whereas in reality, the tributaries are ephemeral and sediment may only have been introduced from the tributary between 1989 and 1992.

Aerial photograph section 4, corresponding to channel type section 36, covers the area where the Sabie and Sand rivers share the same macro-channel, but are separated by a large island which is breached in places. The model predicts a steady increase in sedimentation for section 38. This trend is reflected in Table 20, however, a massive injection of sediment was measured between 1989 and 1992. This injection occurs at a point where the island has been breached and may reflect an input of sediment from the Sand River during this period.

The aerial photograph of section 3 relates to channel type section 30, which is mixed pool-rapid. The model predicts a steady increase in sedimentation, reflecting the effect of the Nwaswitshaka tributary (Fig. 76). This trend has been measured (Table 20). Again, fluctuations could reflect the ephemeral nature of sediment inputs from the tributary.

Aerial photograph section 2 corresponds to channel type section 26, which has been classified as bedrock anastomosing. There is no correlation between model predictions (Fig. 77) and measured sedimentation areas (Table 20). The aerial photography covers a short braided/mixed anastomosing section at Kruger Gate. This section was classified as a bedrock anastomosing channel type, since it was smaller than the scale at which the original classification was conducted and the predominant channel type is bedrock anastomosing. Reclassification of this channel section as braided, with bedrock anastomosing channel types upstream and downstream would greatly improve model predictions. This serves to highlight that the classification and modelling can be undertaken at smaller spatial scales, depending on available data and the research objective. A far more detailed channel type classification of the river can be achieved as a model refinement if this is required.

It should be noted that different flow levels at the times when the photographs were taken are likely to influence the measurements. Since the photographs were taken at similar times of the year (during the winter months, when the discharge is largely constant), the flow levels are not expected to be vastly different and the quantitative data are assumed to provide a reasonable indication of general trends.

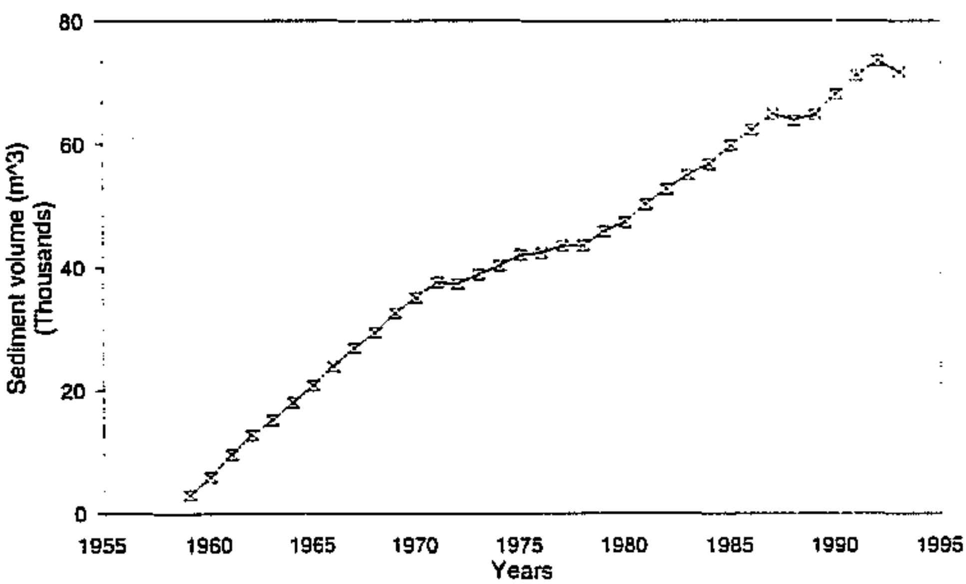


Figure 74. Predicted sediment dynamics of a pool-rapid channel type for the period 1959-1993 in Kruger Park aerial photograph area 6 using the Sabie River Sediment Flux Model.

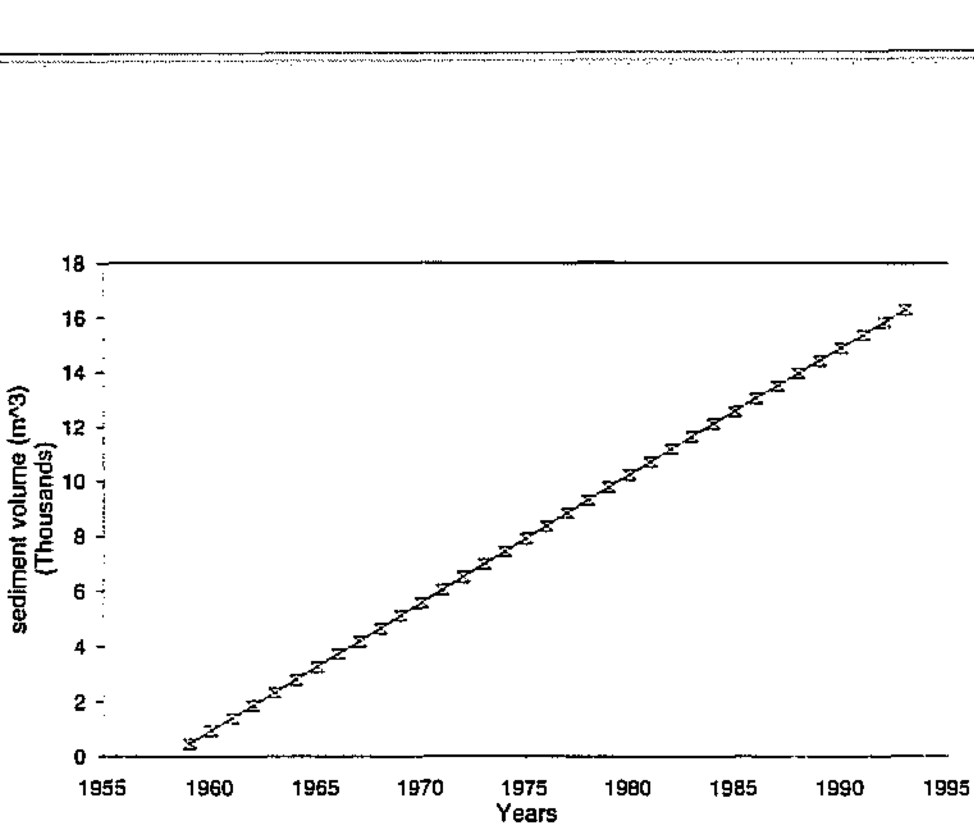


Figure 75. Predicted sediment dynamics of a mixed anastomosing channel type for the period 1959-1993 in Kruger Park aerial photograph area 5 using the Sabie River Sediment Flux Model.

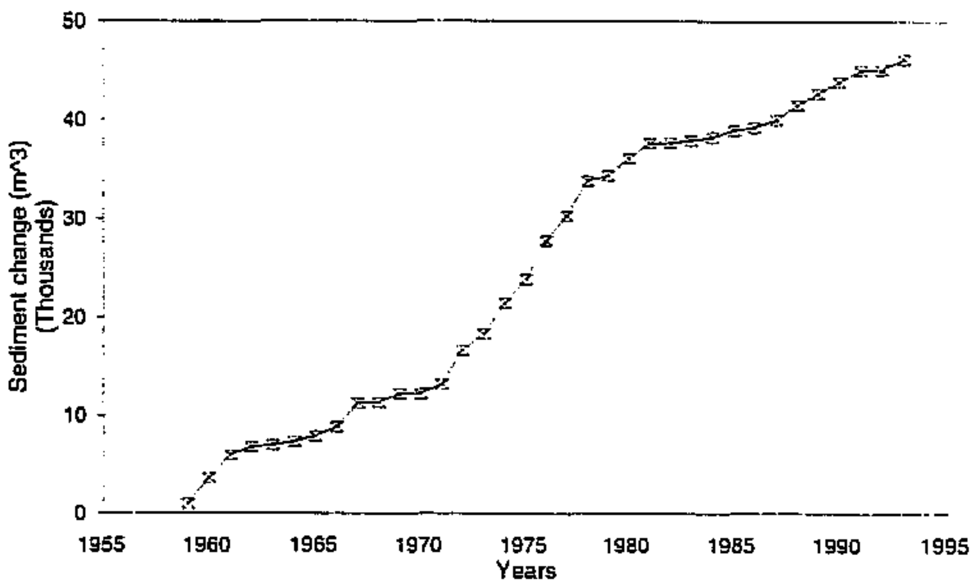


Figure 76. Predicted sediment dynamics of a pool-rapid for the period 1959-1993 in Kruger Park aerial photograph area 4 using the Sabie River Sediment Flux Model.

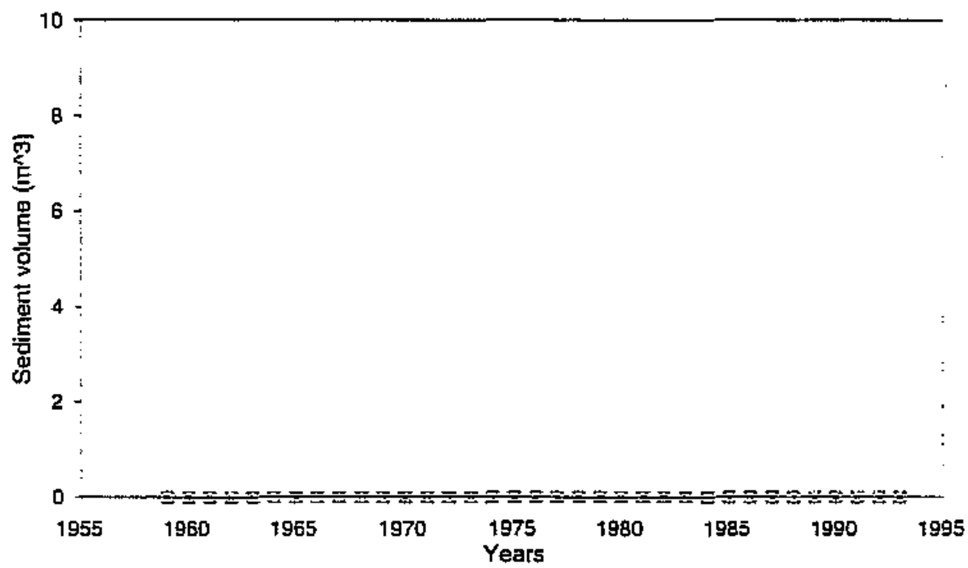


Figure 77. Predicted sediment dynamics of a bedrock anastomosing channel type for the period 1959-1993 in Kruger Park aerial photograph area 2 using the Sabie River Sediment Flux Model.

9.3.4 Model improvements

The model can be greatly improved through:

1. An improved assessment of representative channel type sediment transport capacities.
2. Provision of a longer daily flow record (either simulated or measured), in order to incorporate more extreme events.
3. Improved quantitative assessment of tributary sediment inputs.
4. Improved assessment of the temporal distribution of tributary inputs. This could best be achieved through simulation of daily tributary inputs in response to rainfall events (for example, using ACCRU).

9.3.5 Model transferability

The modelling approach can be transferred to other rivers as follows:

1. Select representative reaches and channel types within the area of study.
2. Survey cross-sections through each of the representative channel types.
3. Measure stage and discharge for three flows (low, intermediate and high) at each cross-section.
4. Develop stage-discharge relationships for each cross-section.

5. Assess the flow resistance for each representative channel type using available literature, engineering experience and the recommendations of Broadhurst *et al.* (1995).
6. Calculate annual potential sediment transport capacities for the representative channel types, as described above.
7. Determine annual sediment inputs from tributaries.
8. Link channel type sections along the length of the study river and calculate mass balances for a measured or simulated daily flow record, as described above.

Table 20. Recorded erosion and deposition sequences for the Kruger National Park aerial photograph sites, figures in brackets represent a recent contribution of sediment from the Sand tributary.

Aerial photograph section	Channel type	Sediment change	
		1986-1989 (m^2)	1989-1992 (m^2)
7	Mixed anastomosing Bedrock anastomosing	10624 0	6058 0
6	Mixed pool-rapid	570	11198
5	Mixed anastomosing	857	8533
4	Mixed anastomosing	1771	3759 (9663)
3	Bedrock pool-rapid	777	1736
2	Bedrock anastomosing Mixed anastomosing Mixed pool-rapid	1314 -2152 413	938 3620 395

9.4 Summary

☺ The return period study revealed the influence of flow regime on the various morphologic units found on the Sabie River. These can be broadly divided into active, seasonal and macro-channel units dependent on the frequency of flow influence.

☺ The results indicate that semi-arid bedrock influenced rivers, such as the Sabie, respond to very different parts of the flow regime than do temperate alluvial rivers, with the important flows being defined by the size of geomorphological feature present.

☺ Such conclusions on the effectiveness of a variety of flows on the geomorphology of the Sabie River have important implications for flow management. Many of the larger scale (macro-channel) sedimentary features are influenced only by very high magnitude low frequency flood events and as such are unlikely to be modified by anthropogenic influences in the catchment. It is the active (perennial) and seasonal channel features that will be most affected by alterations to the lower end of the flow regime.

☺ The regional channel dynamics study identifies three sediment sinks on the Sabie River where long term sediment accumulation can be expected.

☺ Quantitative dynamic modelling of channel type change, based on daily flow records between 1959 and 1993, has been demonstrated and verified for the Sabie River on both decade and annual timescales.

☺ Any lateral sediment input and daily flow sequence may be input to the semi-quantitative channel type dynamic model allowing scenario modelling. This provides an excellent management tool to predict the likely effects of various catchment water allocation policies.

☺ The dynamic model is also able to operate at any spatial scale; the resolution is dictated by the aims of the study and the degree of geomorphological resolution required.

10. A GEOMORPHOLOGICAL APPROACH TO STUDYING RIVERS FOR ASSESSMENT OF ECOLOGICAL FLOW REQUIREMENTS

The study of geomorphological response to changing flow regime of the Sabie River system has led to the development of a new integrative methodology for assessing ecological flow requirements. Traditionally, such assessments were based on potential responses of biota (particularly fish communities) to flow regime modification. This approach was based on the assumption that fluvial systems are static and that a required flow regime can be specified, based on the responses of fish communities to local hydraulic conditions. This study has shown that the Sabie River is changing and is likely to continue changing, even if the flow regime is not modified any further and that modifications to the flow regime can potentially accelerate or retard the rate of this change, or even alter the direction of change completely. Furthermore, geomorphological change results in altered cross-sectional and longitudinal geometry and flow resistance characteristics, which result in modification of local hydraulic conditions. These observations have important implications in terms of ecological responses in that:

1. It may be neither desirable, nor possible, to maintain the current compositions of instream faunal communities (since the geomorphology and hence habitat is changing naturally towards some quasi-equilibrium, which is different from that observed currently).
2. Managing flow regime in order to maintain existing species-community compositions and distributions would involve the establishment of an unnatural system (since natural change is ignored).
3. An understanding of current directions and rates of geomorphological change is important in developing an understanding of existing ecological dynamics.
4. An assessment of ecological responses to changing flow regime is impossible if the geomorphological responses are not also considered.

The geomorphological approach (Fig. 78) provides an integrative framework, which can enhance the traditional approach through a consideration of the effects of flow regime, sediment production and catchment characteristics on the contemporary geomorphological and change vectors or pathways of change. Local hydraulics and sediment dynamics are also considered in terms of effects on local geomorphology (at the channel type and associated morphological unit scale). Such studies lead to an understanding of current channel morphology and geomorphological change vectors (direction and magnitude), resulting from historic catchment conditions and the development of models (conceptual, qualitative and quantitative) for geomorphological change. These models can then be used to predict potential modification of the geomorphological change vectors as a result of catchment disturbance.

Knowledge of local hydraulic requirements for biota and their physical habitat requirements can then be integrated with the understanding of potential geomorphological change, to provide a basis for recommending suitable flow regime(s) for the natural environment and assessing the ecological implications of different management scenarios. Herein lies the major challenge currently facing management and scientists in their endeavours to determine flow requirements and to establish catchment management policies for maintaining the ecological integrity of river systems.

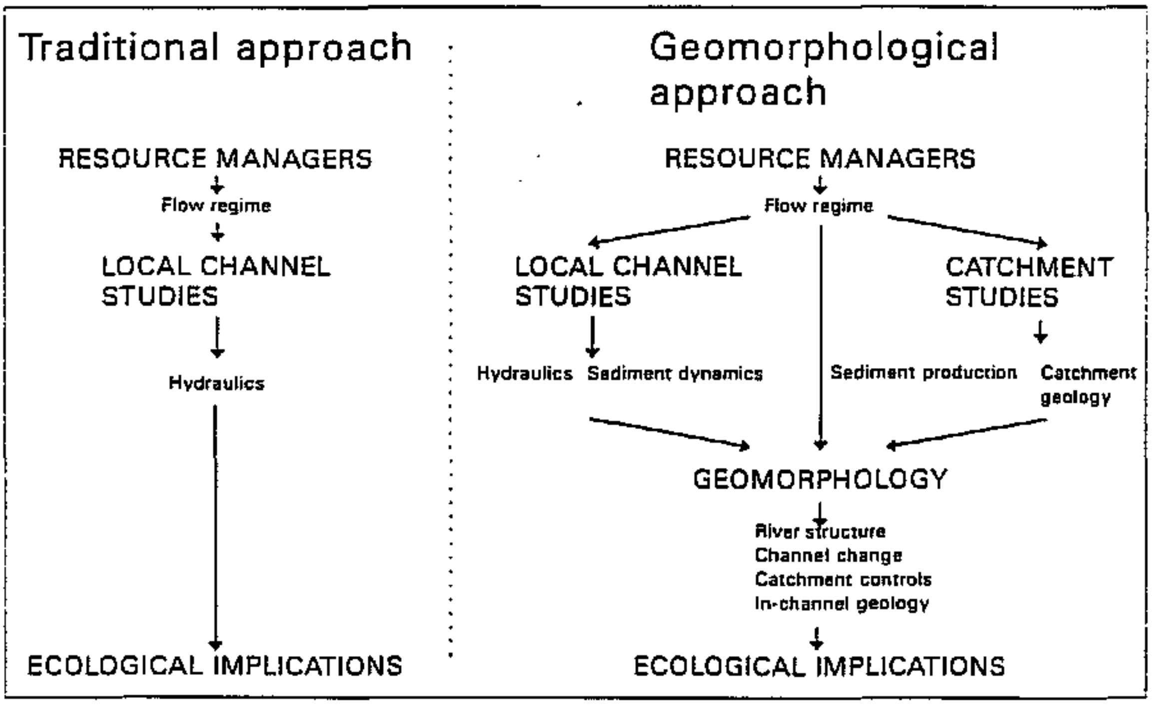


Figure 78. Geomorphological approach to a holistic study of river system functioning.

10.1 The geomorphological approach

The geomorphological approach outlined below is based on the methodology developed in this study and is designed to integrate with water resource development project management at all phases, starting with reconnaissance studies, through to post-project monitoring as required by the Integrated Environmental Management (IEM) process (Louw 1995). It can be applied on projects which are already underway and where river change has been neglected.

Phase One involves collation of available catchment data and classification and description of the geomorphology of the physical system. Available information on catchment control variables can be obtained from Department of Water Affairs and Forestry (DWAF) catchment, basin or systems analysis studies (Reconnaissance Phase) and/or through collaboration with the organisation(s) appointed to do the catchment studies, or from archived sources, depending on the current state of the project. The DWAF reconnaissance study normally covers topics such as geology, soils, climate, vegetation, demography, hydrology, regional geomorphology, possible dam sites, water infrastructure, economic activities, rainfall, land-use, water quality, sediment production and environmental sensitivity (Louw 1995).

If the information is not available, catchment topography, geology and regional geomorphology can be measured and digitised from existing topographic and geological maps. Long-term river history may be obtained from earlier research into the geomorphological history of southern Africa (King 1978, Partridge and Maud 1987). Catchment sediment production and hydrological studies are a standard component of DWAF catchment studies and these data are made available during the reconnaissance studies for water resource development projects.

A geomorphological description and classification of the river channel should form an important component of any reconnaissance study, since such a study is fundamental to assessing riverine environmental sensitivity. Geomorphological description involves a preliminary field reconnaissance for familiarisation and identification of geomorphological characteristics of the river. Further photograph analysis and field study leads to identification and rationalisation of existing morphological units and general channel types. The approach to classification and the agglomerative system proposed in chapter 2 is recommended as a sound basis for classification and description of southern African rivers, in order to focus on the scales most relevant to river scientists. Morphological units and channel types which have not been described on the Sabie River will be identified within such a framework. Description of the catchment controls and physical structure of the river provides the means for a broad ecological assessment from a structured basis.

Phase Two involves an assessment of historical river change and the development of a conceptual model for change. Historical change can be evaluated through a study of change within identified channel types, through detailed studies of historical aerial photographs. Evaluation of geomorphological change can be done qualitatively (Vogt 1992) or with an added quantitative component if more detail is required (Carter and Rogers 1995). Such studies lead to a conceptual model for historic and ongoing change and potential change in response to changing flow regime. The conceptual model then guides information and quantitative data requirements (and the level of detail required) for project decision making beyond the reconnaissance stage. An assessment of the potential ecological implications of current vectors of geomorphological change and effects of flow modification and catchment disturbance at the end of this phase, would lead to informed management decisions from the reconnaissance studies. A reasonable assessment of environmental sensitivity can be made only once the channel change vectors are identified.

Phase Three involves quantification of driving variables and processes and is necessary for DWAF pre-feasibility studies (including assessments of ecological instream flow requirements) and requirements for flow regime management. The pre-feasibility study is designed to investigate all possible options previously identified, to incorporate potential new options and to eliminate unsuitable options. Elimination of options can be on a combination of technical, financial, economic, social or ecological reasons (Louw 1995).

The hydrological regime, using daily flow data from weirs and hydrological simulation models, is analysed in order to identify climatic variability and historical anthropogenic influences on the contemporary geomorphology. Potential catchment sediment yield and the effects of catchment disturbance at key locations on the river are assessed and quantified. Representative sites (channel types) for hydraulic monitoring are selected based on the classification and conceptual model for change. Using measured stage-discharge data from three flows (high, medium and low), and/or hydraulic simulation modelling, stage-discharge relationships are established for each site. Water surface slope measured at each cross-section is used to determine the frictional characteristics at the selected sites. Stage-discharge relationships provide information such as levels of inundation (flow depth), wetted perimeter, cross-sectionally averaged velocity, Froude number, shear stress, Reynold's number and hydraulic radius for any discharge within the measured ranges. Extrapolation beyond the measured range requires additional hydraulic modelling for the extremes. Stage-discharge relationships in association with measured cross-sectional data and classification of the morphological units can be used to establish flows required to maintain different in channel and overbank features (see chapter 9). Analysis of historic flow records then provides an assessment of the frequency of inundation of different geomorphological features. The hydraulic information can all be used to assess the influence of local hydraulics on riverine biota.

Site selection must be conducted swiftly, in order to ensure that adequate time is available for collection of the necessary data, since flows in southern African rivers are highly erratic (Chiew *et al.* 1995). Ideally, site selection and monitoring should be initiated as soon as the decision is taken to undertake the pre-feasibility study. Clearly, the number of sites and the degree of monitoring as described in this report for the Sabie River can be reduced considerably.

Phase Four involves qualitative and quantitative modelling of channel change. The measured water surface slope is used to determine frictional characteristics at the selected sites, which are in turn used to calculate cross-sectionally averaged bed shear stresses. These bed shear stresses are then used to quantify the potential sediment transport for any discharge for the different channel types. Using the quantitative modelling approach described in chapter 9, the sediment dynamics along the length of the river is modelled using simulated daily flows and lateral sediment inputs provided by the water resource managers. Potential geomorphological change along the length of the river in response to a range of management options can thus be predicted. It was not the task of this study to establish the abiotic/biotic links, but, qualitative assessments of the ecological implications are possible. The Kruger National Park Rivers Research Programme is currently involved in making these links more explicit.

The quantitative and qualitative modelling creates the potential for a holistic assessment of the implications of different management options in that the effects of different catchment management scenarios on selected lengths of river are assessed. Management decisions can be based on a consideration of the dynamic nature of the system, incorporating a consideration of the whole flow regime, not just a limited consideration of local hydraulics at sections which will change under a modified flow regime. Clearly, modelling of channel change, however limited, should form an integral part of the Department of Water Affairs and Forestry pre-feasibility study, and hence the steps required to provide for this modelling capability need to be initiated during the reconnaissance study as described above. Option(s) recommended in the DWAF pre-feasibility studies are assessed during the feasibility phase and all aspects of these are investigated in sufficient depth to enable the decision-maker to make informed decisions. Modelling capability established during the DWAF pre-feasibility study can be refined and focused on preferred options during the DWAF feasibility study in order to achieve the best possible decision.

Monitoring to collect biological base-line information occurs during the DWAF design phase and the location of monitoring points and the type of information required can be guided by the geomorphological approach. An operations manual which guides the project and includes provision for managing the natural environment is drawn up during the DWAF operations phase (Louw 1995). Managing geomorphological change forms a crucial component of management of the natural environment and operating rules cannot be established unless potential geomorphological change is modelled.

10.2 Summary

☺ A new, holistic methodology for the assessment of biotic/abiotic links has been developed. The geomorphological approach enhances traditional methods of determining instream flow requirements (IFR) through the explicit incorporation of a consideration of channel change.

☺ The geomorphological approach integrates fully with water resource development project management at all phases, starting with reconnaissance studies through to post-project monitoring as required in the Integrated Environmental Management (IEM) process.

☺ The geomorphological approach is used to establish current geomorphological change vectors (direction and magnitude) and provides a means, through modelling (conceptual, qualitative and quantitative), for assessing the effects on current change vectors of modified flow regime and catchment disturbance.

☺ Since riverine biota are affected by both local hydraulics (which are modified by changing geomorphology) and physical habitat (river morphology), a required flow regime for ecological requirements cannot be specified without explicit consideration of potential geomorphological change in response to proposed flow regimes.

☺ At present, links between geomorphological and ecological change are not explicit, however, these links are currently being established in the Kruger National Park Rivers Research Programme.

☺ Without the ability to predict potential geomorphological change, operational goals for management of the natural environment cannot be set, since changes to the physical and hydraulic state of the river will invalidate any conclusions based on the assumption of a static system.

☺ Geomorphological change studies must be initiated during the DWAF reconnaissance phase and implemented at the different phases in the IEM process in water resource development projects.

11. APPLICATION OF THE GEOMORPHOLOGICAL APPROACH TO THE LETABA RIVER

The research approach used on the Sabie River may be used to study any catchment, but the stages may have to be modified slightly, dependent on the quantity and quality of the data. An attempt is made to utilise the data available for the Letaba catchment to test the methodology. Comprehensive details of the Letaba River catchment characteristics and simulated monthly hydrology are detailed in the catchment reports (Steffen, Robertson and Kirsten 1990) and are reviewed only briefly below.

The river has been classified and mapped along its length in the Kruger National Park and the relative influence of the catchment control variables of Morisawa (1985) has been evaluated. This information was used to construct a conceptual model of change for the river that is more restricted than for the Sabie. Field monitoring networks were established and limited hydraulic and hydrodynamic data collected (due to the ephemeral nature of the river at present). This allowed limited quantitative regional modelling which evaluates the morphological effects of individual flood events on the system.

11.1 Letaba catchment characteristics

The Letaba catchment covers an area of 13400km^2 in the Northern Province of South Africa. In the Lowveld region, the major tributaries are the Molotsi and the Klein-Letaba Rivers, with the Shingwedzi River joining the Letaba downstream of the Mozambique border (Fig. 79). The catchment has been classified as semi-arid, receiving between about 500 and 1800mm of rainfall in the mountainous western parts of the catchment, falling to between 450 and 700mm in the east (Fig. 80) . Evaporation is high, ranging from 1400mm in the west to 1900mm in the east (Fig. 81). Precipitation is concentrated in the summer months, whereas evaporation potential is more evenly distributed. Runoff is now seasonal or ephemeral, with surface flow in the lower reaches of the river occurring only in response to severe storm events in the catchment.

Much of the geology (75%) consists of granite and gneiss, volcanic rocks outcrop further east, followed by sedimentary rocks of the Karoo sequence (Fig. 82). This, combined with the soils, has generated extensive areas of land with few limitations on crop production.

Afforested areas covered 47600ha in the upper catchment in 1985 (Fig. 83) and require 64Mm^{3}a^{-1} of water. Large areas upstream of the Kruger National Park have been settled and there is intense subsistence farming and irrigation along the rivers (Fig. 83). Irrigation of fruit, vegetable and grain cash crops used 220Mm^{3}a^{-1}. Domestic and industrial water use combined amounted to only 16.9Mm^{3}a^{-1} ,with a further 6.9Mm^{3}a^{-1} exported to urban areas outside of the catchment. Potential increase in demand as a result of increasing agricultural, industrial and rural demands is likely to outstrip water availability within the catchment. Similarly, land degradation and sediment production potential will increase (Steffen Robertson and Kirsten 1990). It is therefore likely that the already degraded Letaba River will experience further reductions in water volume and an increase in sediment inputs. Geomorphological and ecological consequences will be severe. During the study period the catchment experienced severe drought causing the river to become ephemeral in nature.

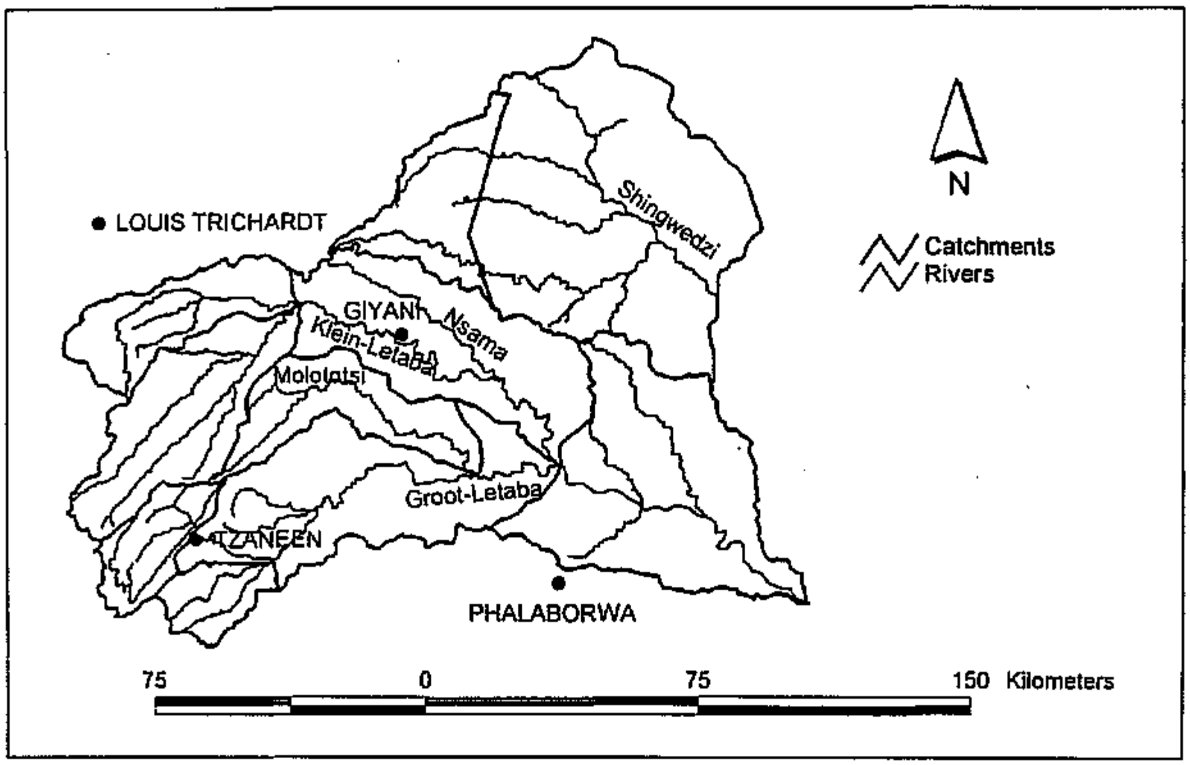


Figure 79. The Letaba River catchment, Northern Province, South Africa.

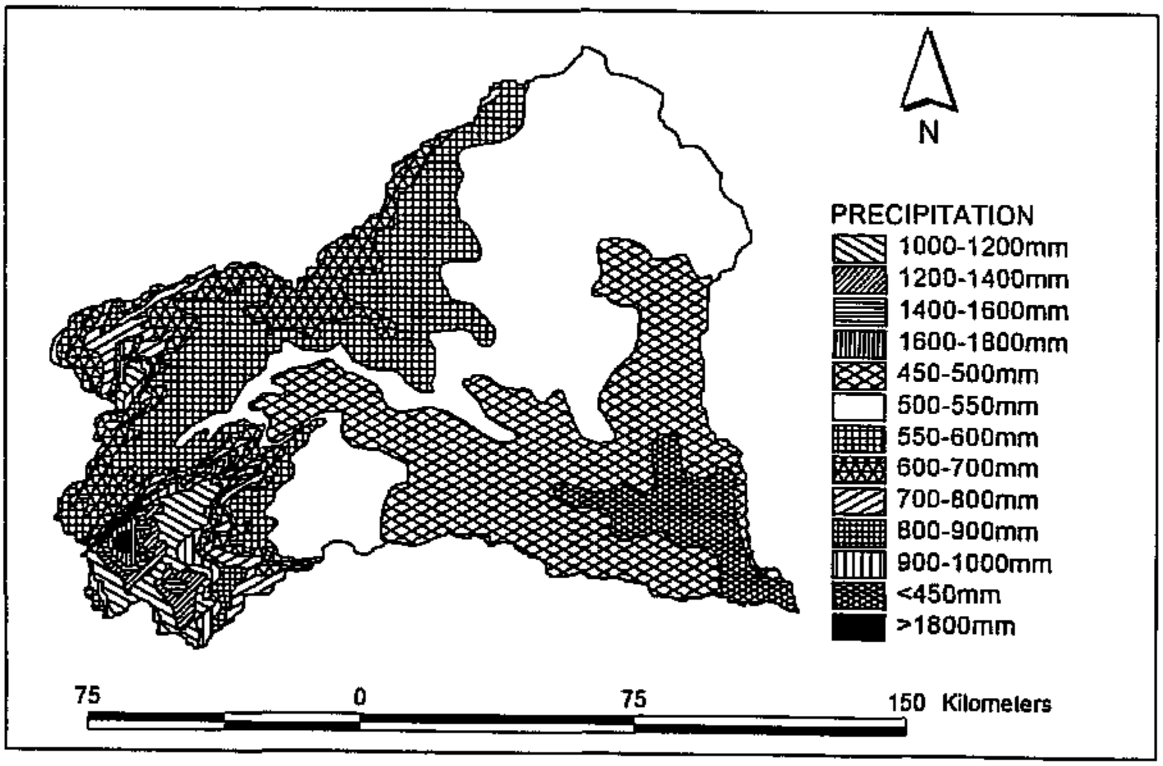


Figure 80. Average annual precipitation for the Letaba River catchment.

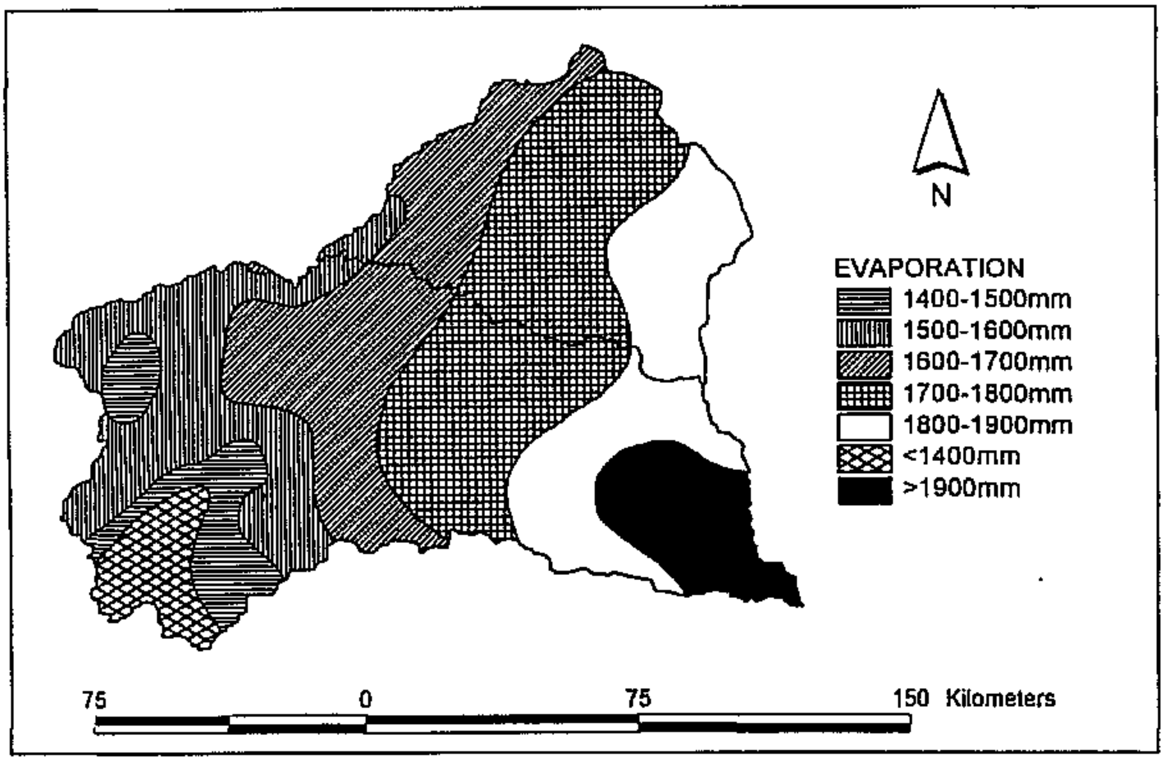


Figure 81. Average annual evaporation for the Letaba River catchment.

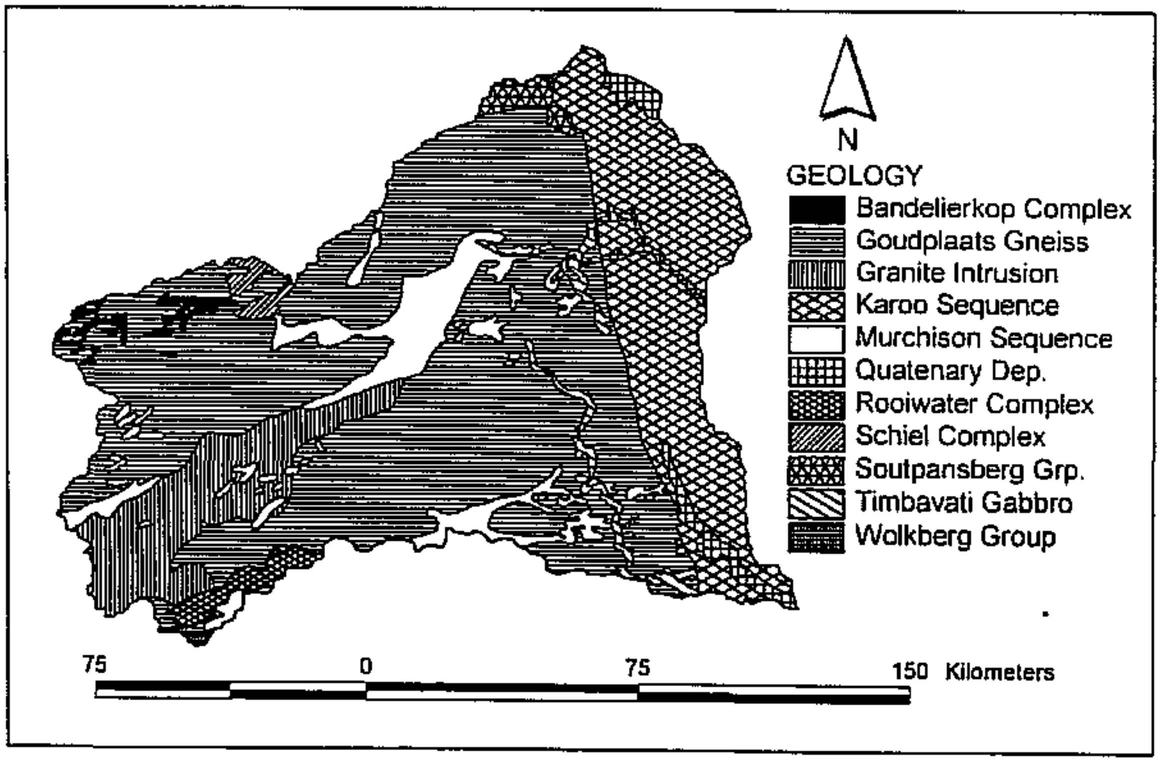


Figure 82. Simplified geology of the Letaba River catchment.

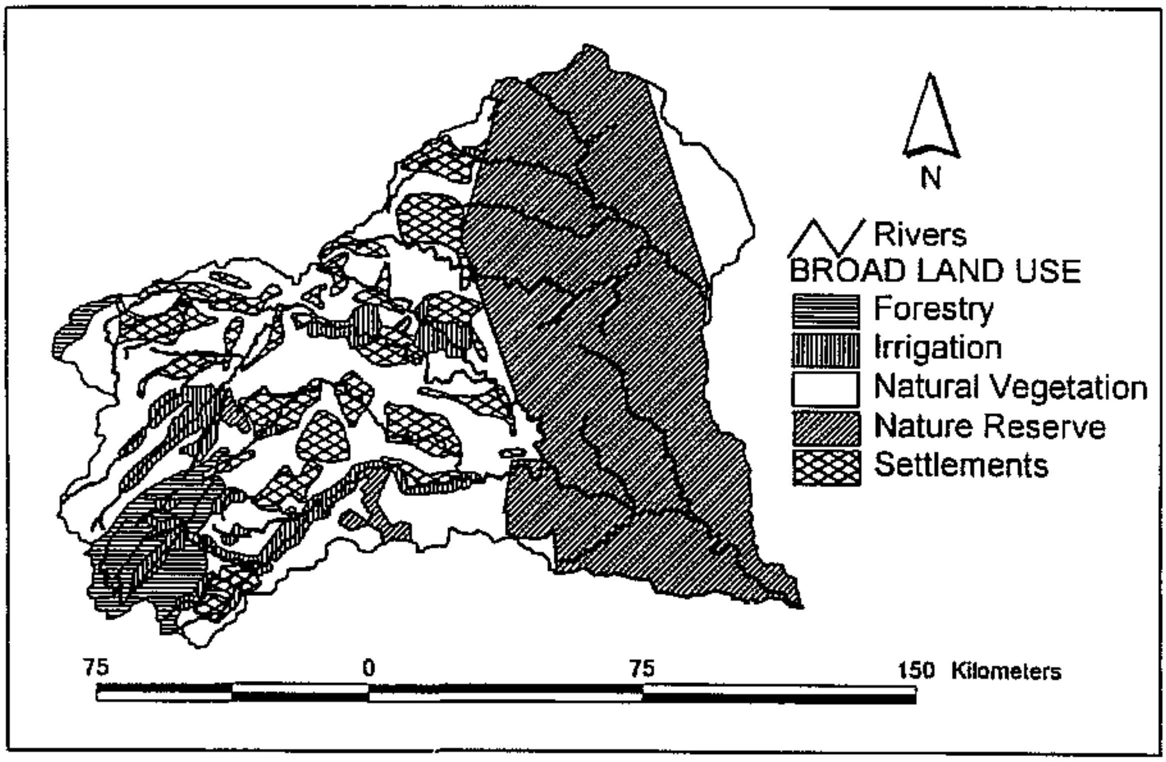


Figure 83. Land-use in the Letaba River catchment.

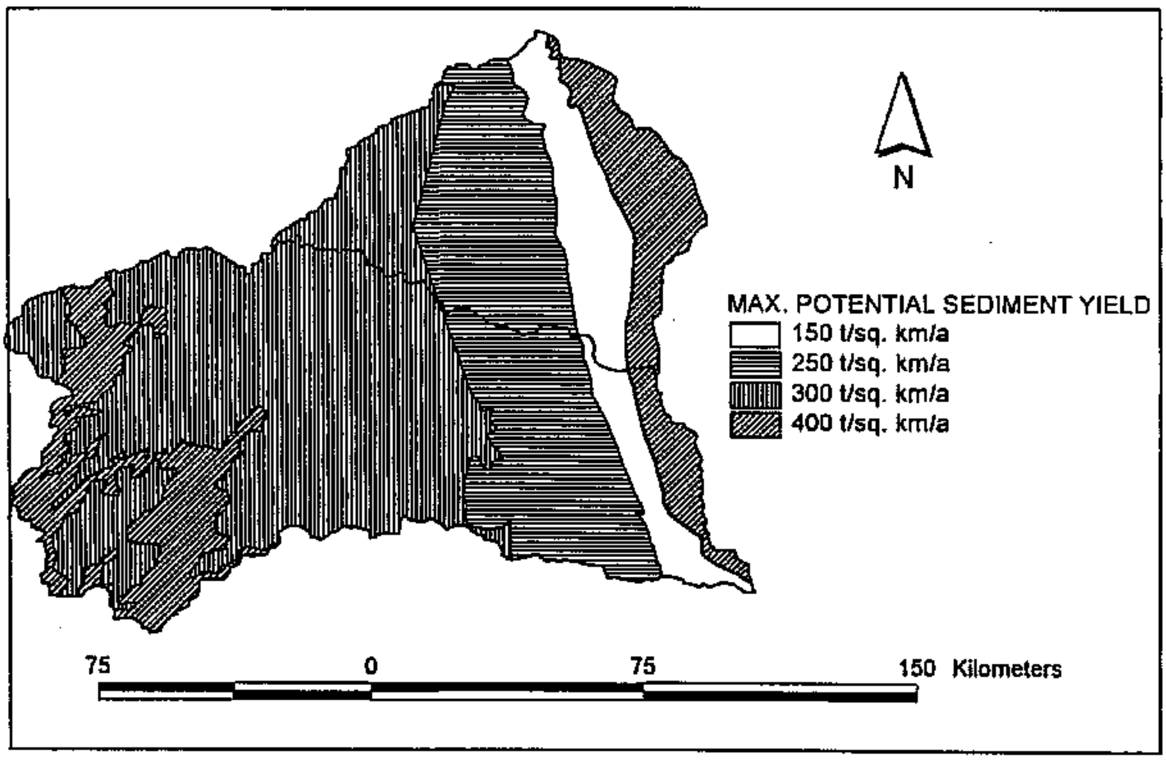


Figure 84. Maximum potential sediment yield in the Letaba River catchment (after Steffen, Robertson and Kirsten 1990)

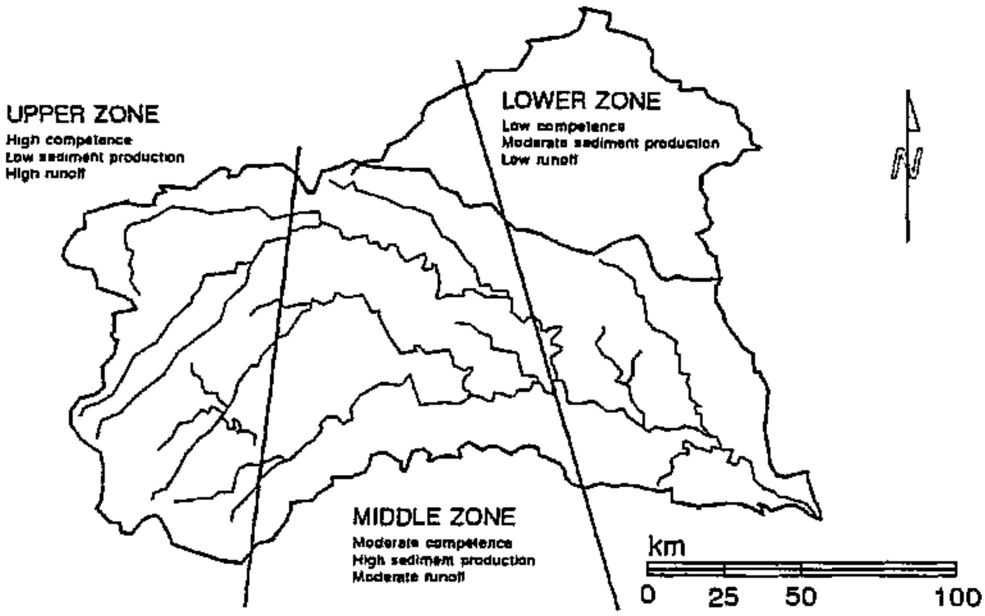


Figure 85. Geomorphological zones of the Letaba River catchment.

Sediment production in the Letaba River catchment has been estimated from land-use, soil type, geomorphology, geology, vegetation and rainfall variables (Steffen Robertson and Kirsten 1990). Yields range from $150tkm^{-2}a^{-1}$ to in excess of $400tkm^{-2}a^{-1}$ (Fig. 84), with the highest yields occurring in the densely populated rural areas. The Letaba River has been broadly classified into 3 sediment production zones (Fig. 85).

11.2 Physical nature of the Letaba River

The section of the Letaba River in the Kruger National Park was the focus of this analysis (Fig. 79). Aerial photographs for 1989 and field observation were used to categorise the geomorphology of the Letaba River. Generally, the river has incised several metres into bedrock and alluvial material to form a macro-channel. The influence of bedrock is considerably reduced from that seen on the Sabie River, with a preponderance of alluvial reaches. The channel types identified are described below:

Alluvial anastomosing

This channel type is characterised by a wide sand sheet covering the macro-channel floor, dissected by two or three deeper channels. These channels divide and rejoin over distances in excess of the width of the macro-channel forming an anastomosing channel system (Fig. 86).

Often the channels are lined with reed and scrub vegetation. Analysis of the effect of large flows on these features has revealed that their planform is quite stable with the river flowing in these channels as the flood stage reduces.

Mixed anastomosing

Some sections of the river display a wider macro-channel than the average for the river (Fig. 87). Both sedimentary and bedrock features are found in these areas and the channel is characterised by a highly tortuous multiple distributary network that covers the entire width of the macro-channel.

Alluvial braided

Short sections of the river are characterised by a multi-channel network of alluvial distributaries that dissect the sand sheet macro-channel infill. The low flow channels split and rejoin over distances that approximate the distributary width (Fig. 88). Planform change is rapid.

Mixed pool-rapid

Bedrock exposures on the macro-channel floor influence the course and structure of the low flow channel, generating a series of bedrock rapids and associated upstream pools. Often the flow network forms a series of sub parallel pools (Fig. 89). Sedimentation across much of the macro-channel in these areas has formed extensive sand sheets dissected by higher flow alluvial distributaries.

Alluvial single thread

There is evidence of switching between alluvial anastomosing and single thread systems in alluvial sections of the river. Low flows are conveyed along a single thread channel; often the channel is close to one side of the macro-channel, but alternates from side to side bearing no relation to the macro-channel planform (Fig. 90).

Alluvial channel types dominate the river in the Kruger National Park, particularly around Letaba Rest camp. Bedrock influence increases in the area downstream of Shimuweni Dam and close to the confluence with the Olifants River (Fig. 91). Large terrace features are common at the sides of the macro-channel along much of the river. These are composed of much finer alluvial material and aggrade as a result of silt deposition following major flood events. A geomorphological hierarchy for the Letaba River is presented as Fig. 92.

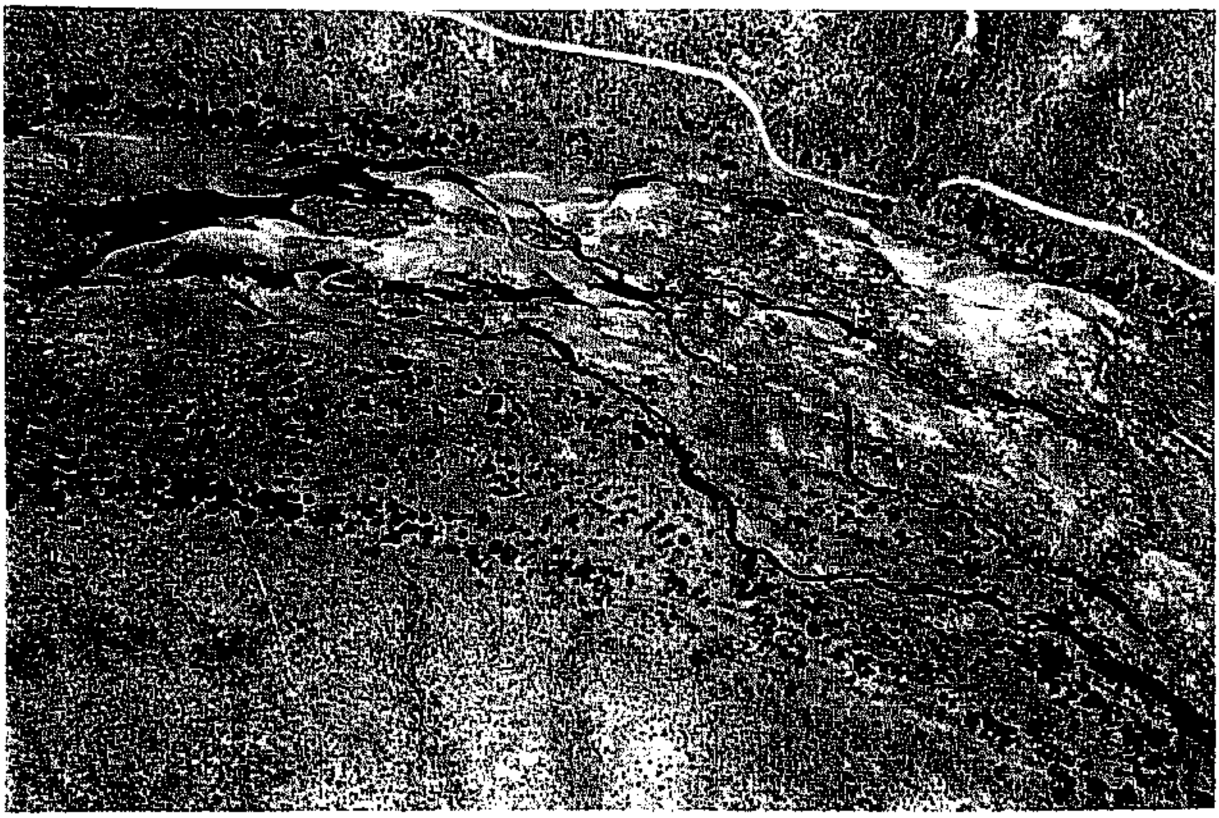


Figure 86. An alluvial anastomosing channel type on the Letaba River in the Kruger National Park.

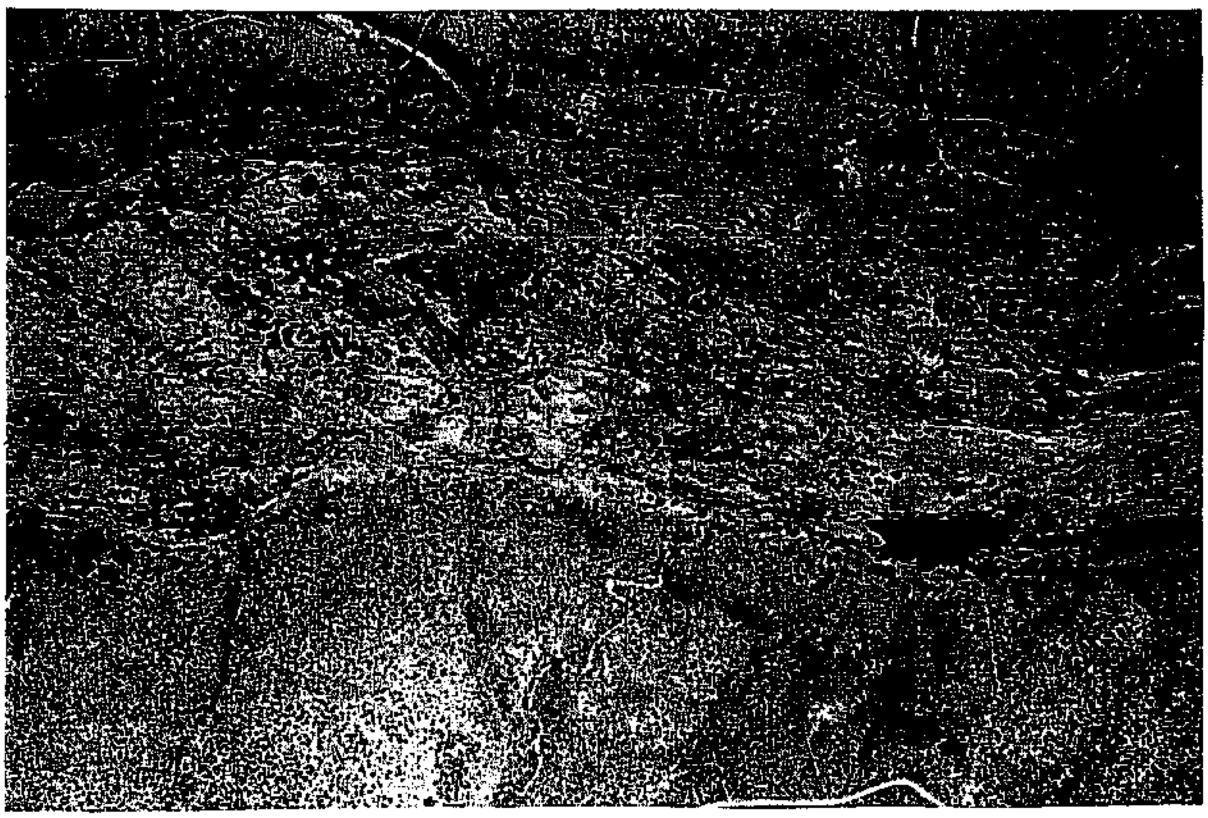


Figure 87. A mixed anastomosing channel type on the Letaba River in the Kruger National Park.

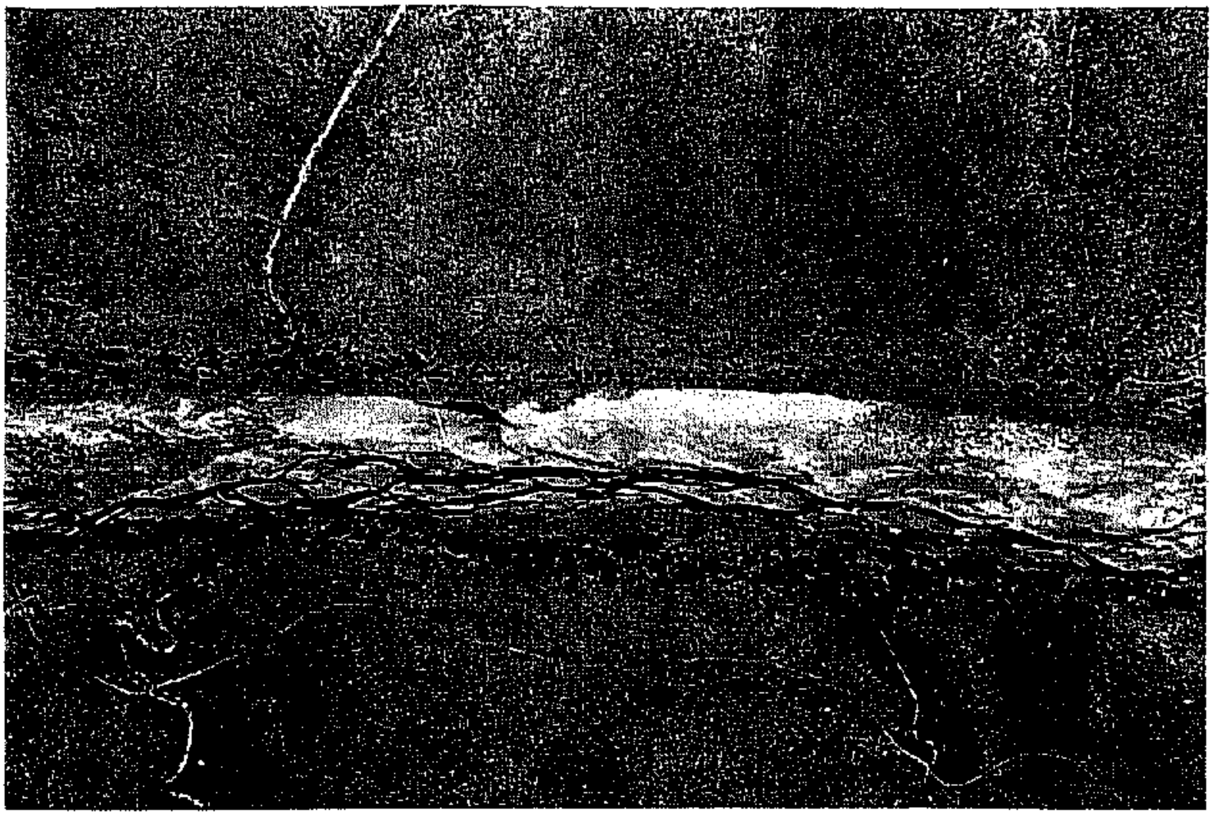


Figure 88. A braided channel type on the Letaba River in the Kruger National Park.

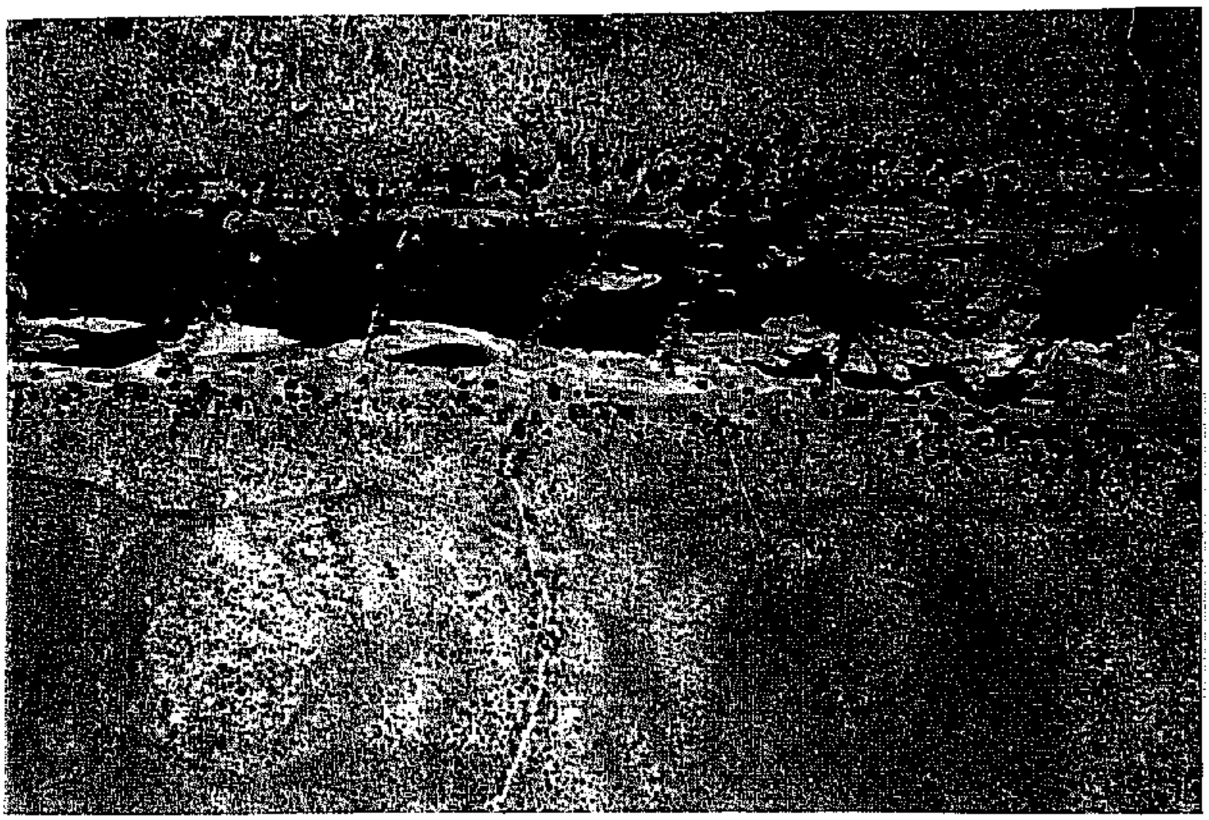


Figure 89. A mixed pool-rapid channel type on the Letaba River in the Kruger National Park.

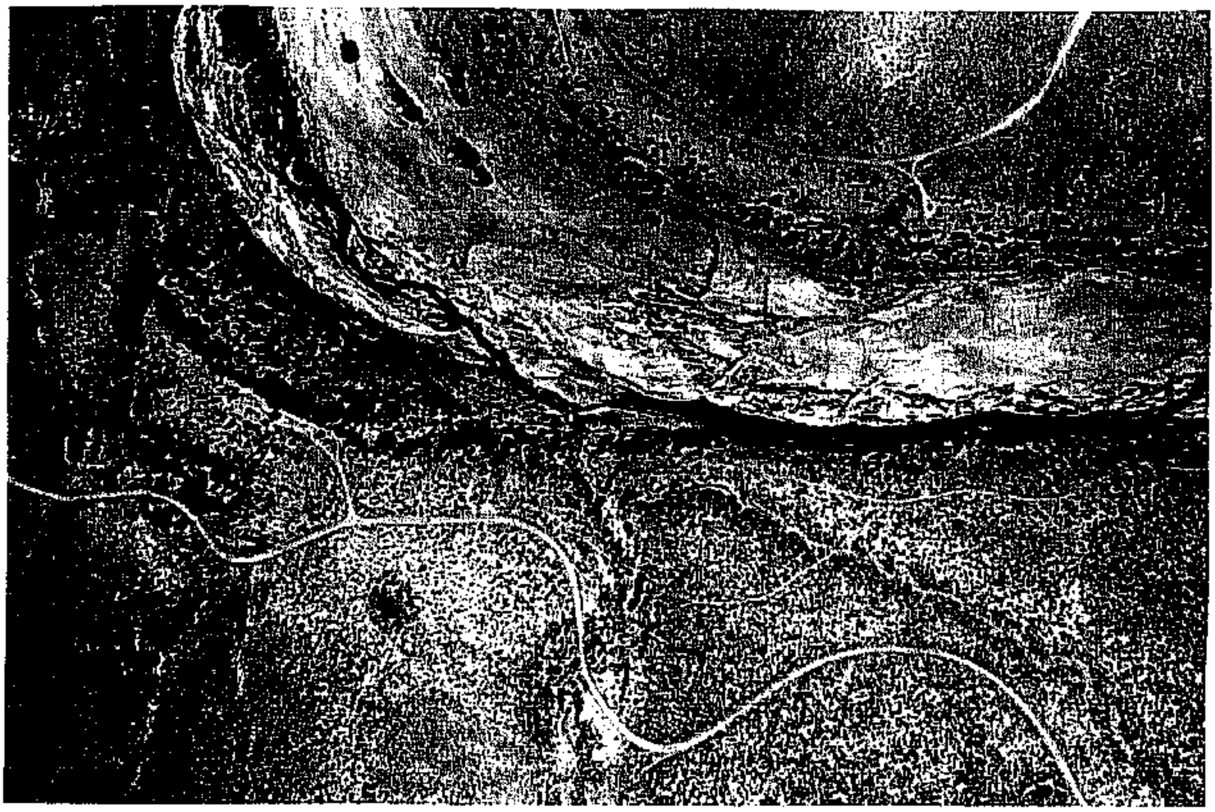


Figure 90. An alluvial single thread channel type on the Letaba River in the Kruger National Park.

11.3 Conceptual model of change

A number of catchment factors interact to influence the geomorphological nature of the Letaba River (Fig. 93). Geological control is minimised where it outcrops in the macro-channel, as its influence has been substantially reduced by large scale sedimentation. Land degradation within the catchment has generated increasingly large amounts of sediment, dramatically altering the nature of the river in many areas. The flow regime has also played a major role as a channel control factor, in particular, abstraction has caused the river to change from a perennial to an ephemeral system as the frequency and duration of flow has been reduced. This has drastically altered the channel dynamics of the Letaba River system and has resulted in an entirely different hydraulic and hydrodynamic system.

Given the range of channel types identified in section 11.2 it is possible to formulate a conceptual model of channel change for the Letaba River that details directions of change in response to altered catchment factors (Fig. 94). The model again indicates that catchment hydrology, local hydraulics and hydrodynamics, and sediment production require detailed investigation in order to understand geomorphological change within the river.

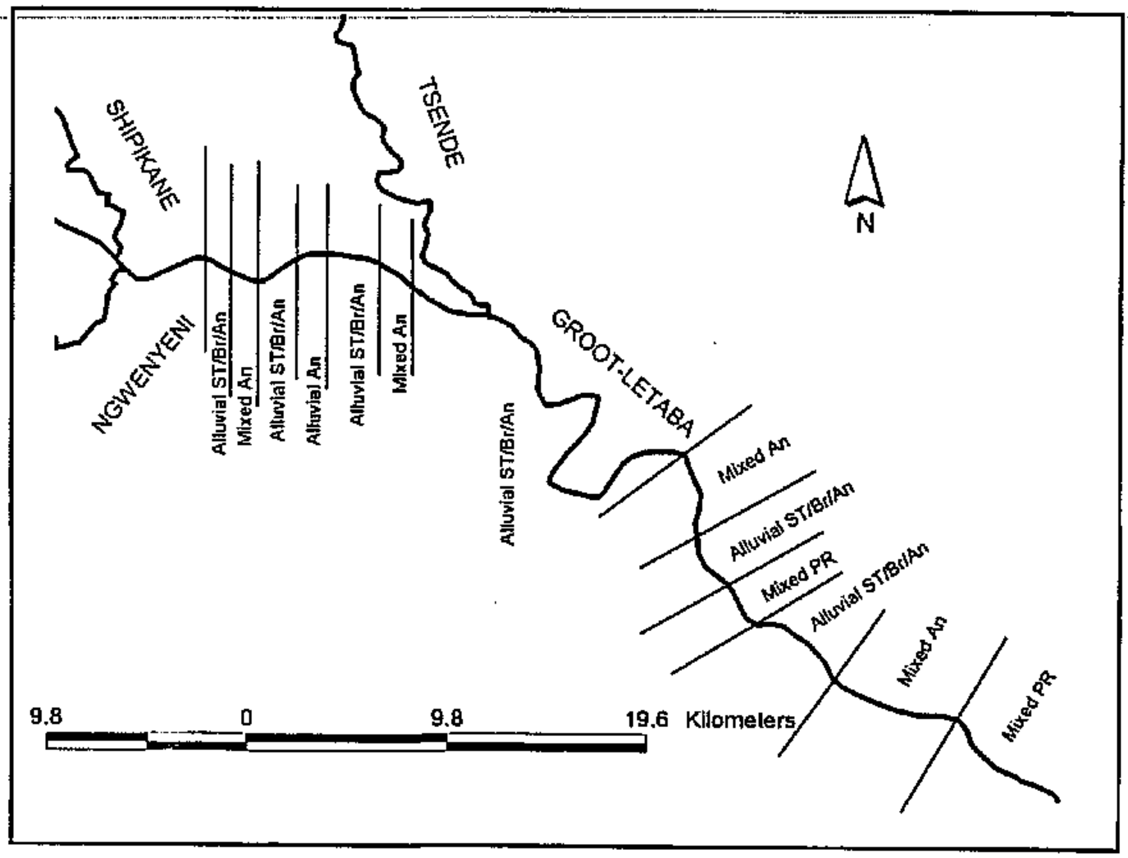


Figure 91. The geomorphological structure of the Letaba River in the Kruger National Park.

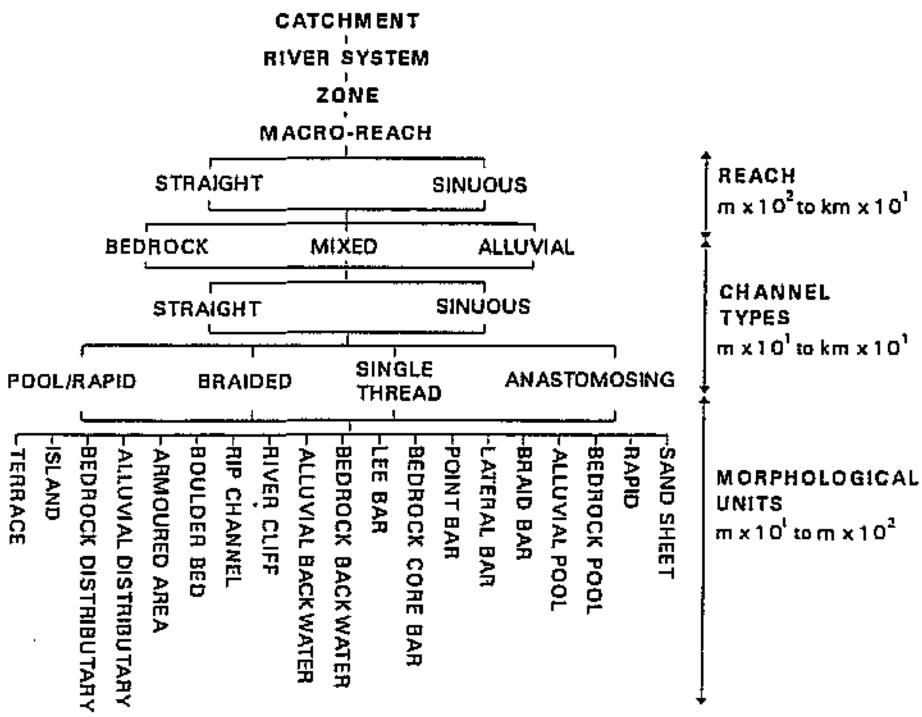


Figure 92. A hierarchical geomorphological classification of the Letaba River in the Kruger National Park.

11.4 Hydraulics and in-channel sediment dynamics

A network of 21 regional monitoring sites were established on the Letaba River, but the ephemeral nature of the system precluded the collection of hydraulic data beyond that for two flood flows (Fig. 95 and Appendix F).

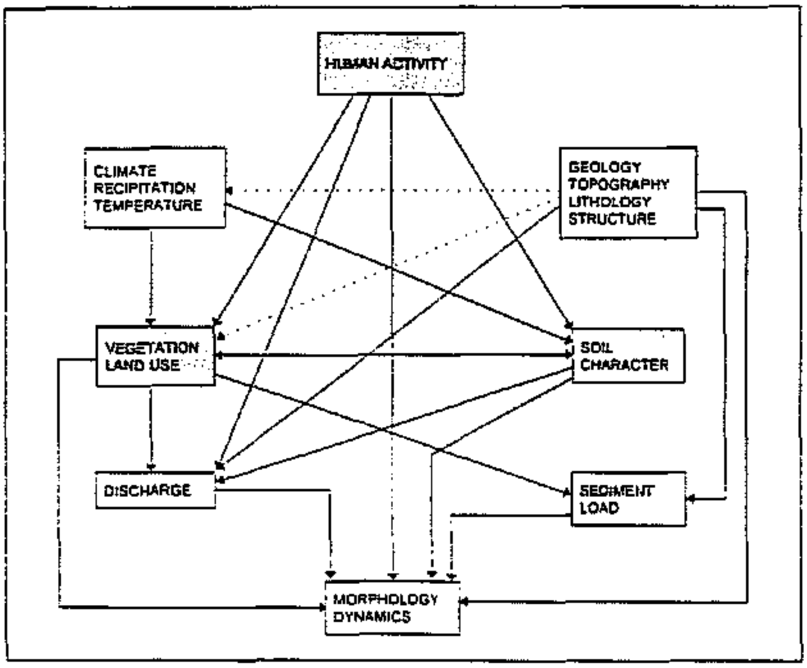


Figure 93. The principal catchment control factors influencing the geomorphological dynamics of the Letaba River in the Kruger National Park.

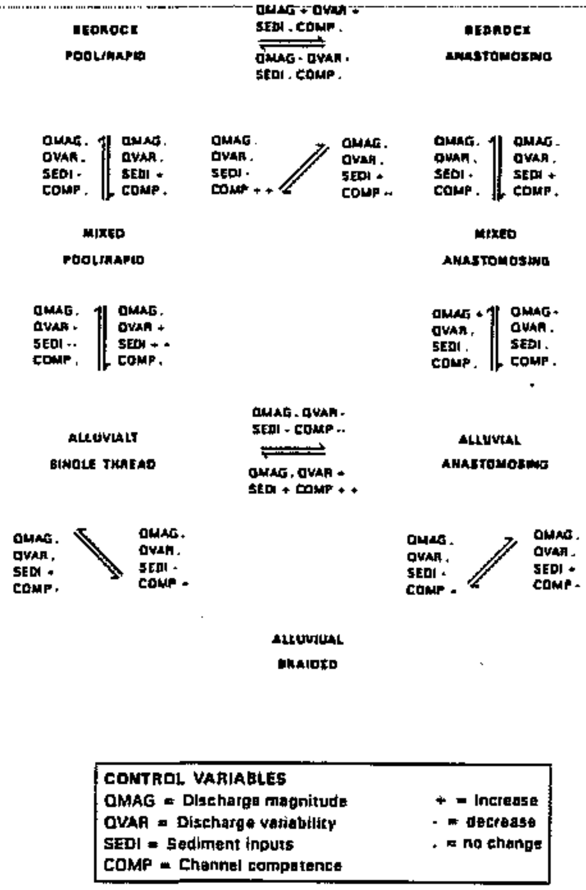


Figure 94. A conceptual model of channel change for the Letaba River in the Kruger National Park.

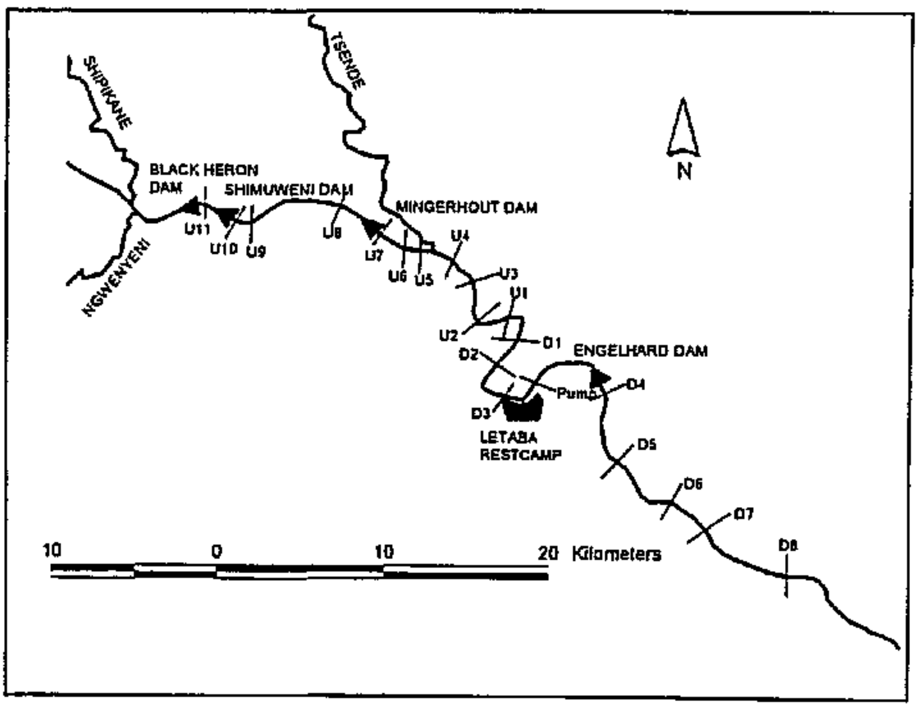


Figure 95. Regional cross-section locations on the Letaba River in the Kruger National Park.

11.5 Modelling channel change on the Letaba River

Aerial photographic evidence and field survey was used to determine the degree of change occurring on the Letaba River in the last 30 years.

11.5.1 Observed channel change

Large scale change on the Letaba River has not been observed, but Vogt (1992) noted the following changes to the geomorphology and planform of the low flow channels:

> Single thread: Some positional change, occasional new channels cut through existing sediment, some new in-channel lateral deposits in the 1960s and 1980s. Some dissection of large point bars in 1974.
>
> Multiple thread: Channel abandonment by bar coalescence in the 1960s and 1980s and associated additional in-channel lateral deposits. New channels across existing sediments in the 1970s.

This sequence suggests periods of deposition in the 1960s and 1980s, separated by an erosional phase in the 1970s.

Analysis of aerial photographs for 1965 (1:60000), 1972 (1:30000), 1977 (1:50000) and 1989 (1:50000) revealed low flow channel infilling and shallowing in alluvial sections between 1965 and 1972, whereas channel planform was generally maintained and deep pools remained. Between 1972 and 1977 erosion occurred at several locations, creating new channels and scouring pools. Channel shifting was noted and sinuosity increased along some sections of the low flow channel. Channel shifting continued on a reduced scale between 1977 and 1989, low flow channels became better defined but the pools that had scoured previously showed evidence of re-sedimentation. The major planform shape and larger pools remained stable during this period.

Evidence of short term change was obtained through resurvey of 20 cross-sections established on the Letaba River in 1993 (Appendix E). The geomorphological effects of the flood event of February 1995, which generated a peak flow gauge reading of $655m^3s^{-1}$ at Englehard Dam, were monitored. The resurvey results indicate remarkably little change, with the low flow channel remaining stable. Some sections recorded dissection as a result of waning flow channel development across the sand sheet. Bulk sediment mass change was also estimated (Table 21) and indicates that deposition occurred at the following sections: upstream 9,8,5,1 and downstream 5. Erosion occurred at sections downstream 1, 2, 4 and 7. Considerable deposits of finer sediment were left on the terrace features towards the sides of the macro-channel.

11.5.2 Inferred channel change and qualitative change pathways

Using the methodology outlined in chapter 8, it is possible to infer the long term channel change pathways for the Letaba River. Considerable deposition has occurred along much of the river system in the Kruger National Park since the formation of the macro-channel. Bedrock anastomosing and bedrock pool-rapid areas would have been the characteristic channel type of the river. However, large scale deposition of sand and finer material have created mixed anastomosing areas in the bedrock anastomosing channel types, characterised by alluvial anastomosing bars and mixed distributary networks displaying alluvial and bedrock features (Figs. 96 and 97). In areas that were previously bedrock pool-rapid, sedimentation has covered much of the macro-channel, filling pools and burying many of the bedrock rapids creating mixed pool-rapid channel types (Figs. 98 and 99) and finally fully alluvial channel types such as alluvial single thread, alluvial braided and alluvial anastomosing, which appear to switch between each other as the flow regime changes (Figs. 100 and 101).

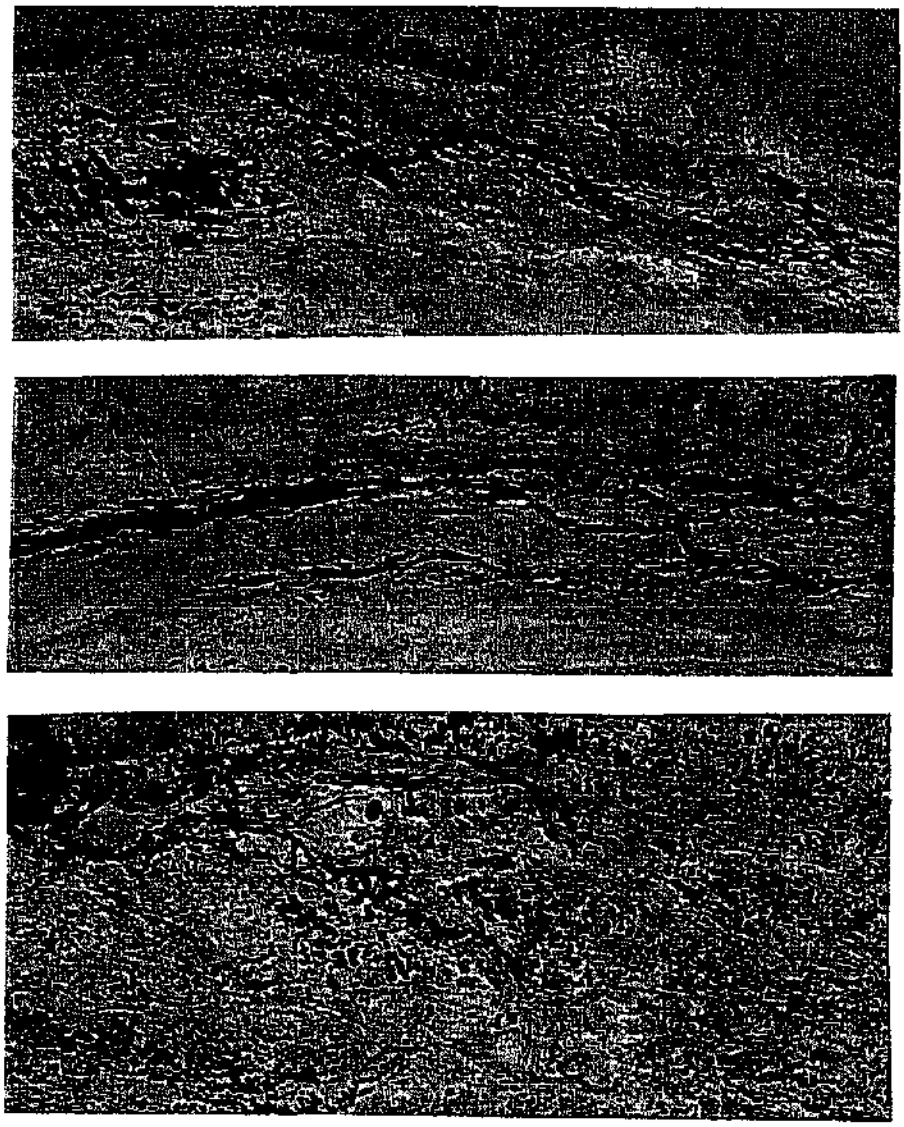


Figure 96. 'Space for time' evolution of a bedrock anastomosing channel type on the Letaba River in the Kruger National Park.

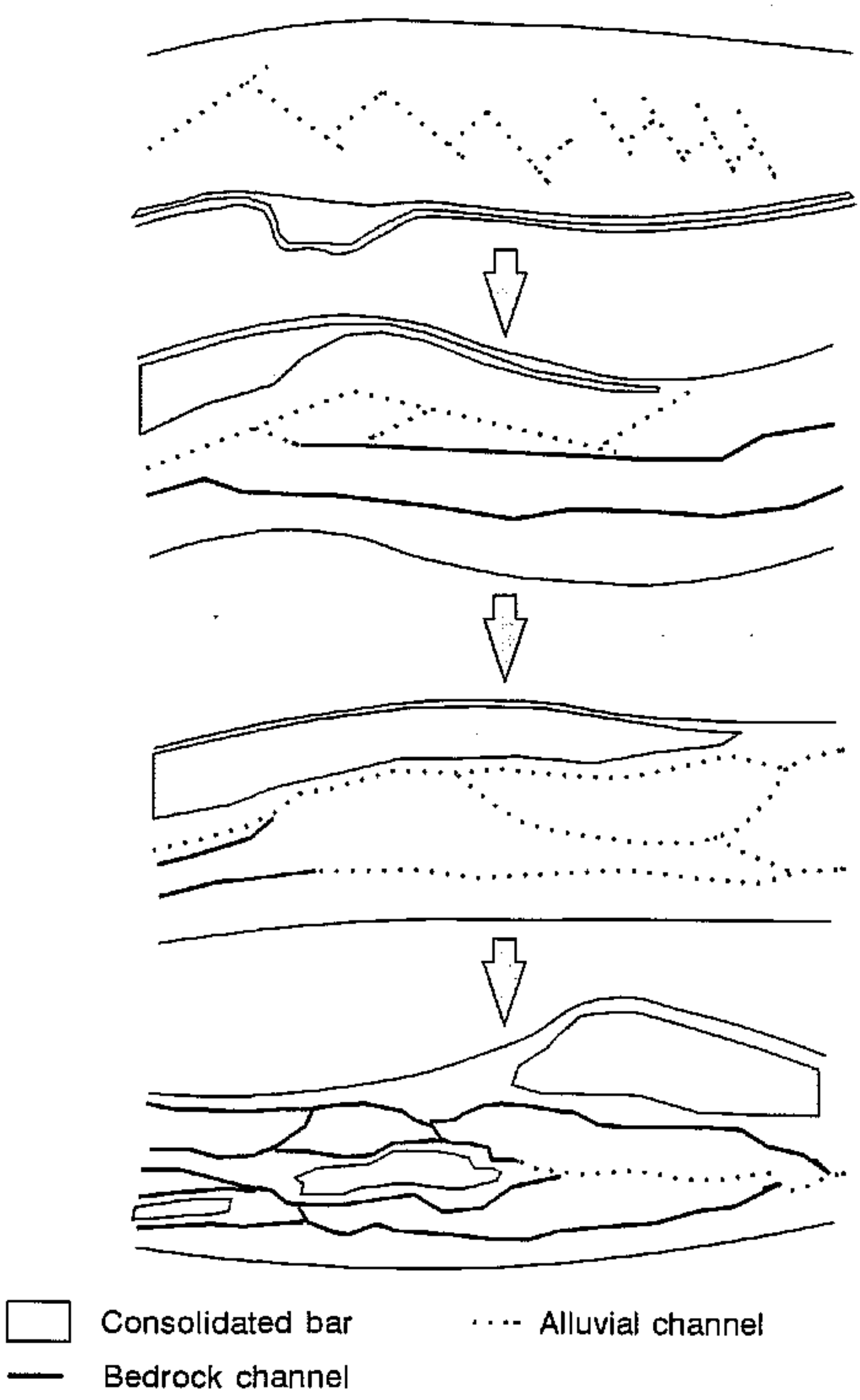


Figure 97. A qualitative model of channel evolution for the Letaba River in the Kruger National Park: bedrock anastomosing - mixed anastomosing - alluvial anastomosing.

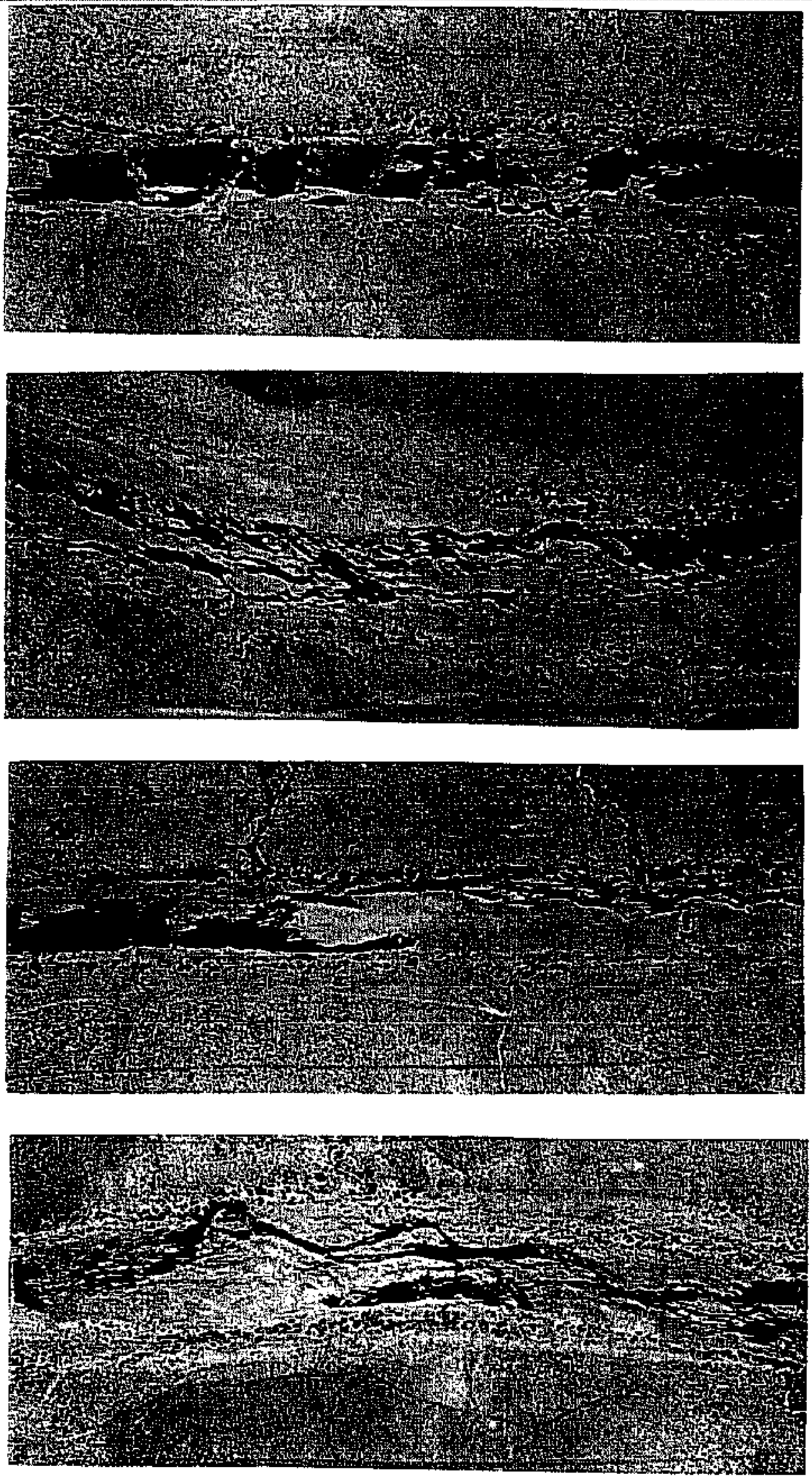


Figure 98. 'Space for time' evolution of a bedrock pool rapid channel type on the Letaba River in the Kruger National Park.

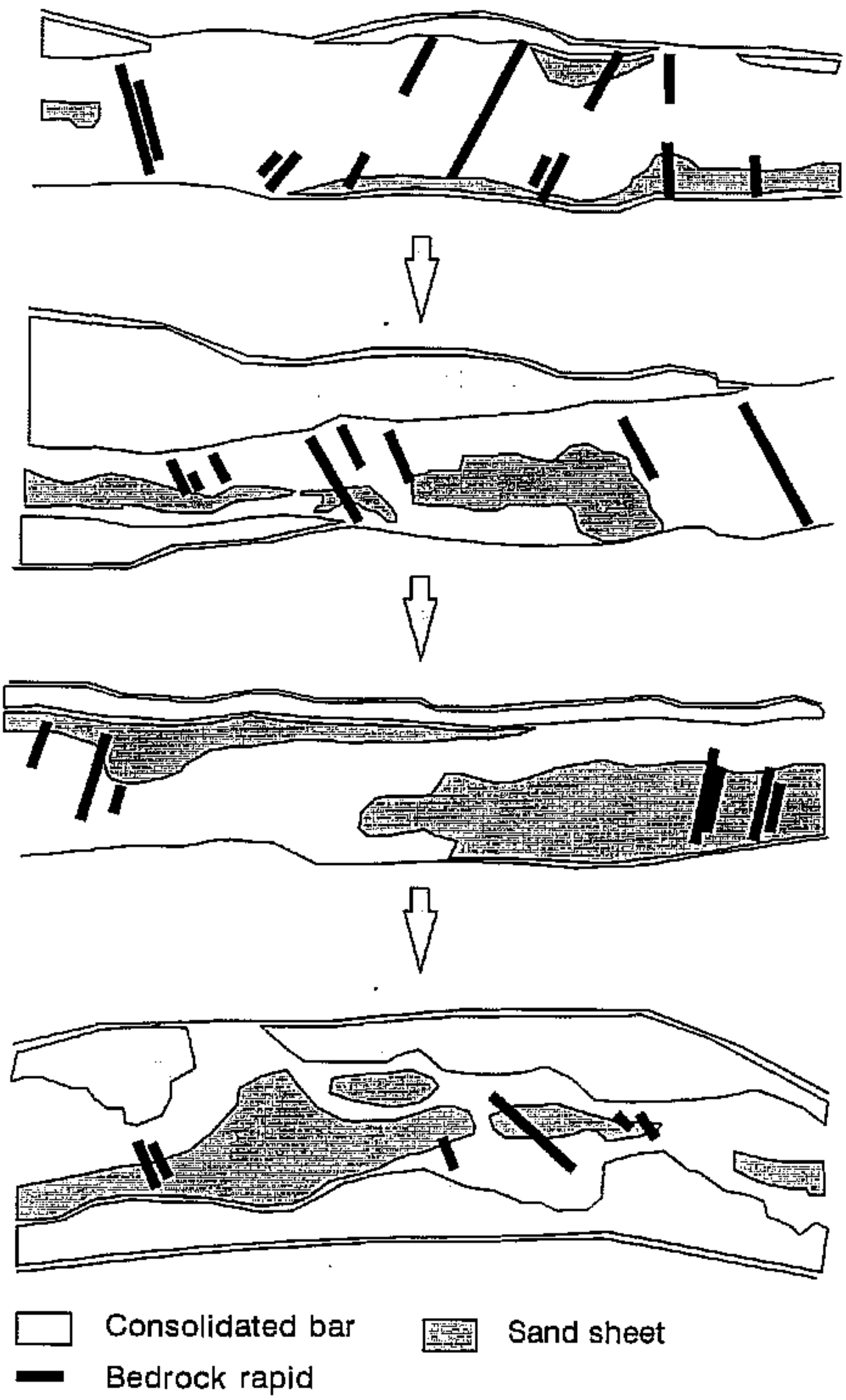


Figure 99. A qualitative model of channel evolution for the Letaba River in the Kruger National Park: bedrock pool-rapid - mixed pool-rapid.

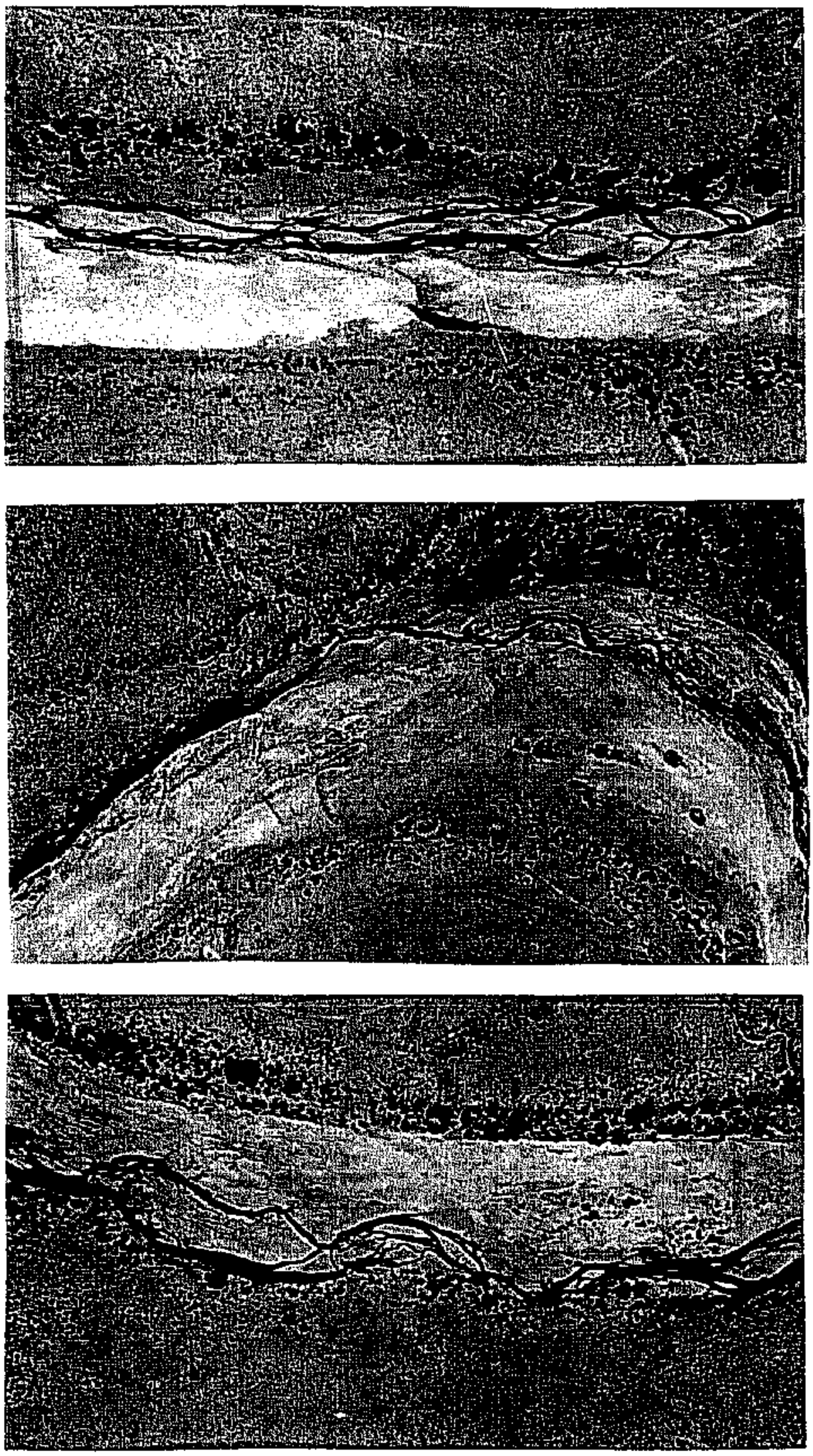


Figure 100. 'Space for time' evolution of an alluvial channel type on the Letaba River in the Kruger National Park.

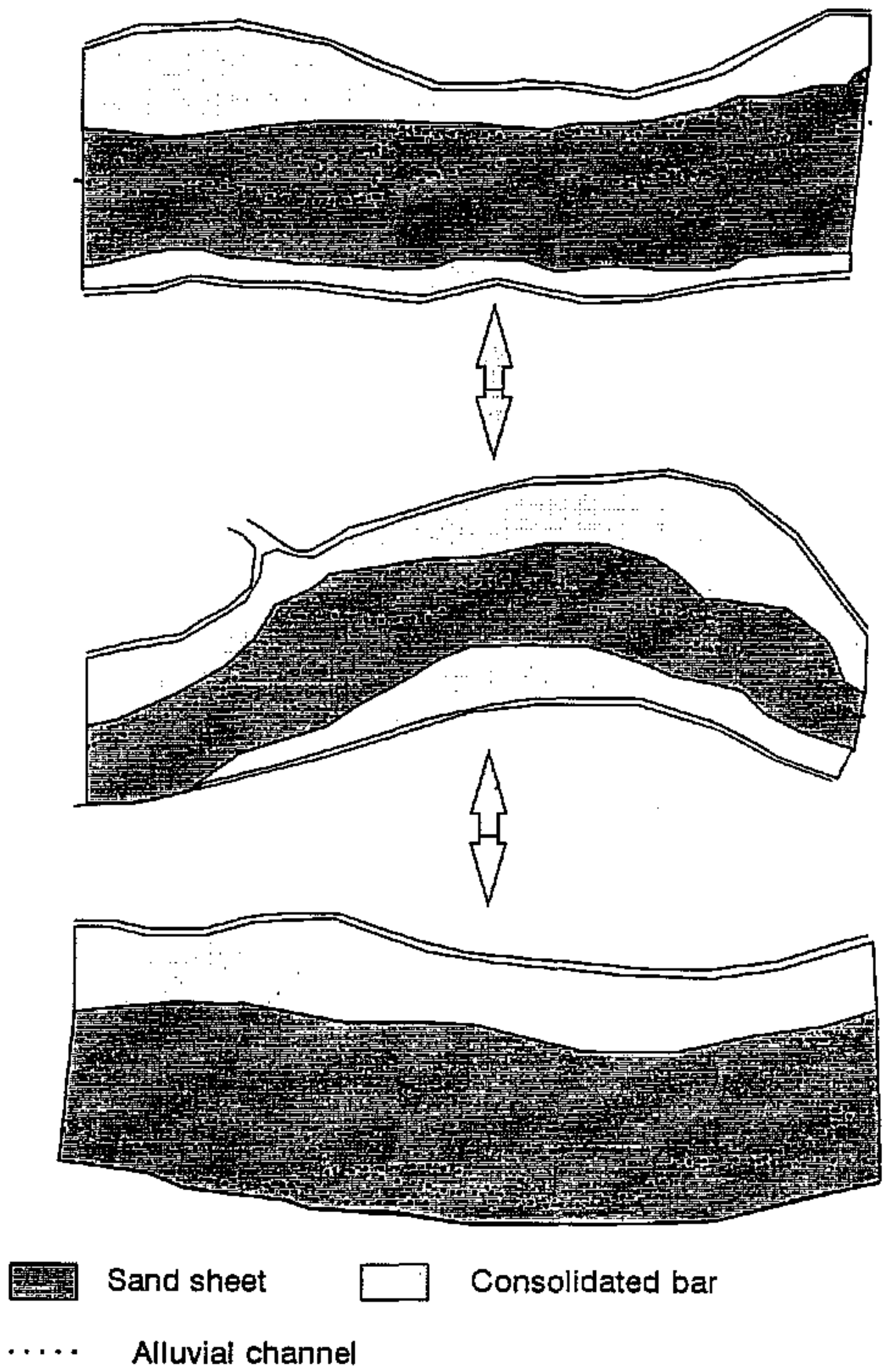


Figure 101. A qualitative model of channel evolution for the Letaba River in the Kruger National Park: alluvial single thread - alluvial anastomosing - alluvial braided.

Table 21. Observed and predicted cross-sectional changes in sediment volume in response to a 655 m^3s^{-1} flow on the Letaba River in the Kruger National Park (Appendix F).

Section	Observed change	Predicted change
upstream 11	minor erosion	stable
upstream 10	not resurveyed	-
upstream 9	minor deposition	stable
upstream 8	major deposition	erosion
upstream 7	not resurveyed	deposition
upstream 6	stable	erosion
upstream 5	moderate deposition	deposition
upstream 4	stable	erosion
upstream 3	stable	deposition
upstream 2	stable	deposition
upstream 1	moderate deposition	erosion
downstream 1	moderate erosion	deposition
downstream 2	moderate erosion	erosion
downstream 3	stable	deposition
pump station	not resurveyed	-
downstream 4	major erosion	erosion
downstream 5	minor deposition	deposition
downstream 6	minor erosion	deposition
downstream 7	moderate erosion	deposition
downstream 8	minor erosion	erosion

11.6 Quantitative models

Meaningful quantitative and semi-quantitative modelling of the Letaba River, beyond the generation of areas prone to regional sedimentation, is precluded in this study due to the lack of flow data.

The 21 co-ordinated regional cross-sections were used to model the hydrodynamic nature of the extreme flow ($655m^3s^{-1}$) of February 1995. The results predict a varied pattern of erosion and deposition (Table 21), with erosion at upstream 6, 4, 1 and downstream 5. Deposition is predicted at upstream 7, 5, 3, and 2, and downstream 2, 3, 5, 6, and 7. which compares poorly with the surveyed changes. Reasons for this include the use of a single flow to model a flood event, the use of regional slopes in the study where local slopes would have been a more accurate representation of conditions at each cross-section and the poorly understood behaviour of ephemeral rivers in response to flood events. Similarly, the surface-sub-surface hydraulic interaction and lateral sediment inputs were not considered.

11.7 Summary

☺ The Letaba catchment is highly degraded, to the extent that the river is now an ephemeral system where sand deposition has largely masked the effects of underlying bedrock.

☺ A set of qualitative channel change models is presented for the Letaba River in the Kruger National Park based on space for time substitution.

☺ Bedrock anastomosing channel type change occurs via deposition of sand and consolidated macro-channel deposits.

☺ Bedrock pool-rapid channel type change occurs as sand sheets build up to mask the effect of bedrock rapids.

☺ Alluvial single thread, braided and anastomosing channels appear to alternate as the planform of the alluvial distributary channels alter.

☺ Quantitative modelling of channel change has been limited due to the quality of the base data available for the river.

☺ The transfer of the research rationale demonstrated on the Sabie River is limited here, due to the lack of data on the system.

12. CONCLUSIONS AND RECOMMENDATIONS

The project on the Geomorphological Response to Changing Flow Regimes of the Sabie and Letaba River Systems provides a descriptive basis for the interface between hydrology and biotic response to changing flow regime. This report provides the communication system whereby morphology (physical habitat) and local and regional hydraulic conditions can be discussed, described and quantified.

The existing geomorphology and the nature of changes in the Sabie and Letaba rivers result from a complex interaction of water discharge and sediment, the development of the vegetation along the rivers and the effects of human activity (dams, weirs and water usage). The processes and their interaction need to be understood in order to quantify change in the rivers in response to changes in different contributing conditions. The Sabie and Letaba rivers display a mixed bedrock-alluvial character. Existing models and techniques, developed for alluvial rivers in dynamic equilibrium, must be used with extreme caution and the implications of applying these to the Sabie and Letaba rivers must be well understood.

The original aims of the research project have been achieved. A comprehensive description and structuring of the geomorphology of the Sabie and Letaba rivers is proposed. Patterns of temporal change have been investigated and change theory established. A conceptual channel change model is suggested for both rivers and this has been translated into qualitative and semi-quantitative system evolution models for the Sabie River. Similar results for the Letaba River were precluded by the lack of hydraulic information for this ephemeral system.

12.1 Principal conclusions

1. The Sabie and Letaba rivers both display a large well defined incised macro-channel that have contained all recorded flows within their banks.
2. Within this macro-channel on both rivers, a smaller scale network of perennially active and seasonally active channels exist.
3. The flow regime of the Sabie River is perennial but extreme, with low constant winter flows and high variable summer flows. The Letaba catchment has been significantly impacted by human influence and currently displays an ephemeral flow regime in response to extreme rainfall events in the catchment.
4. The morphological associations within these channels may be structured to reveal five principal channel types on the Sabie River: bedrock anastomosing, mixed pool-rapid, mixed anastomosing, alluvial braided and alluvial single thread. The Letaba River may be classified as having five principal channel types: alluvial anastomosing, mixed anastomosing, alluvial braided, mixed pool-rapid and alluvial single thread.
5. Four main dynamic catchment controls on channel form have been identified for both rivers. These are catchment sediment production rate, local channel transport capacity, flow variability and flow magnitude.
6. Each of the channel types identified displays its own characteristic hydraulic and channel flow resistance parameters.

7. Changes to the catchment control factors are occurring in both catchments as a result of climatic variability and anthropogenic influence, in the form of land degradation and water abstraction for agriculture, forestry, industrial and domestic use.
8. Significant sedimentation is predicted for three locations on the Sabie River in the Kruger National Park. This is already reflected in a significant increase in alluvial influence in these areas and represents zones of long term sediment build up.
9. Sedimentary unit change as a result of erosion and deposition is operating at a number of scales. Active channel features are changing in all channel types with a general build-up of bars during reduced flow years. Such a change is continual and appears to fluctuate as the flow and sediment regime alter. Larger scale macro-channel features change at a much slower rate, in response to rare very large flood events.
10. Return period studies of the flow regime influencing the sedimentary features reveal that active channel features are overtopped by the 1 to 1.5 year return period flow on the annual maximum series. Macro-channel features are generally subject to inundation only by the 3 to 5 year flood, but some features are flooded only during more extreme events such as the 18 year return period flood. These findings support the qualitative change rates suggested above.
11. A model is presented that links the various channel types along the Sabie River in a semi-quantitative sense, predicting annual sediment deposition and erosion in response to a daily average flow regime. Predictions using the model agree well with changes observed on the Sabie River. The model uses daily discharge values and an annual local sediment input time series, as such it can predict change at the channel type scale. Simulated flow regimes can be input to model a range of water management scenarios for comparison with natural and historic change.

12.2 Further research

The level of understanding of river systems similar to both the Sabie and Letaba in southern Africa can be increased if research efforts are concentrated in the following directions:

1. Continued development of the channel overspill model to simulate hydraulic conditions in bedrock influenced sections of the rivers.
2. Monitoring and analysis of a greater range of flows than was experienced during the course of this research, to refine the techniques used to predict the effect of larger magnitude flows.
3. A detailed study of the surface-subsurface flow interaction in ephemeral systems, which will better predict water volumes necessary to restore such systems to a state of perennial flow.
4. Further refinement and validation of the semi-qualitative channel change model to improve on its predictive capabilities.
5. Integration with ecological knowledge in order to establish geomorphological/ecological response linkages.

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APPENDIX A: FIELD TECHNIQUES

APPENDIX A.

FIELD TECHNIQUES USED IN THE PROJECT

1. FLUVIAL GEOMORPHOLOGY

1.1 Selection of monitoring sites

Site selection was conducted on two levels. The first was aimed at evaluating the dynamics of the whole river between the railway bridge on the KNP western boundary and the Mozambique border (Regional) The second monitoring network operated at the Local scale, and evaluated the dynamics of single examples of each channel type (Bedrock anastomosing, mixed anastomosing, mixed pool-rapid, alluvial braided and alluvial single thread).

1.1.1 Regional sites

Regional channel cross-sections were selected to cover the full range of channel types observed on the Sabie river (Fig. a).

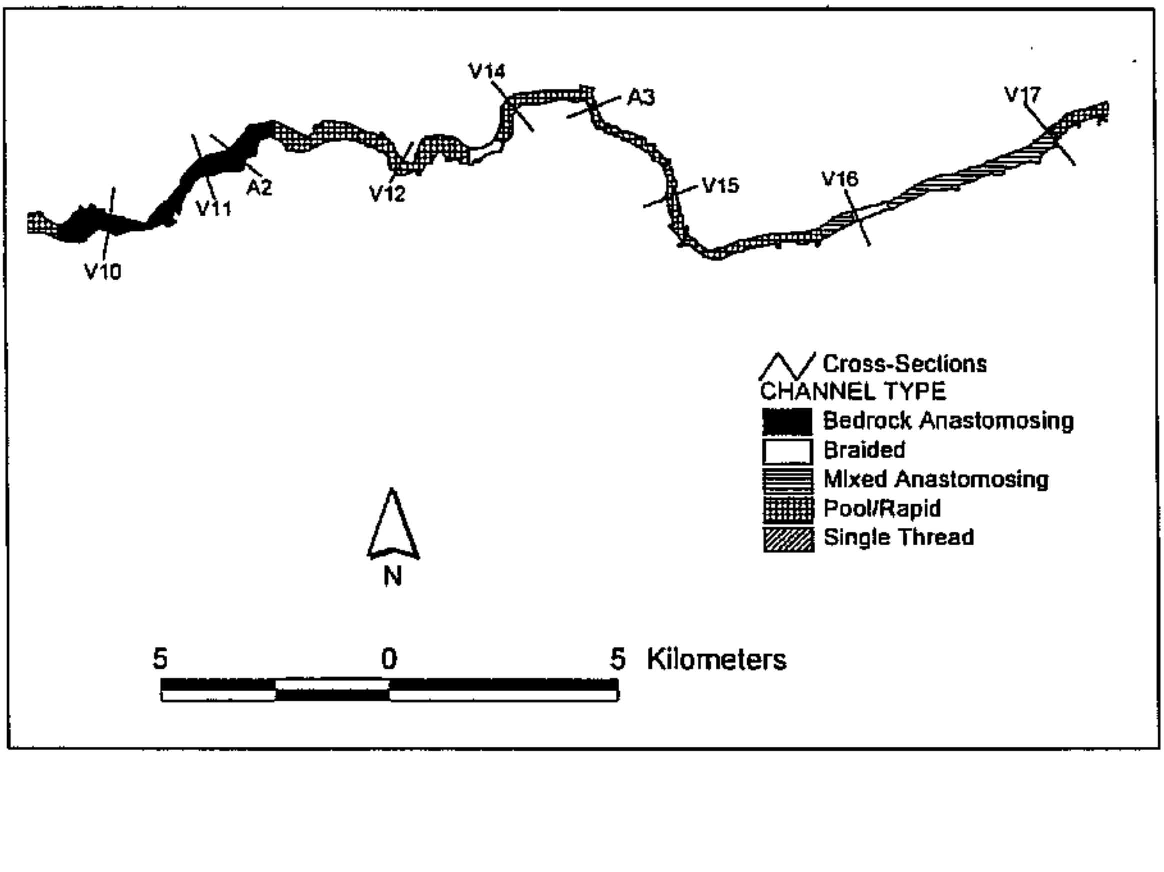


Figure a. Example location of regional channel cross-sections designed to cover all channel types.

1.1.2 Local sites

Local channel cross-sections were selected in order to cover all of the low flow hydraulic controls operating at the representative sites of each of the channel types (Fig. b).

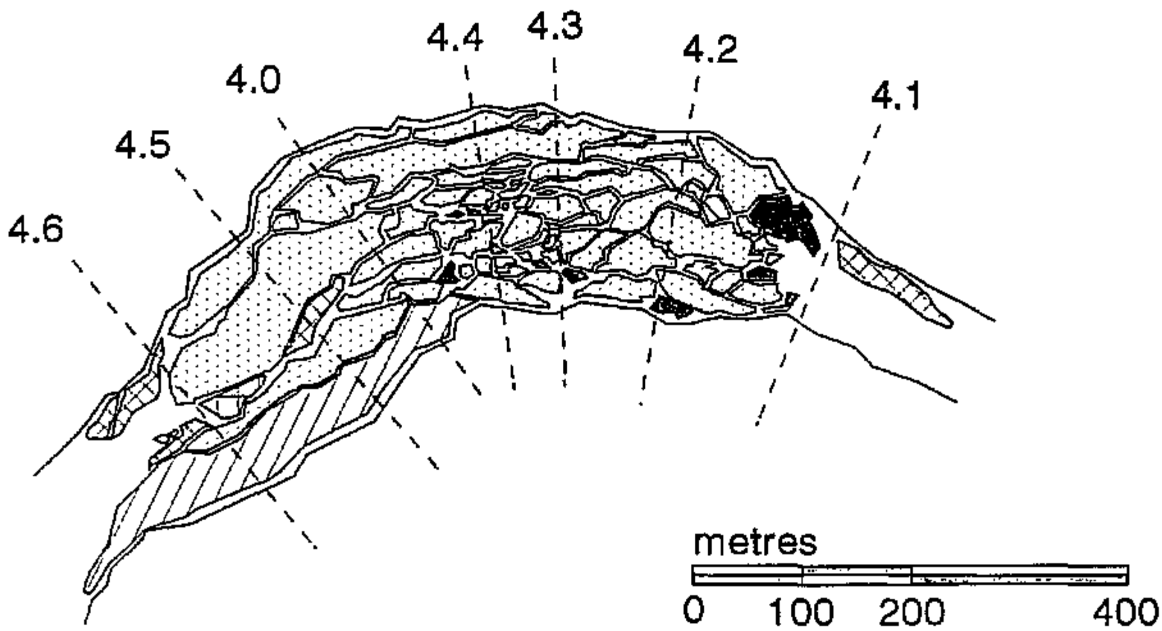


Figure b. Cross-section location selection at the local scale to monitor low flow hydraulic controls.

1.2 Cross-section survey method

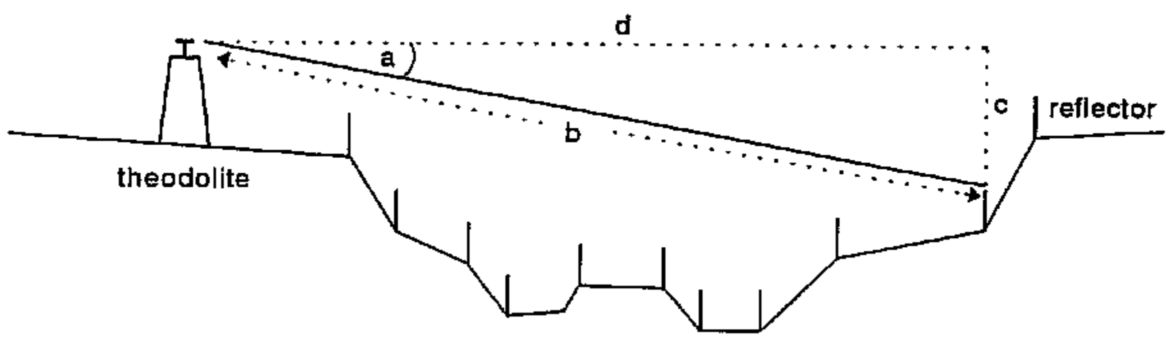
Surveying of the regional and local cross-sections involved two processes: setting up and co-ordinating the benchmarks at each section and surveying the channel geometry relative to these benchmarks.

1.2.1 Benchmark co-ordination

Benchmarks were initially cemented in at the top of the macro-channel on the line of the cross-section perpendicular to the planform of the macro-channel. The benchmarks were co-ordinated in order to determine their relative position in space along the river. A Geographical Positioning Satellite (GPS) system was used for this task. Local triangulation points were utilised and the benchmarks were co-ordinated relative to these by setting up the satellite receiving equipment over successive pairs of benchmarks, linking the traverse to the triangulation points wherever possible. The displacement signals received at each benchmark, together with data available on the relative positions and velocities of the recorded satellites, were converted to x:y:z co-ordinates. The Department of Water Affairs and Forestry (DWAF) provided the equipment, computer programs and expertise for this task.

1.2.2 Survey of channel geometry

A total station theodolite and reflector system was used to measure the cross-section. This was set up over the benchmark and the height difference between the benchmark and the instrument recorded. A line was cut through the vegetation across the section and the reflector was moved across the channel (noting the reflector height) stopping to measure each break of slope. Data were recorded on the angular distance to the reflector, the horizontal angle and the vertical angle, these were used to calculate the cross-section distance and drop from the instrument using the sine and cosine rule (Fig. c). The instrument-benchmark distance and reflector height was then subtracted from the recorded vertical drop to generate cross-section elevation figures relative to the benchmark.



vertical drop c = sin a * b

horizontal distance d = cos a * b

Figure c. Cross-section geometry survey method using a theodolite.

1.3 Morphologic unit mapping

Individual morphological units were mapped for each cross-section based on observational data from walkover surveys and analysis of the aerial photographs.

2. DISCHARGE

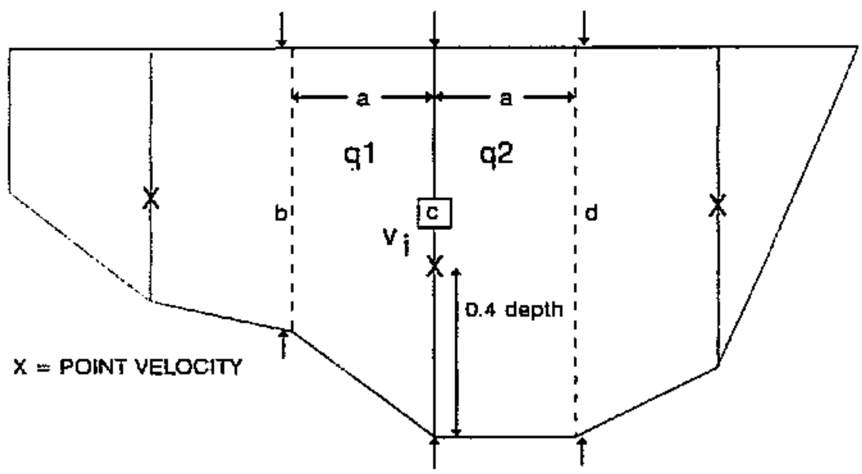
The rate of water flow in the Sabie River was determined from DWAF gauging stations (archive information) and by direct flow gauging.

2.1 Use of archive information

Gauging stations were located at several points along the study rivers, these provided good quality records of daily flows and interrogation of the weir traces provided instantaneous measures of peak flows.

2.2 Flow gauging

Where the gauging stations drowned out at high flows, or where flows were divided between several distributary channels, it was necessary to carry out discharge estimation using the velocity-area method. Gauging was conducted using a Valeport electromagnetic flow meter that measures small diferences in electrical conductivity between points in the downstream and cross-stream directions, these differences may be directly converted to channel velocity. The cross-section (usually a bridge site for safety) was first divided into at least 20 sub-sections (often >50 due to the width of the channel) and flow depths were determined by dropping a weighted measuring tape into the flow. Sub-section flow areas were calculated from this data using the trapezium rule (Fig. d). The flow meter was then introduced into the flow at 0.6 of the flow depth at the midpoint width of each sub-section (this corresponds to the average velocity in the vertical assuming a logarithmic velocity profile with distance from the bed). An average velocity was recorded over a 60 second period and the sub-section discharge calculated from the product of the sub-section velocity and sub-section area. Total channel discharge is given by the summation of the sub-section discharges (Fig. d).



$q1 = (½(b+c)*a)*Vi$ $q2 = (½(c+d)*a)*Vi$

$Q = \sum q1..qn$

Figure d. Velocity-area method of discharge calculation.

3. RATING RELATIONSHIPS

The water stage relationship to discharge was determined for each cross-section as such information reflects local hydraulics and channel roughness characteristics, and can be related to the flow record to investigate flow level-frequency relationships. These data were collected on a real time and historic basis and involved relating flow levels to discharge recorded at the gauging stations during steady flow (constant flow method) and elevated flows (variable flow method).

3.1 Real time flow monitoring

3.1.1 Determination of flow level

The instantaneous flow level at any cross-section was determined by levelling from the co-ordinated benchmark down to the water surface. The levelling instrument was set up with a clear view of both the benchmark and the water. A reading was taken to the staff placed on the benchmark and on the water surface, the relative difference in the staff readings is equivalent to the drop from the benchmark to the water (Fig. e). The time at which the data were collected is also recorded, for use in discharge determination.

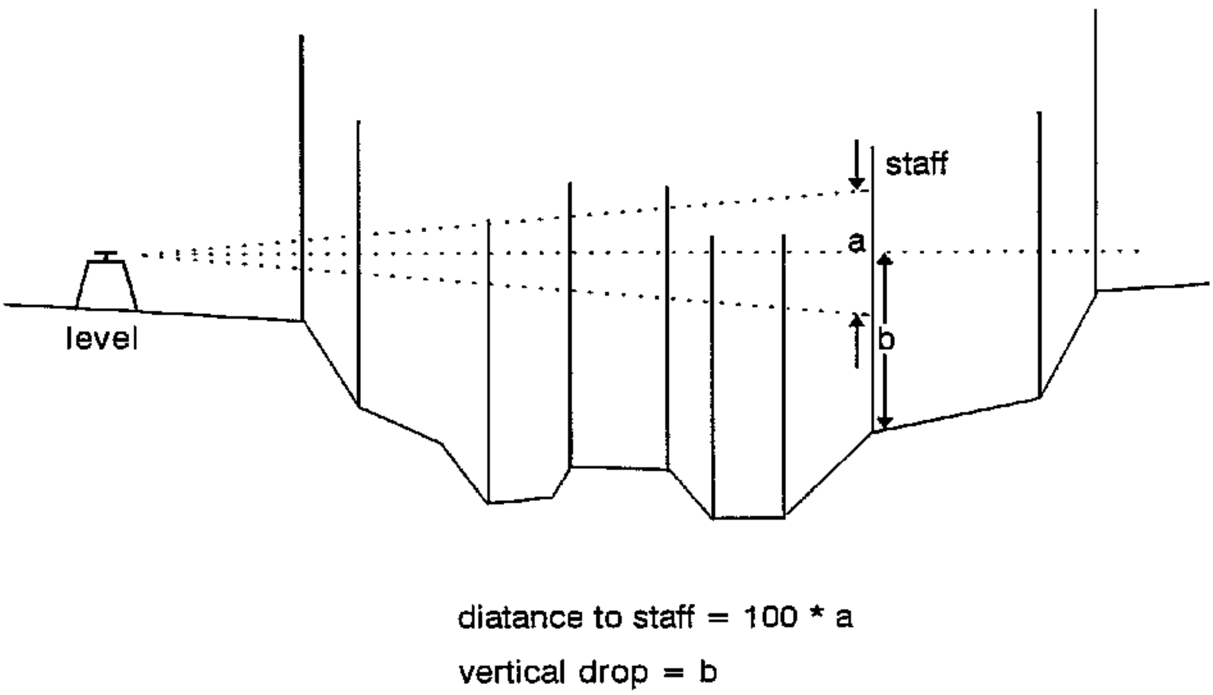


Figure e. Real time flow level determination using a levelling technique.

3.1.2 Determination of flow discharge

Discharge may be determined by one of two methods depending on the flow on the day.

Constant flow period method
Where the flow is constant (discharge is neither increasing or decreasing) the flow recorded at the nearest gauging station at the time the stage level was taken, can be used to approximate the flow at the cross-section (Fig. f).

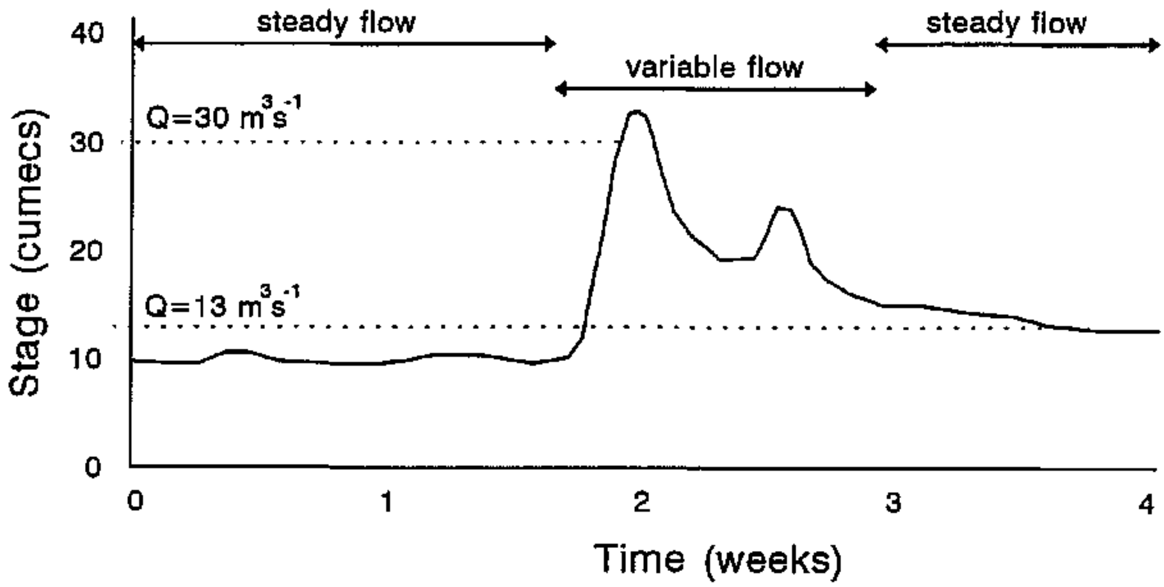


Figure f. Constant and variable flow definitions from gauging weir traces.

Variable flow period method

Where discharge is increasing or decreasing (Fig. f), a flood wave correction factor must be applied to the weir data in order to determine the flow at the cross-section. Two gauging stations are utilised, one upstream and one downstream of the cross-section. The time taken for the flow peak to travel between the two gauges is estimated from the weir traces (Fig. g). This time is divided by the distance between the two stations to determine a rate of travel for the flow peak. This rate is then multiplied by the distance between the upstream gauging station and the cross-section to determine how long the flow was lagged between the two sites. The weir trace was then used to determine the flow at the gauge lagged by the travel time to the cross-section (Fig. g).

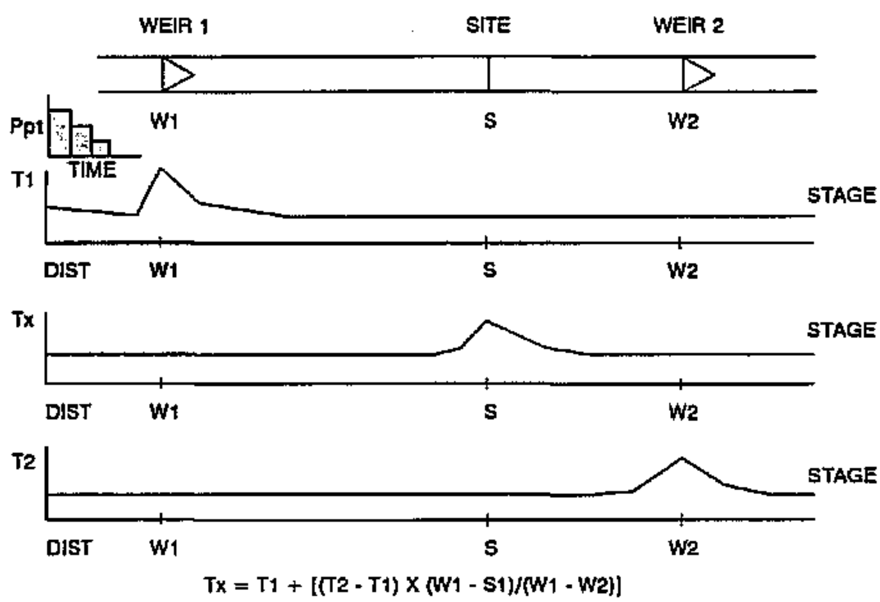


Figure g. Weir lag time method to determine cross-section discharge under variable flow conditions.

3.2 Monitoring historic flows

Flows occurring during periods when direct monitoring was not possible were monitored at a low level using peak level flow recorders.

3.2.1 Installation of monitoring equipment

Monitoring of flow peaks was achieved at each cross-section using mechanical methods. Paired, three metre poles were cemented into the channel at each cross-section so that the higher pole overlapped the lower pole by approximatly half a metre. These poles were then painted with water soluble paint.

3.2.2 Determination of peak flow level

Given increased flow, the painted poles would be progressively inundated and the paint washed off, this line could later be surveyed back to the benchmark at each section to determine the peak flow stage using the levelling technique detailed in section 3.1.1 (Fig. h).

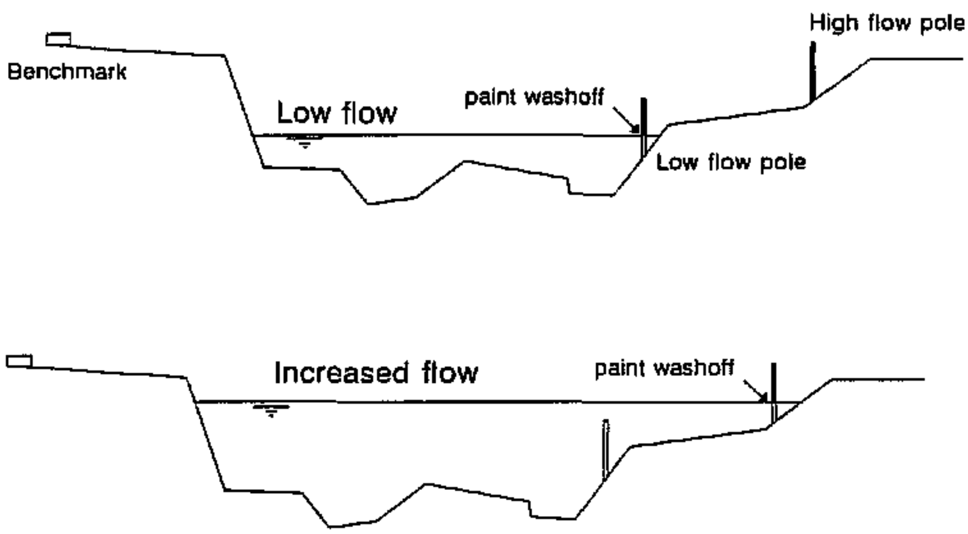


Figure h. Use of painted high level flow recorders to collect peak flow stage data.

3.2.3 Determination of peak flow discharge

The methods detailed in section 3.1.2 were used to determine historic peak flow discharges.

3.3 Data analysis

The stage data was plotted against the corresponding discharge data to construct a stage-discharge or rating curve for each cross-section.

4. SEDIMENT CHARACTERISATION

Bed-material was collected and analysed to determine the size frequency characteristics of the sediment at each of the cross-sections. This was used in channel roughness and sediment transport calculations.

4.1 Sampling surface bed-material

Surface samples were collected from each morphological unit across each of the cross-sections. on average 3-5 kilograms of sediment was collected in each sample and this was bagged and labelled and taken back to the laboratory for dry sieve analysis.

4.2 Sampling sub-surface bed-material

Sub-surface samples were collected from each morphological unit across each of the cross-sections by augering through the surface sediment. On average 3-5 kilograms of sediment was collected in each sample and this was bagged and labelled and taken back to the laboratory for dry sieve analysis.

4.3 Data analysis

Each sample was dried and sieved through a set of gravel and sand sieves ranging from 20mm down to 0.0125mm. the contents of each sieve pan was weighed and the result recorded. Larger clasts were hand measured and weighed. The cumulative size frequency was determined by summing the weights recorded in each sieve pan from the smallest upwards and dividing each by the total weight of the sample (this produces the standard percentage less than frequency distribution). Size frequency plots were then constructed and characteristic grain sizes determined (D_{50}= 50% frequency grain size, D_{84}= 84% frequency grain size) (Fig. j).

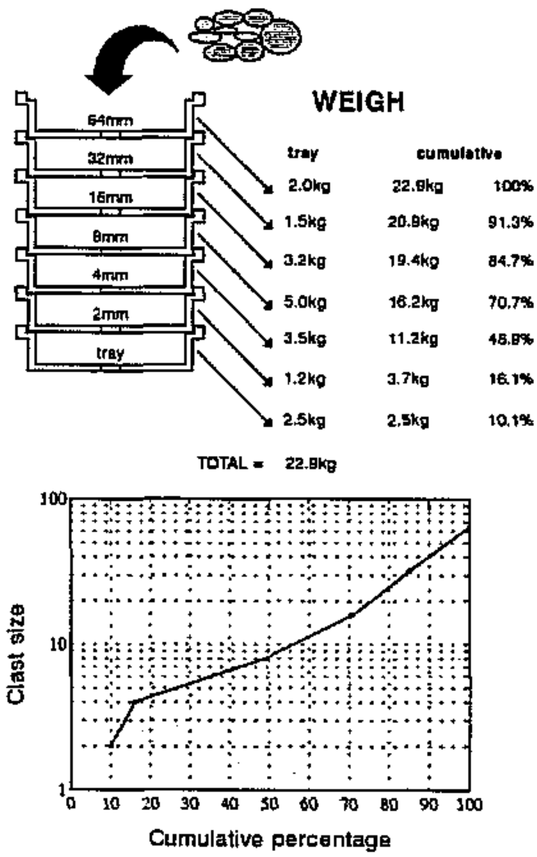


Figure j. Determination of bed-material characteristics.

5. SEDIMENT TRANSPORT AND CHANNEL CHANGE

Short term (seasonal flows and single flow event) and long term (10s of years) changes in sediment distribution within the macro-channel was investigated to identify areas prone to sedimentation and to determine pathways of channel change.

5.1 Short term channel change

Change in sediment distribution due to event based or seasonal flows was monitored at each cross-section by three methods, two involve cross-section monitoring and the third utilises aerial photographs to assess channel change.

5.1.1 Multiple resurvey method

Channel change can be determined at the cross-section scale by repeating the cross-section survey technique detailed in section 1.2.1. Evaluation of the two cross-sections by direct comparison indicate areas of erosion and deposition (Fig. k)

Figure k. Multiple resurvey of cross-sections to determine erosion and deposition.

5.1.2 Scour and deposition monitoring

Scour chains, or rods and plates can be used in situations where scour and deposition occurring during individual flow events require monitoring (this is important in ephemeral systems and where bulk sediment transport figures are required). Holes was dug and 1.5 metre chains were buried vertically to a depth of 1 metre across the macro-channel in exposed high energy areas, the remaining chain lengths were left on the channel bed. Reinforcing rods (13mm diameter) of a similar length were used in lower energy areas and a metal plate was threaded onto each rod and left on the surface of the channel. Scour during a flood event exposes the buried chains to the level of the new erosion surface and causes the plates to move down the rods. Subsequent deposition during waning flows re-buries the chains and plates. Resurvey of the monitoring sites to the depth of the chains or plates provides data on erosion and subsequent deposition (Fig. 1).

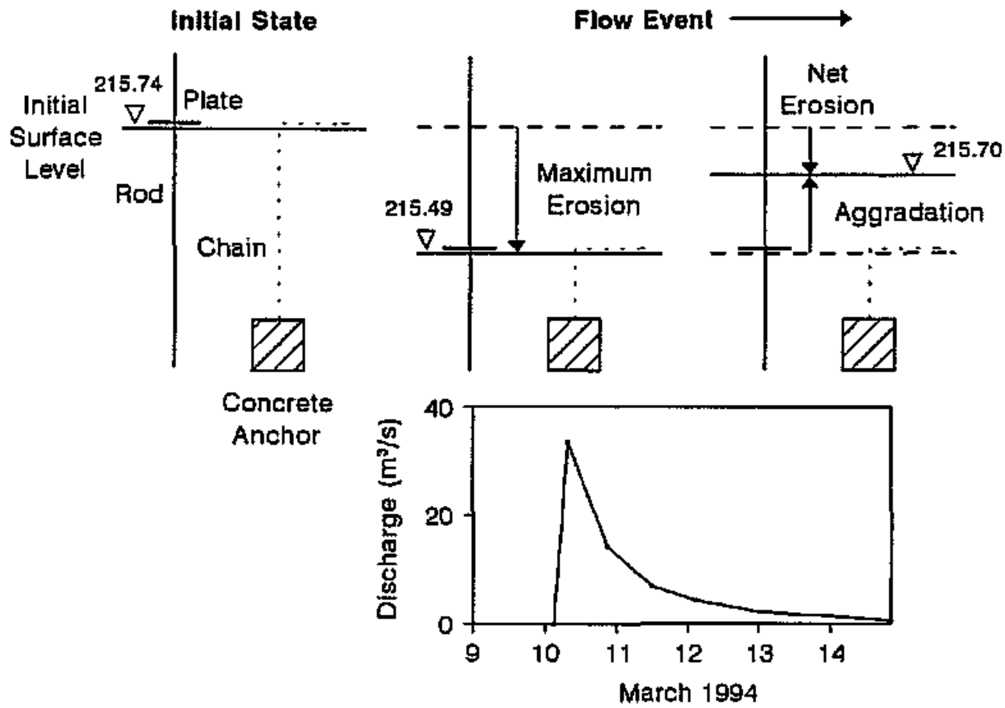


Figure 1. Use of rods and chains to determine flood event scour and deposition.

5.1.3 Aerial photographic interpretation

Mapping of individual areas of exposed morphological units using annual aerial photographs of the same area of channel at the same discharge provides an indication of the changes occurring to the morphology in the reach around each cross-section. Change in area can be calculated for each geomorphlological unit.

5.2 Long term channel change

Long term sediment dynamics can be investigated directly using ground penetrating radar and probing techniques and indirectly using aerial photographs.

5.2.1 Sediment accumulation

Direct methods for determining sediment accumulation at a cross-section include ground penetrating radar and probing.

Use of Ground Penetrating Radar

Ground penetrating radar uses sound wave signals to identify changes in the sedimentary sequence below the bed of the macro-channel, bedrock and water table levels are also recorded. A portable ground penetrating radar is simply dragged across the cross-section and the radar data recorded. These data are analysed using a specialist computer package which rationalises the signals.

Use of sediment probes
Mechanical probing to determine depth to bedrock can be conducted by first augering to the water table at a known point across a cross-section. A 6 metre, 20mm diameter, length of reinforcing rod, sharpened to a point at the tip, can then be inserted into the saturated sediment and forced down to the bedrock boundary. The length of buried rod is then recorded and this is related to the cross-section (Fig. m).

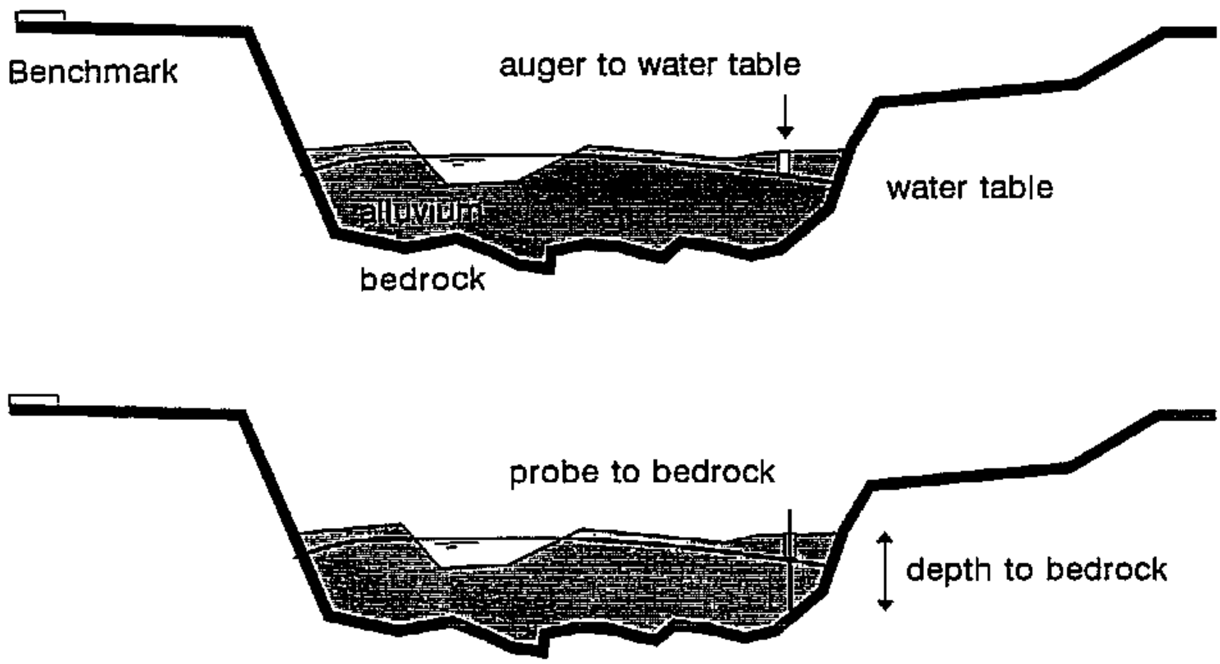


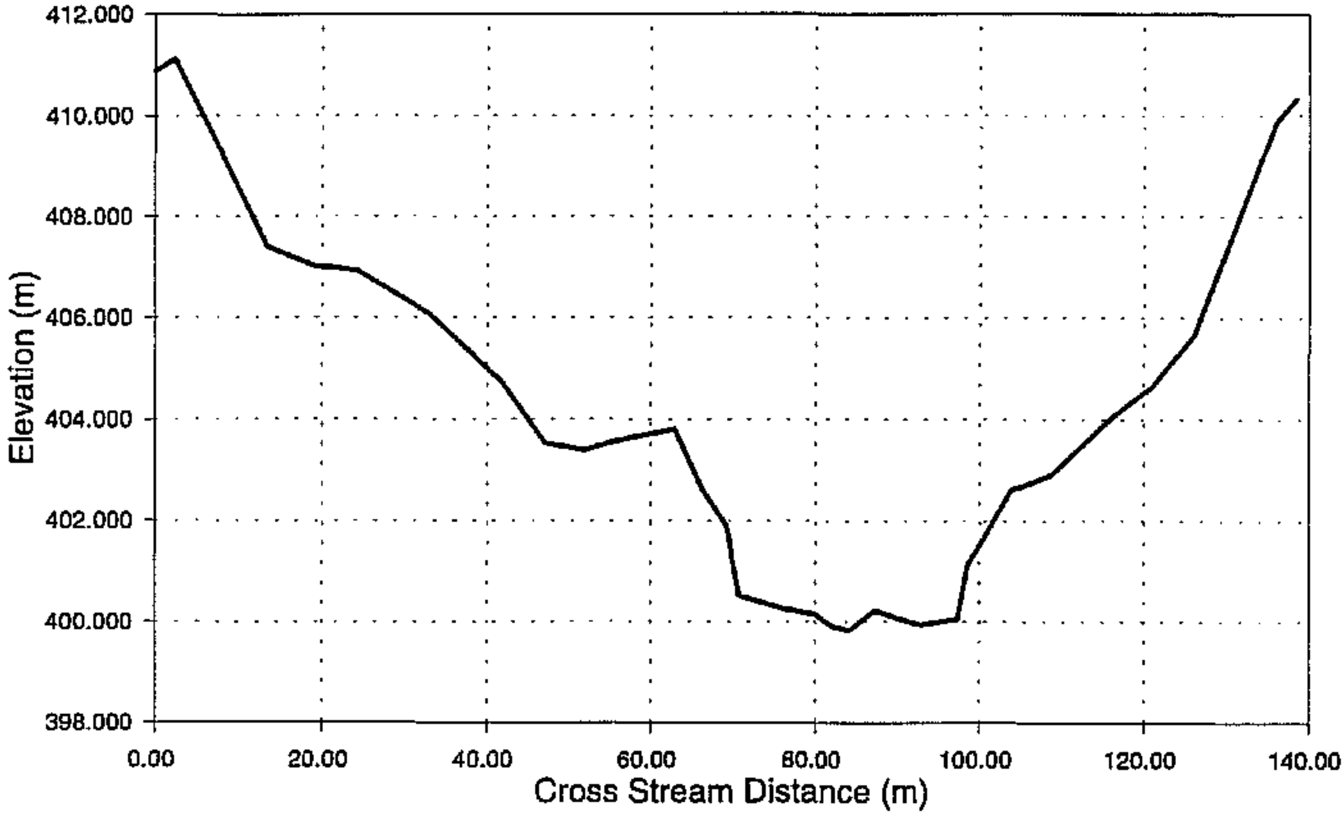
Figure m. The use of mechanical probing to determine sediment depth to bedrock.

5.2.2 Aerial photographic interpretation

The long term pathways of channel morphological change can be inferred from analysis of the aerial photographs of the river using space for time substitution. Photographs of several examples of each channel type should be analysed to determine the standardised aerial coverage of each morphological unit for each photograph, and these should then be ranked according to overall area of sediment visible in each photograph. Analysis of the changes in each morphological unit can then give an indication of the change in geomorphological composition as a result of progressive sedimentation.

APPENDIX B: SABIE RIVER REGIONAL CROSS-SECTIONS

SABIE SECTION 1



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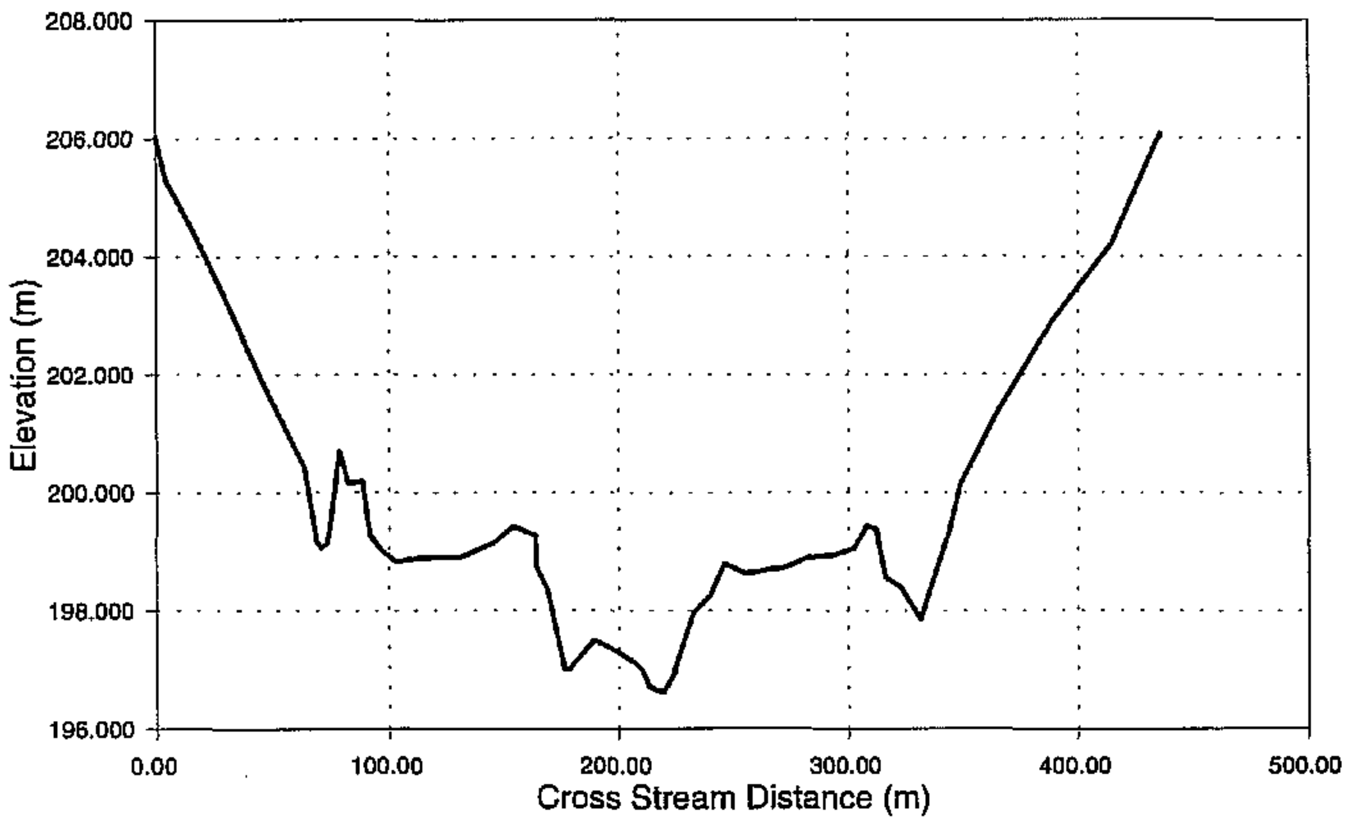

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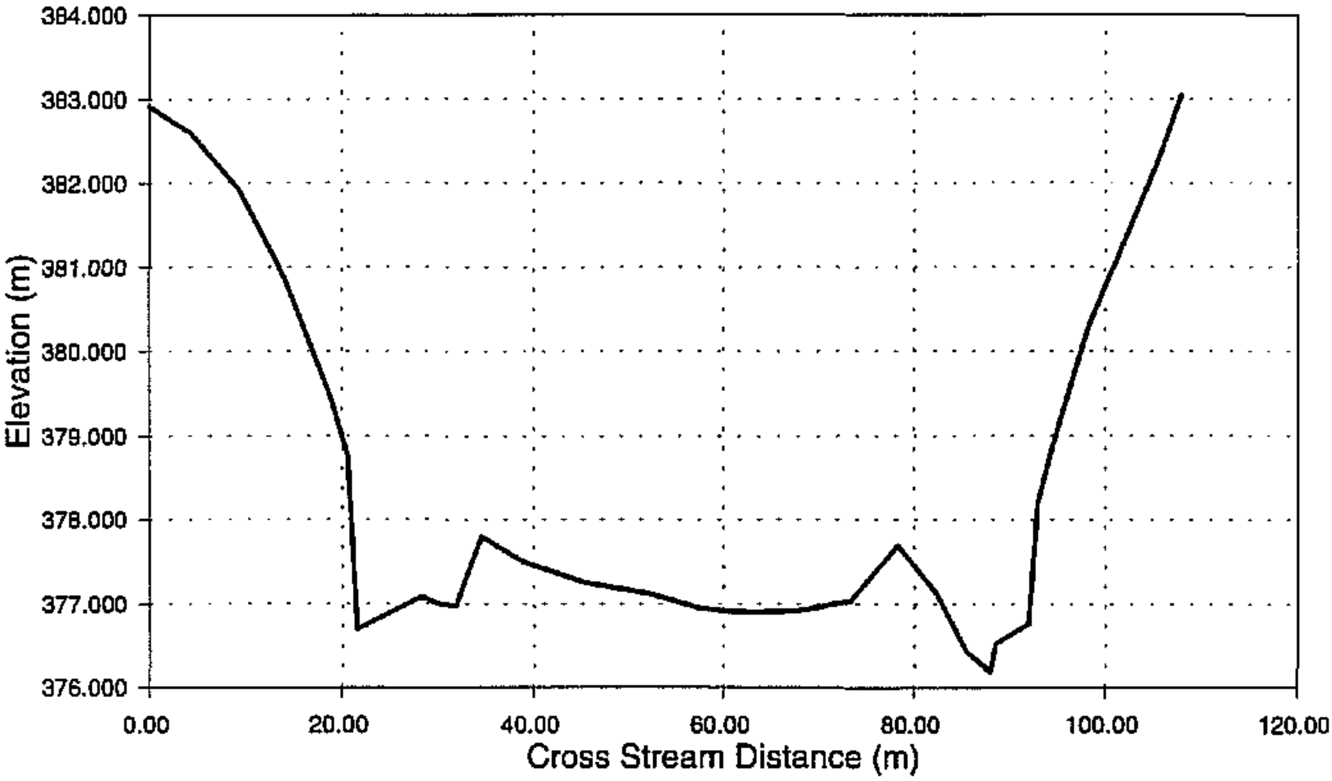

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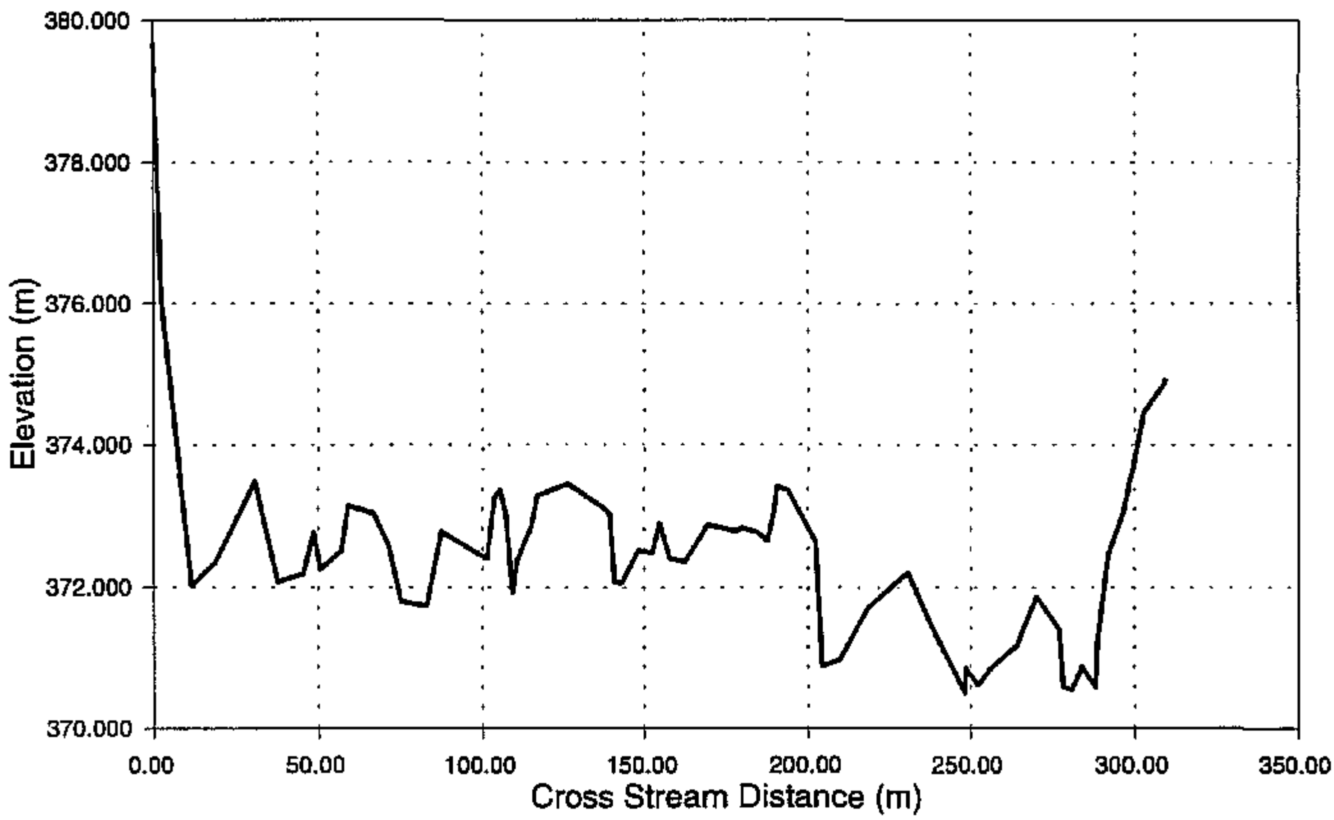

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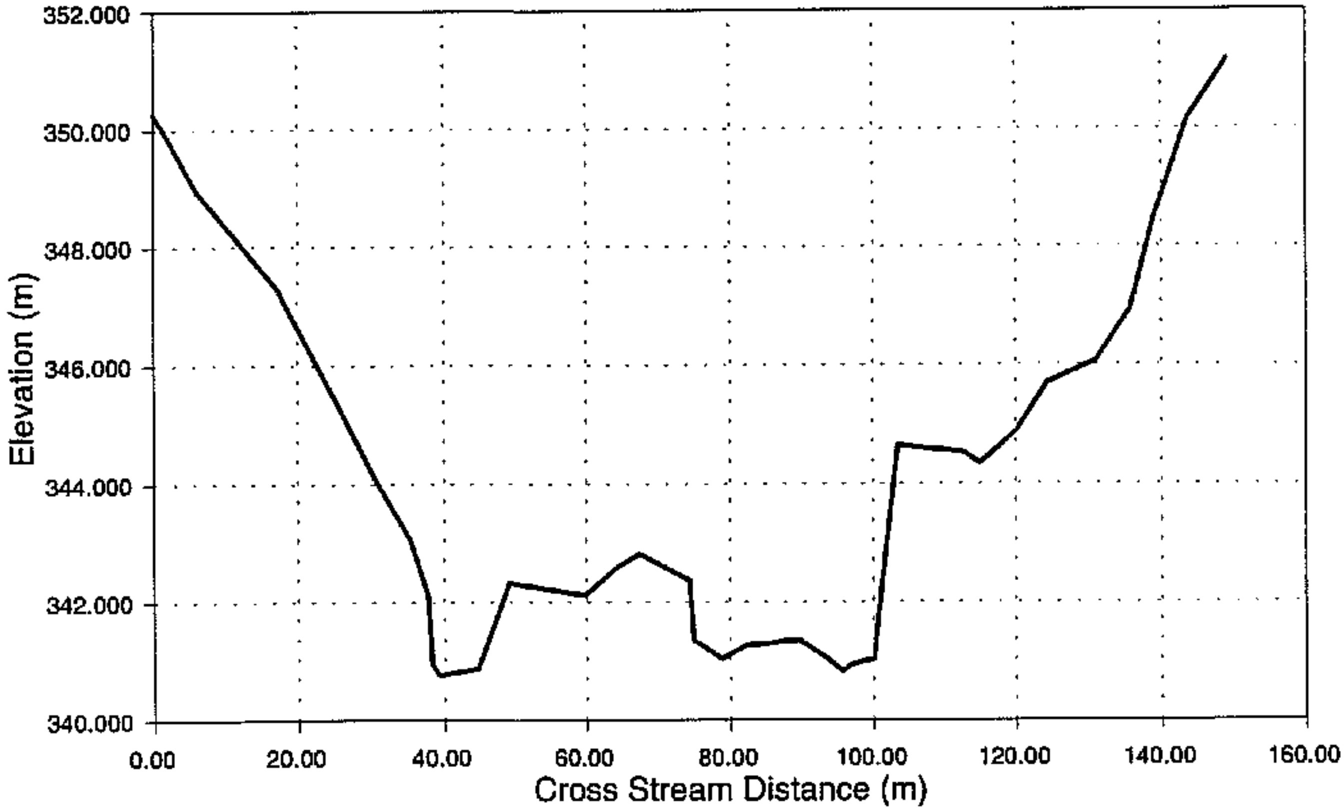

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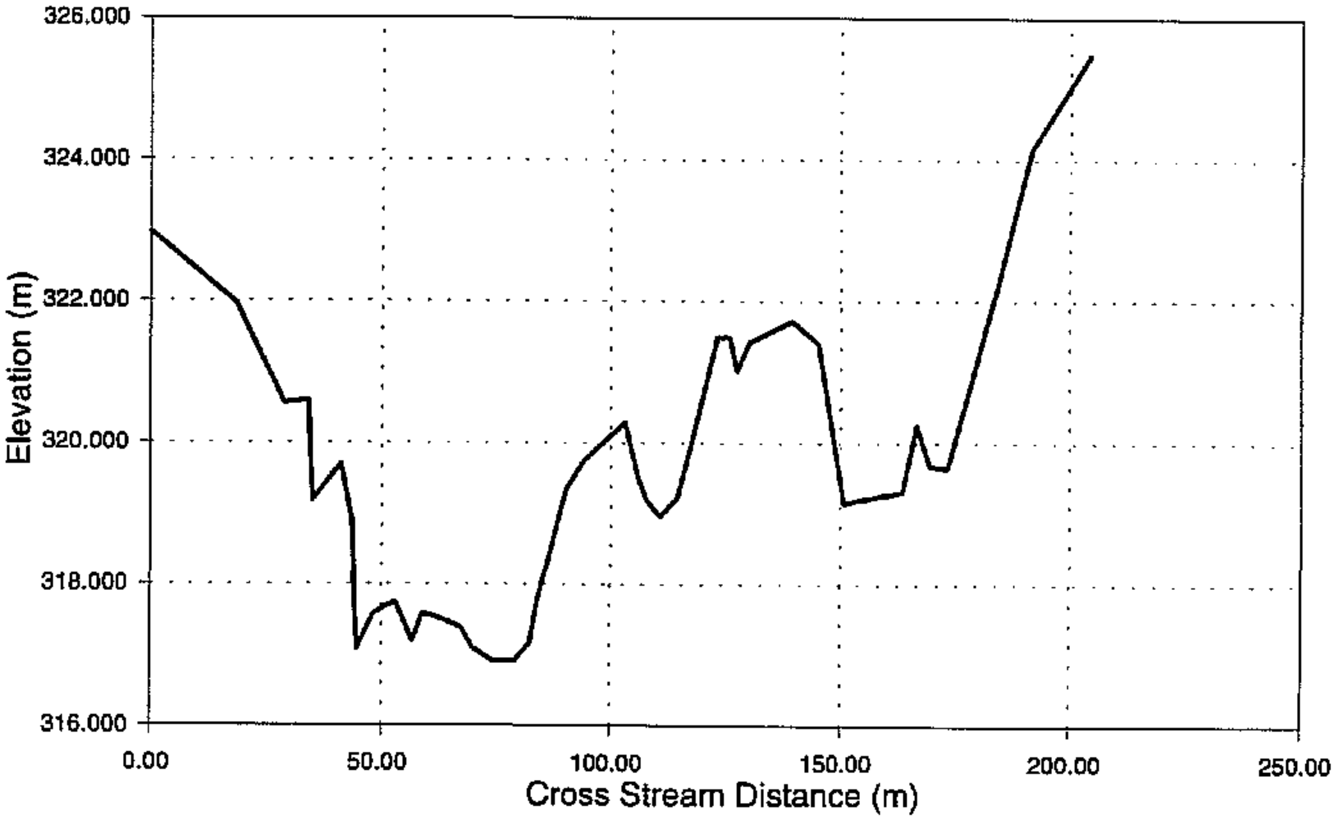

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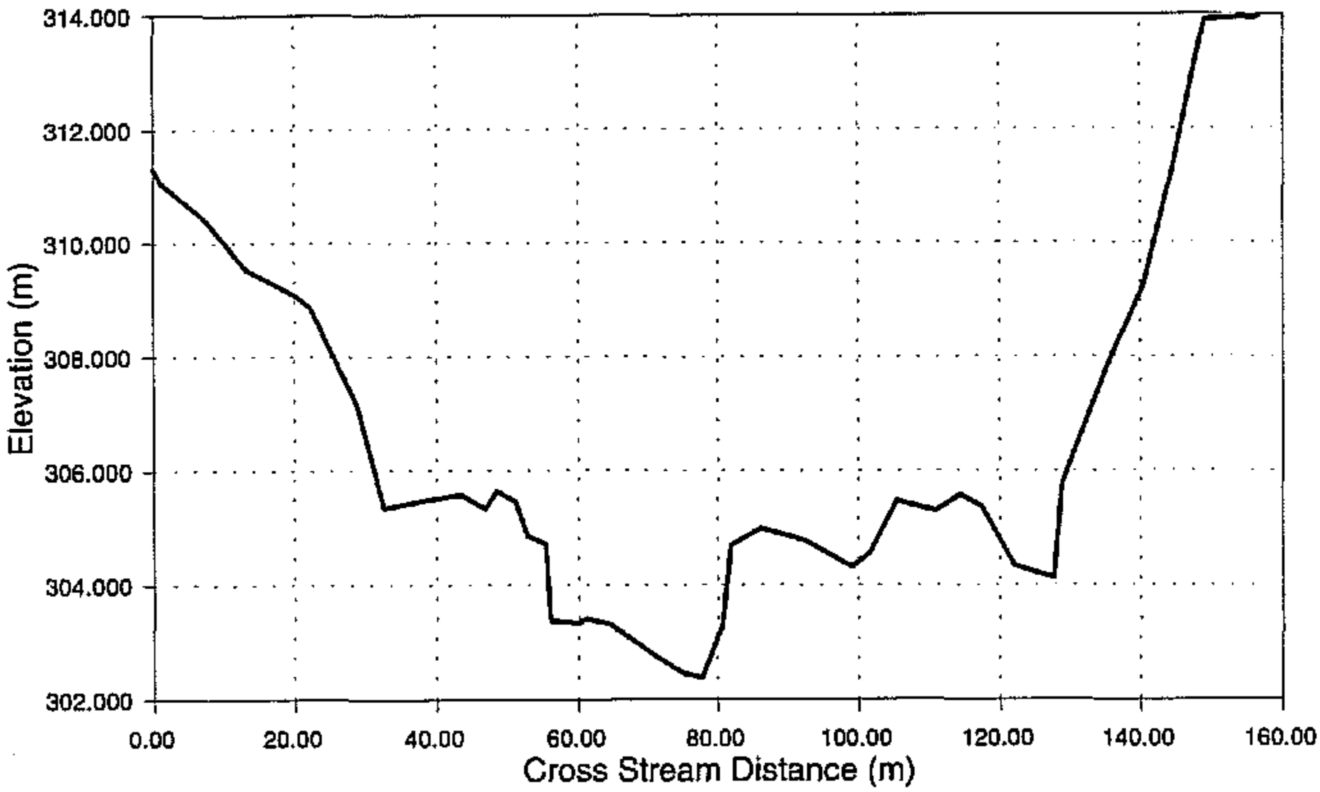

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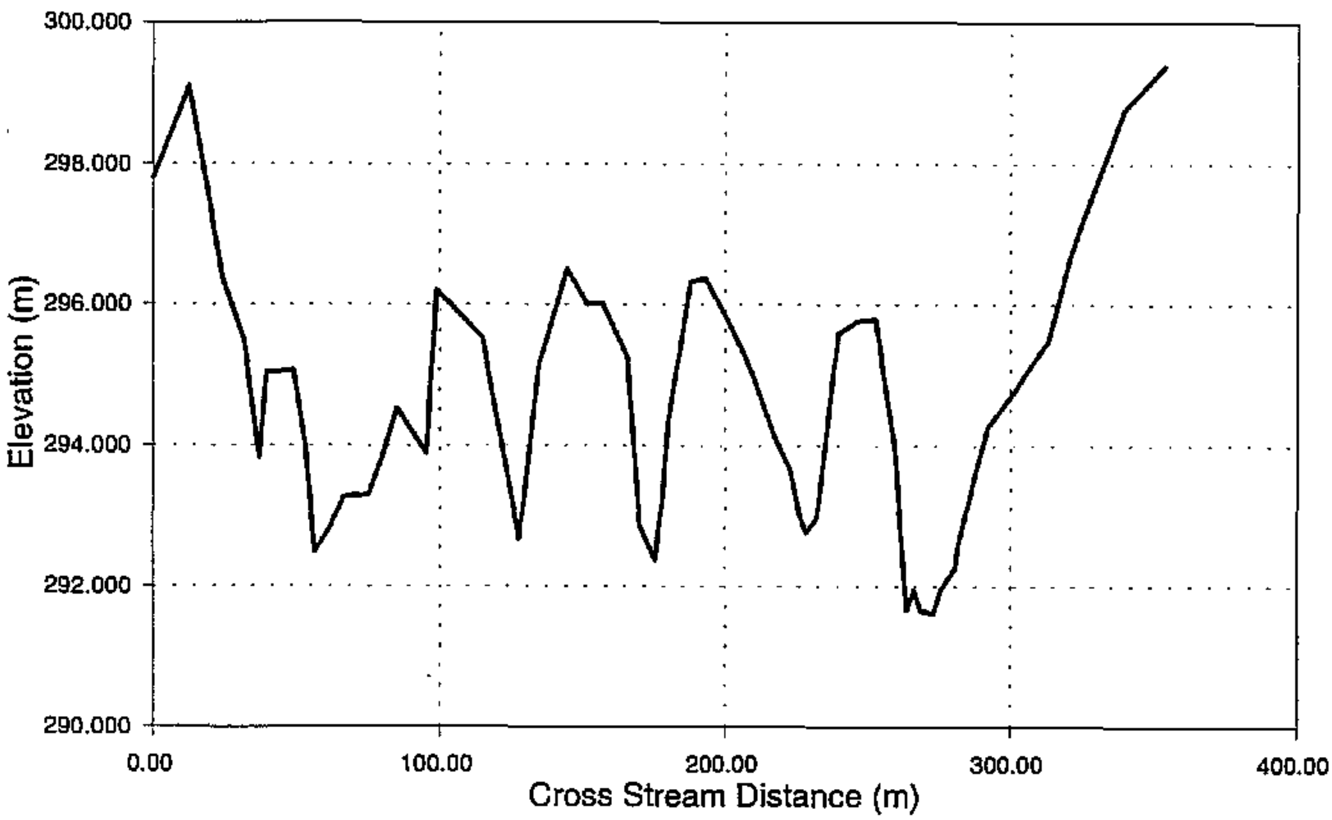

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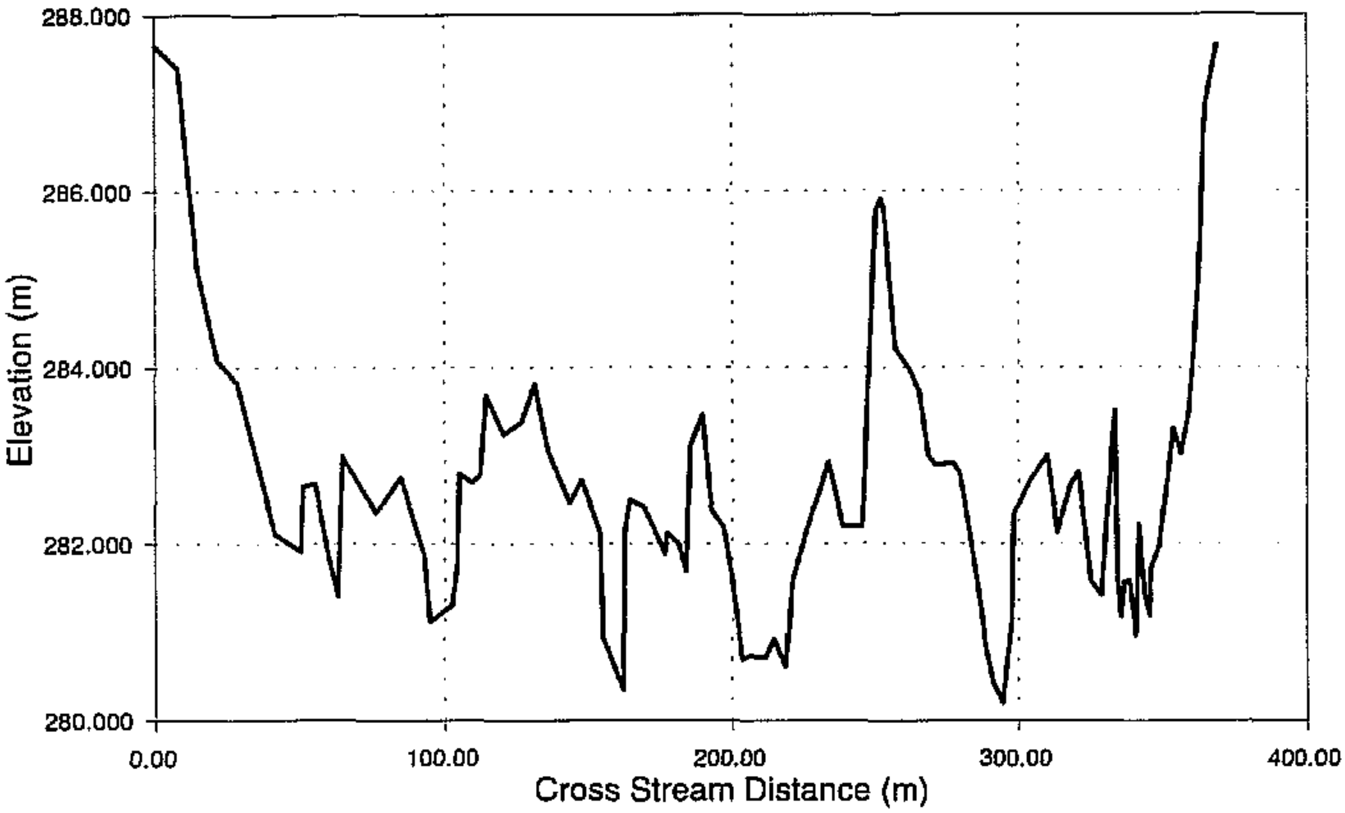

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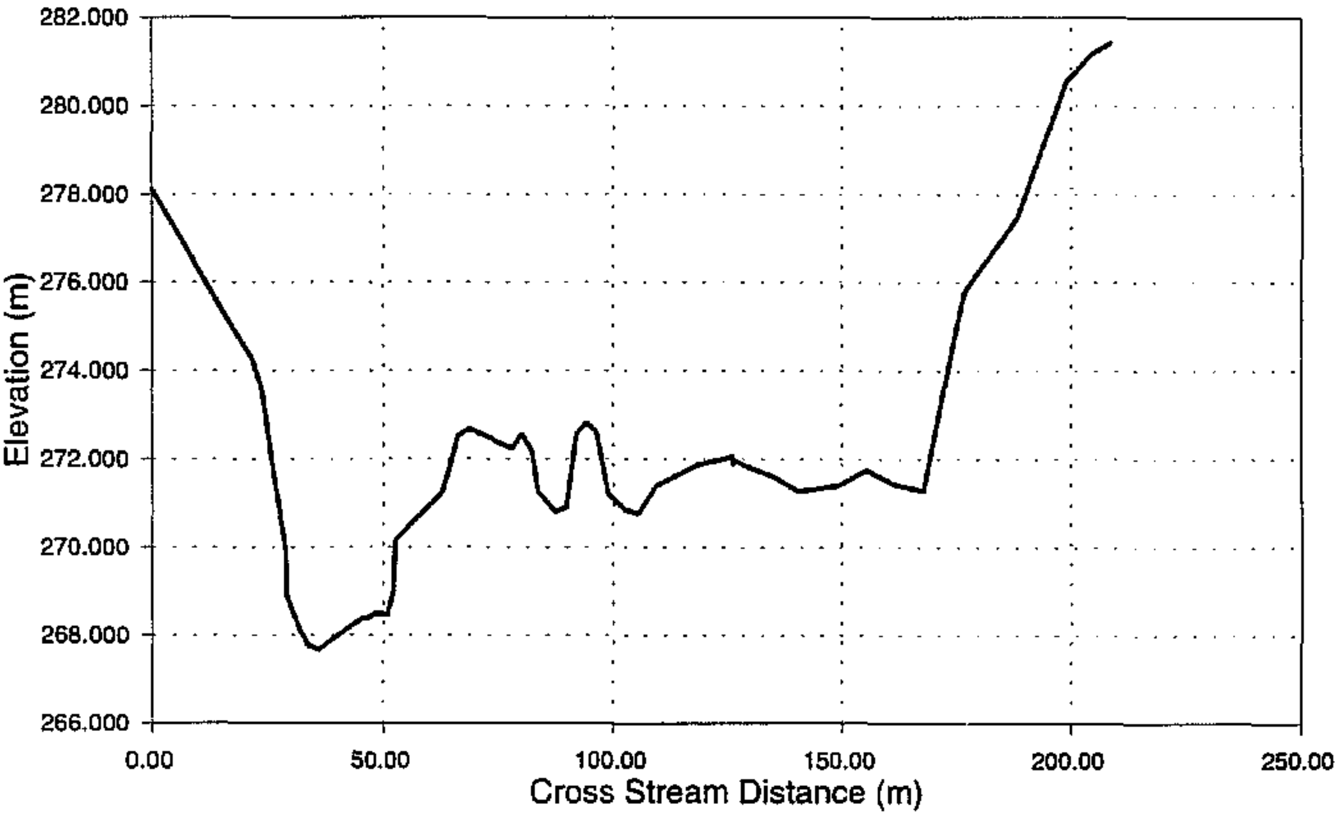

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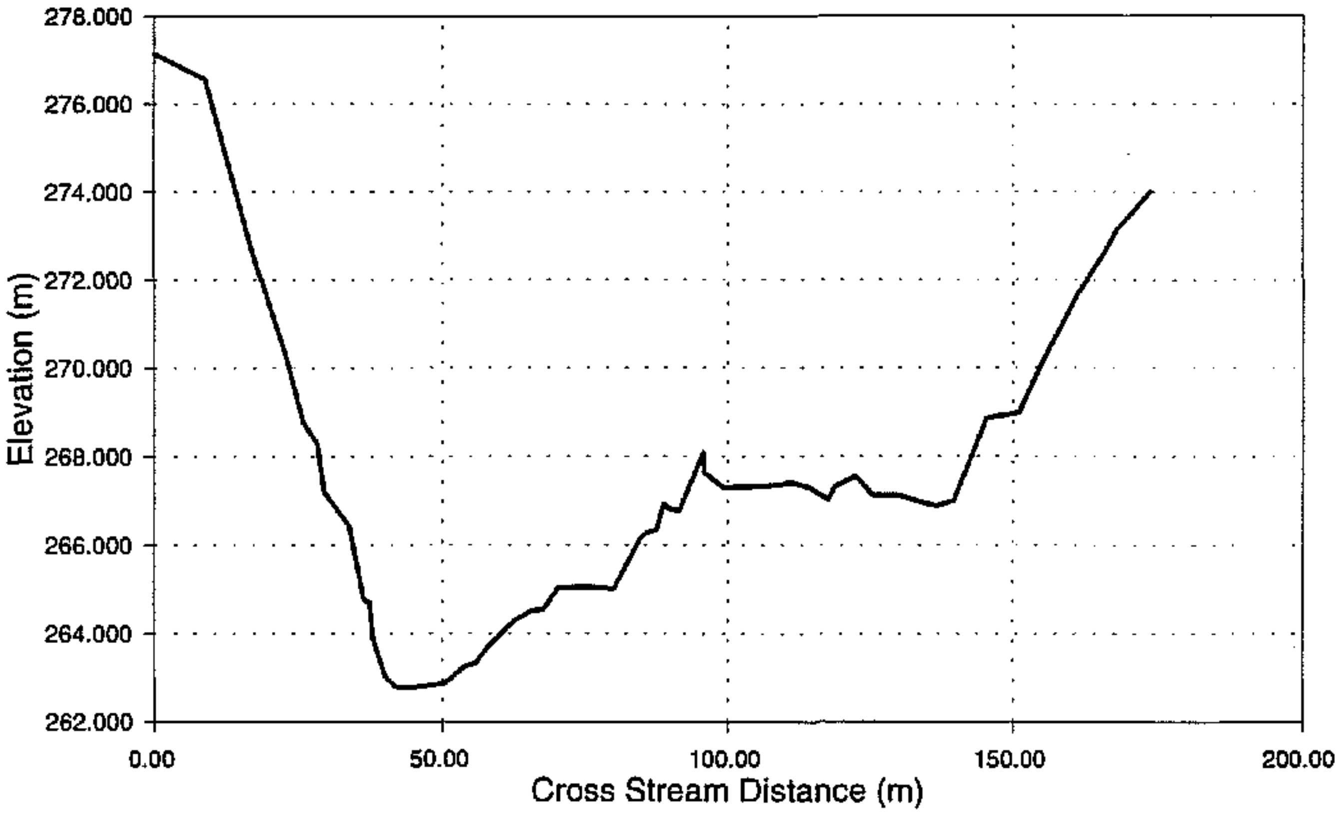

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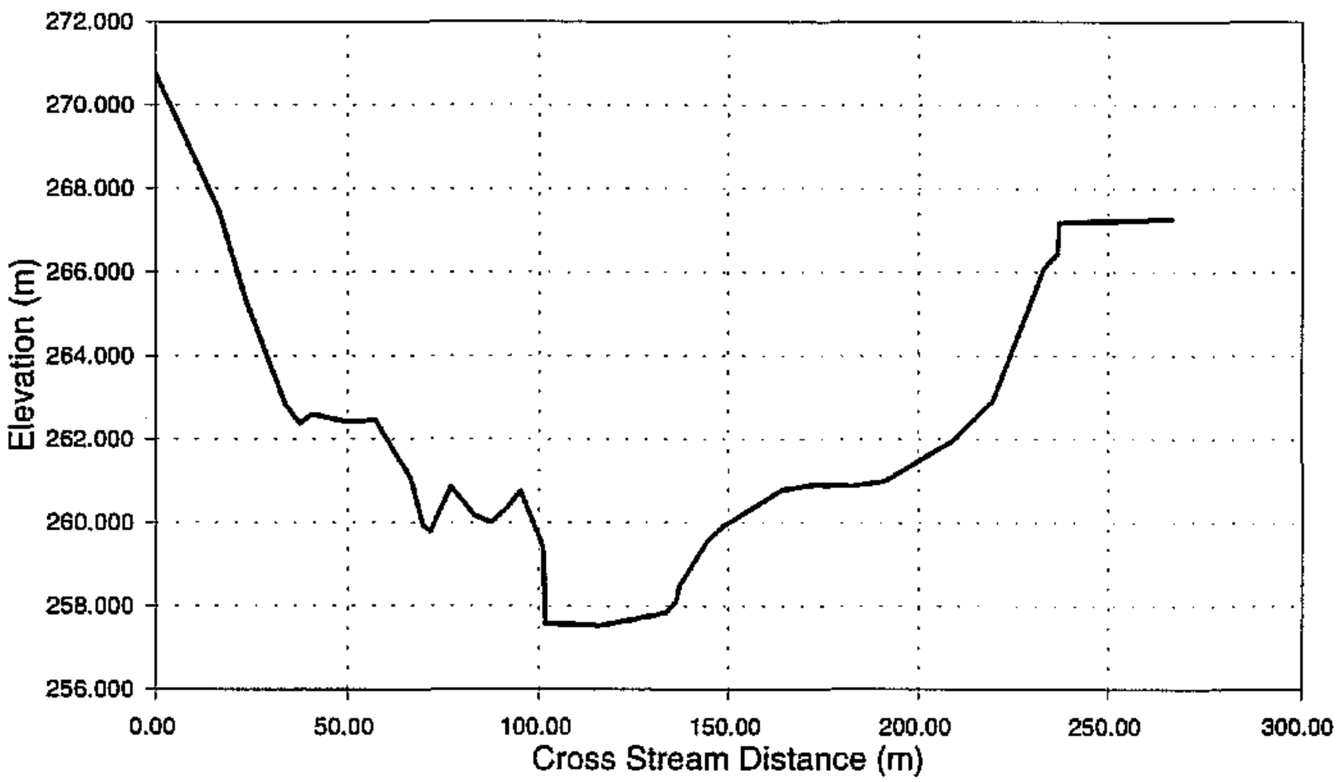

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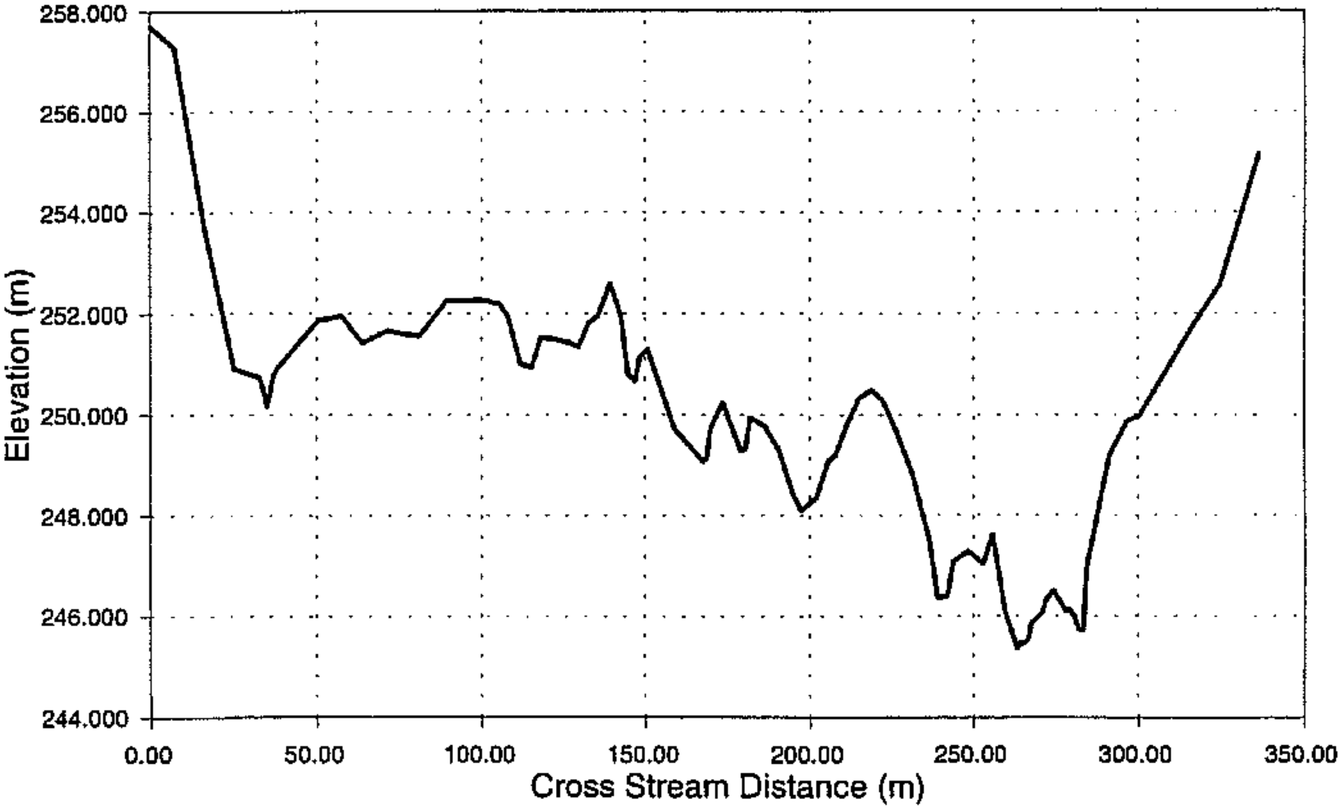

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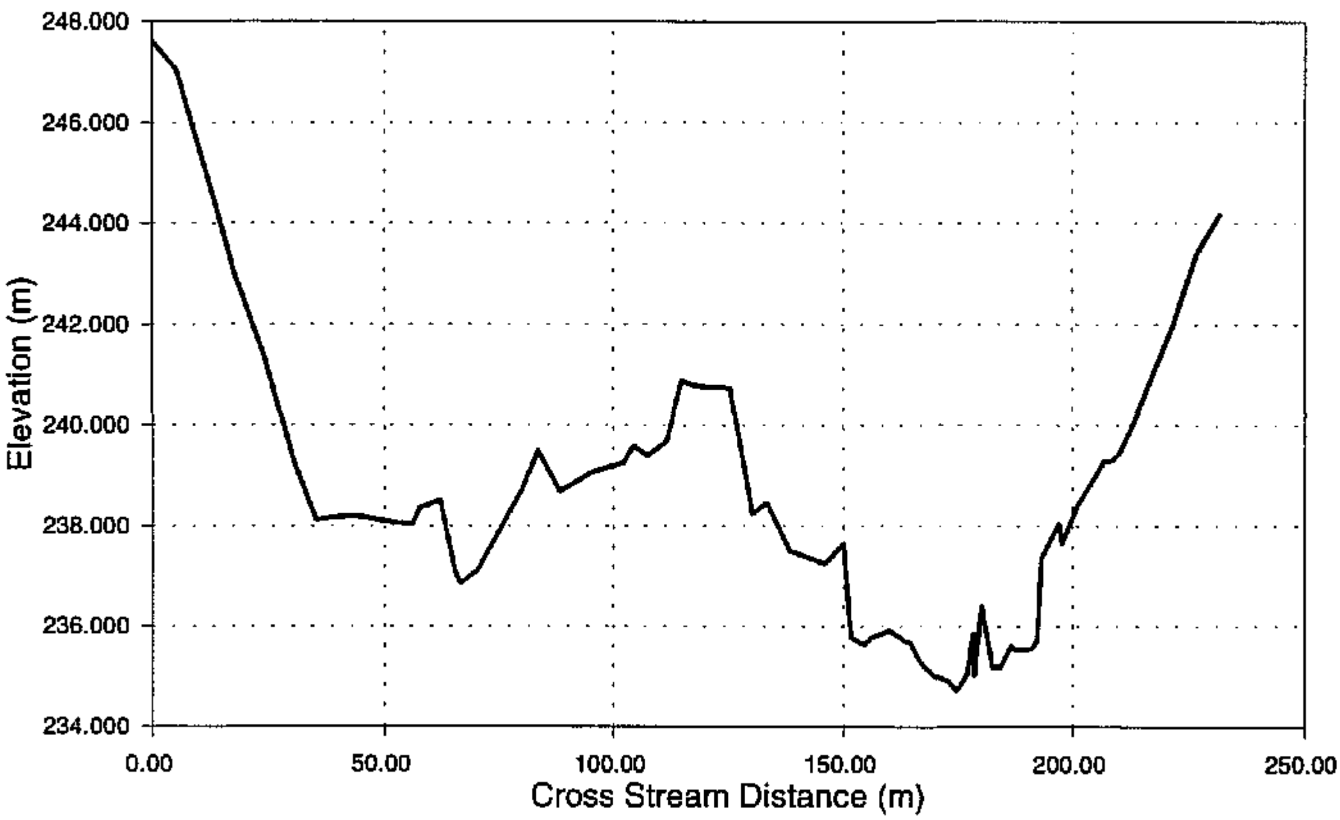

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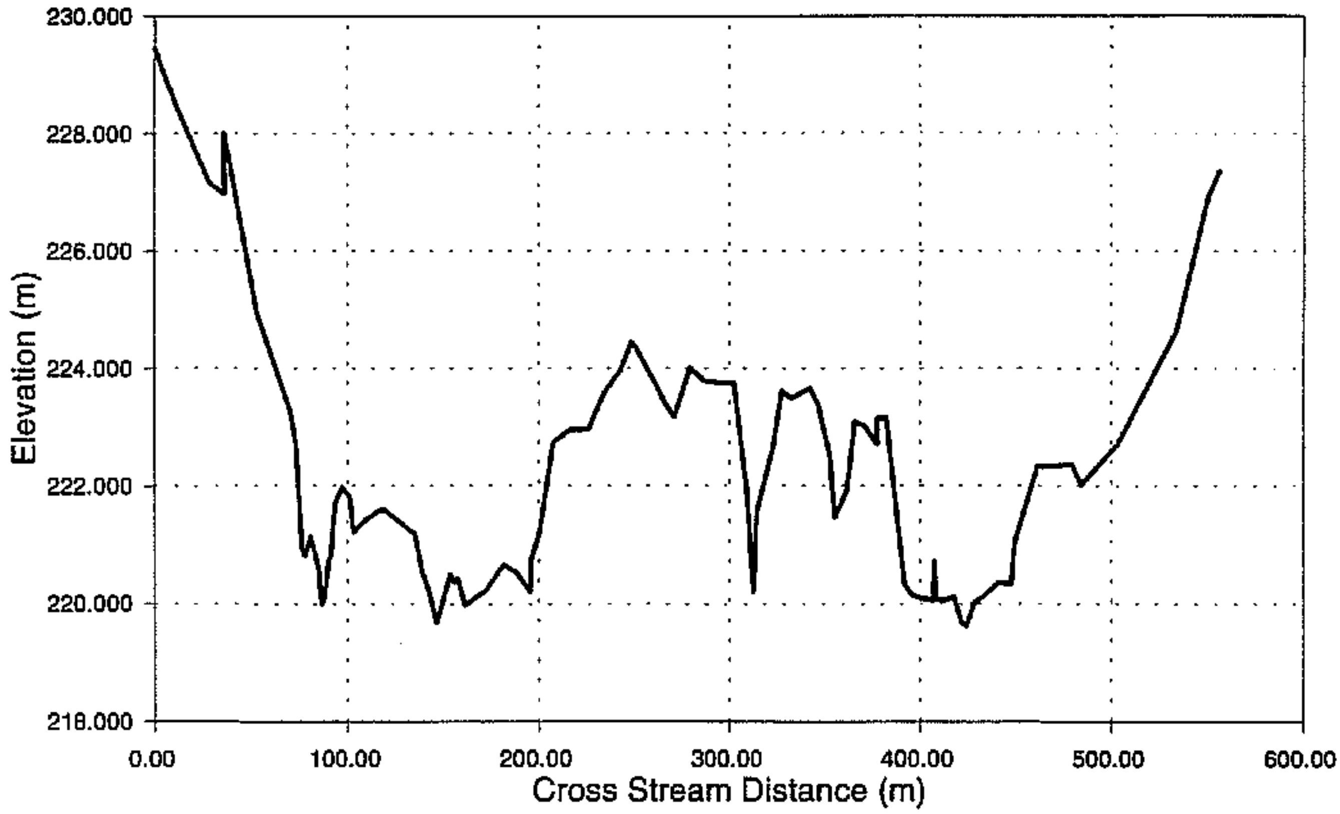

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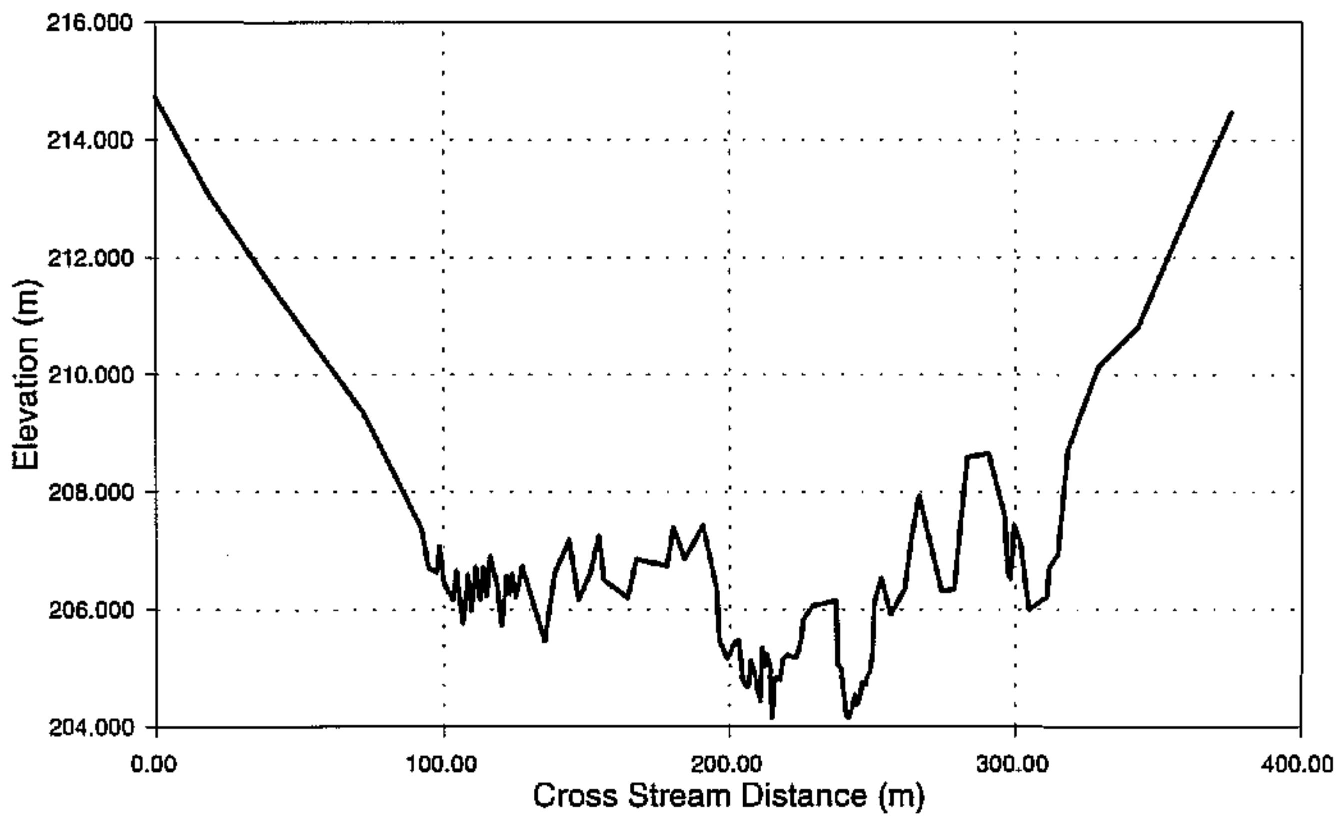

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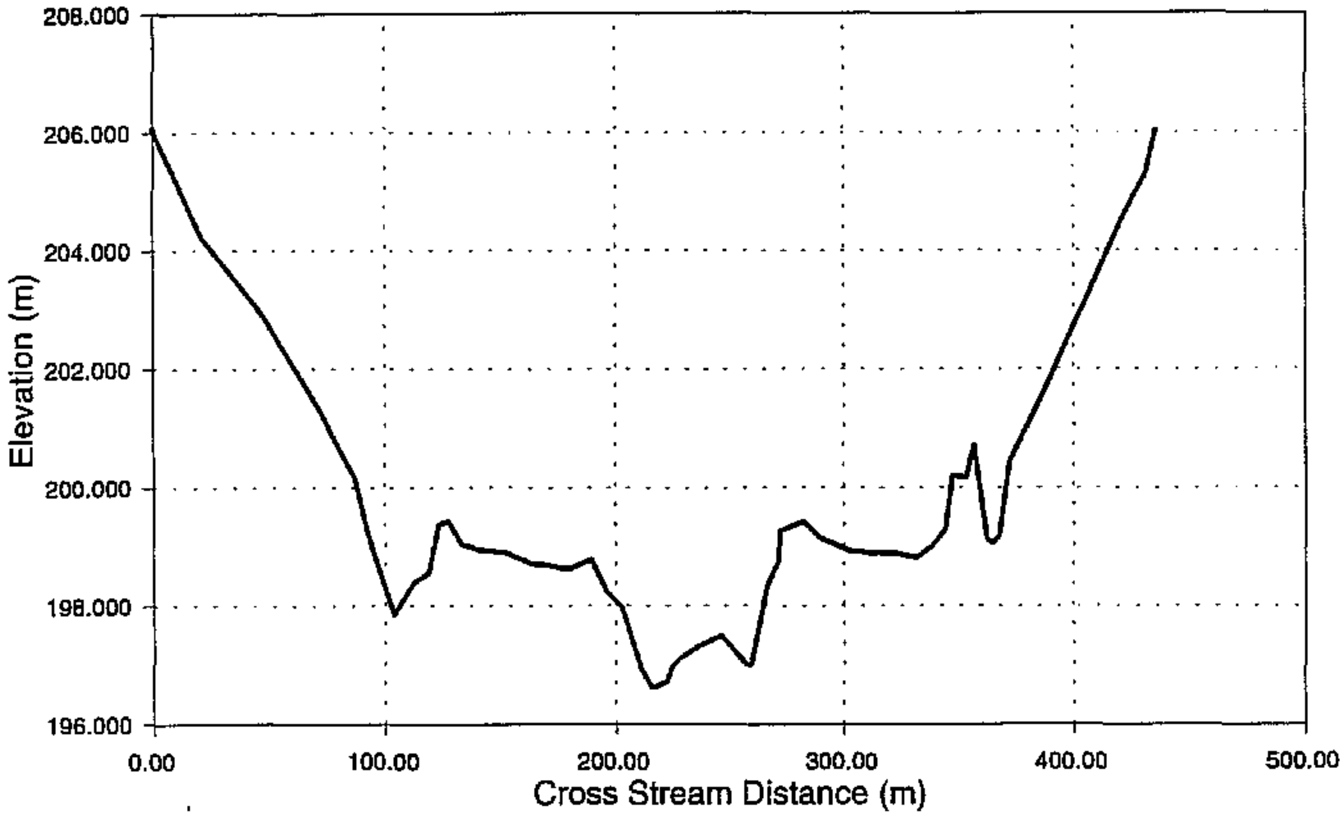

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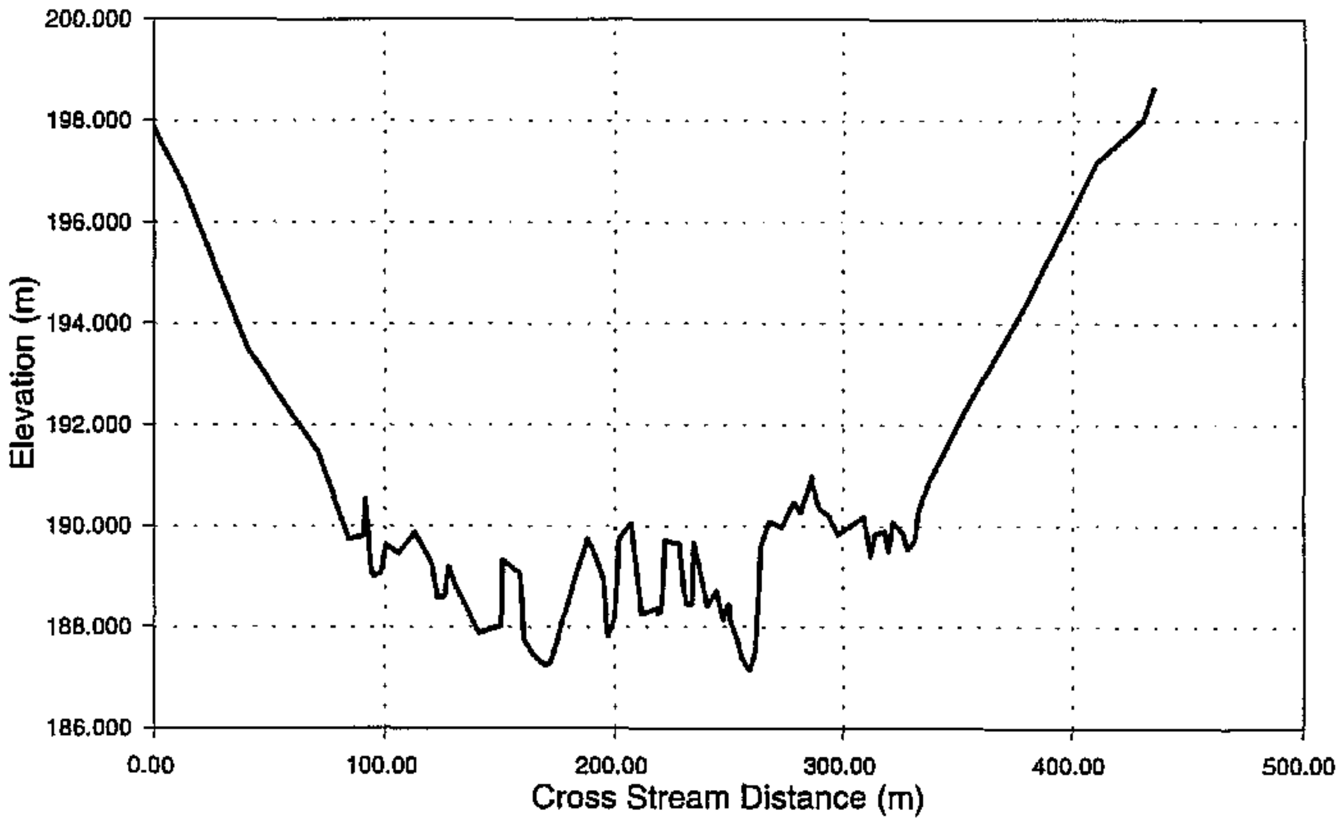

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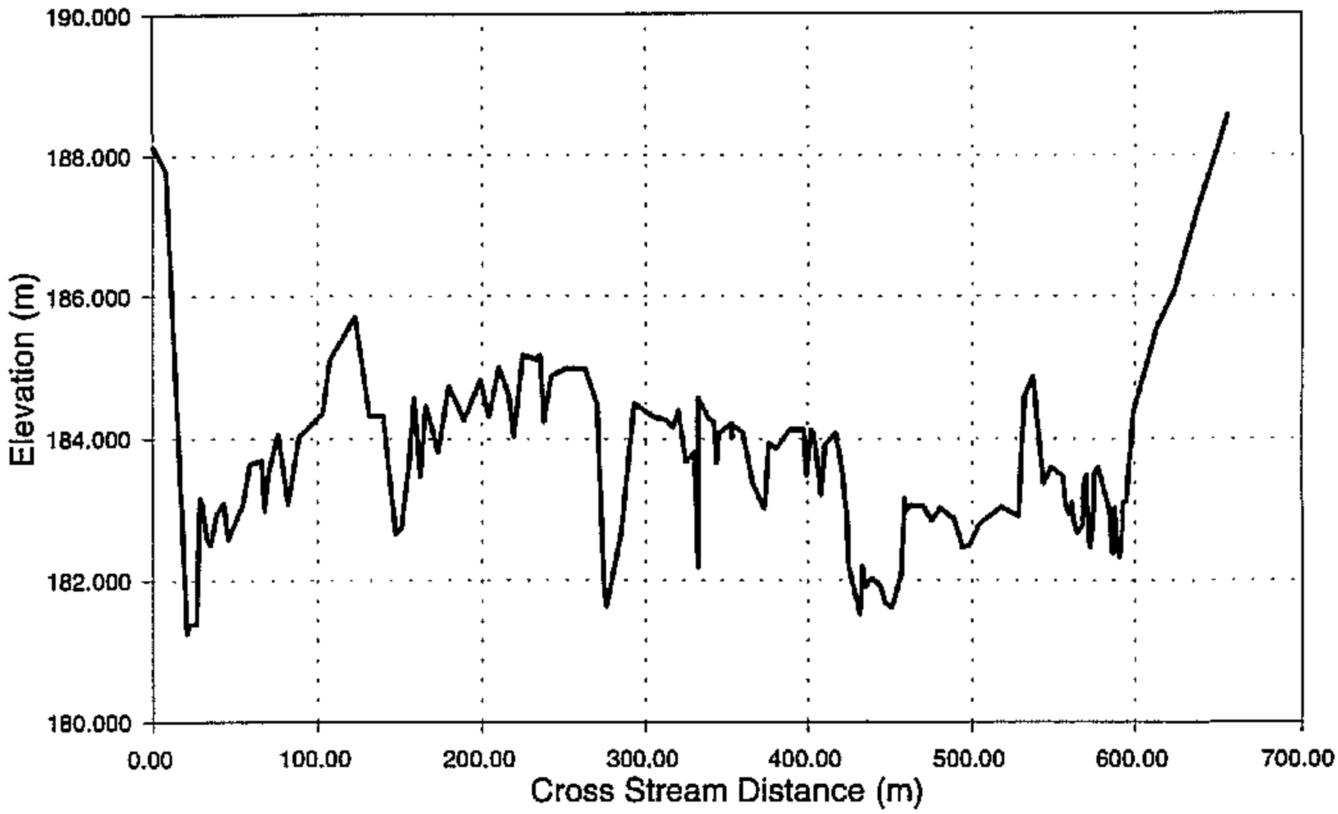

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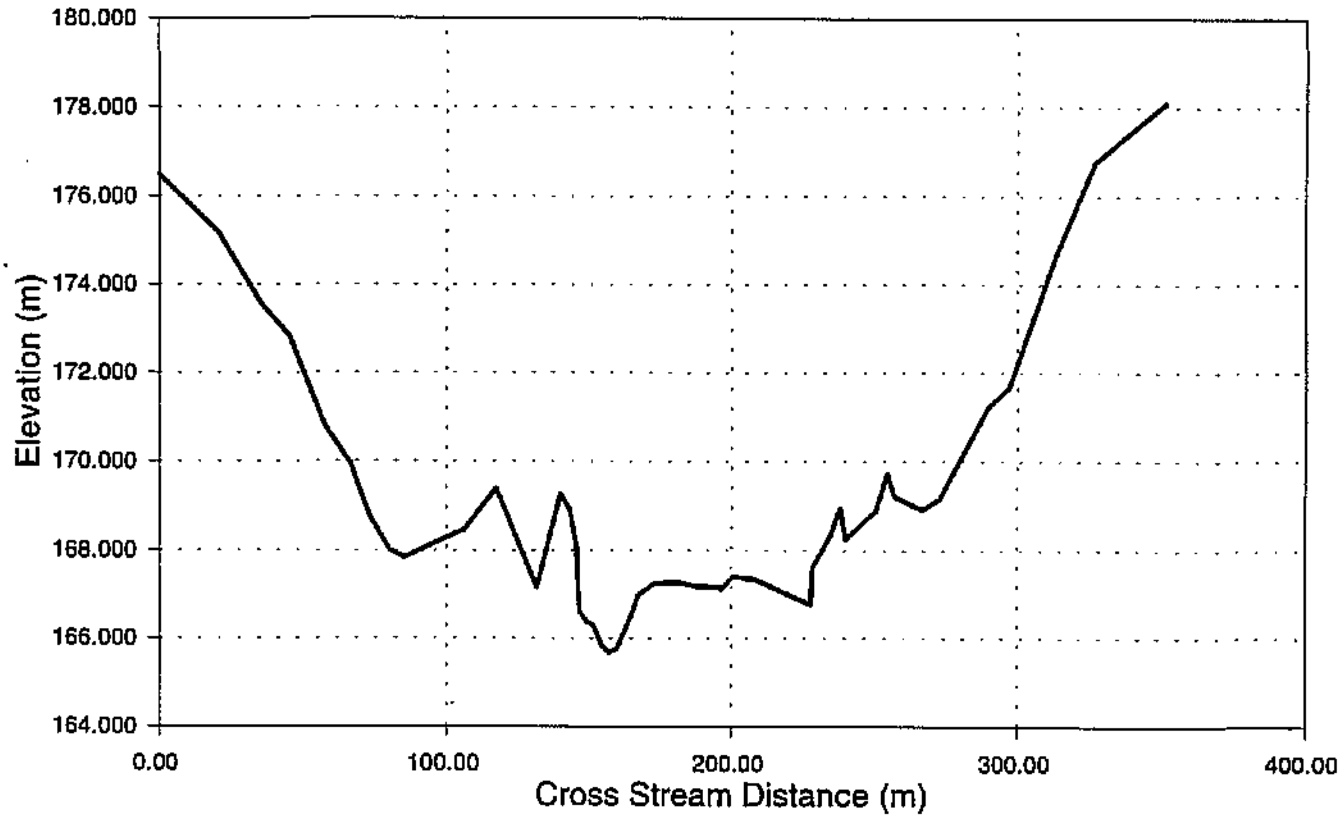

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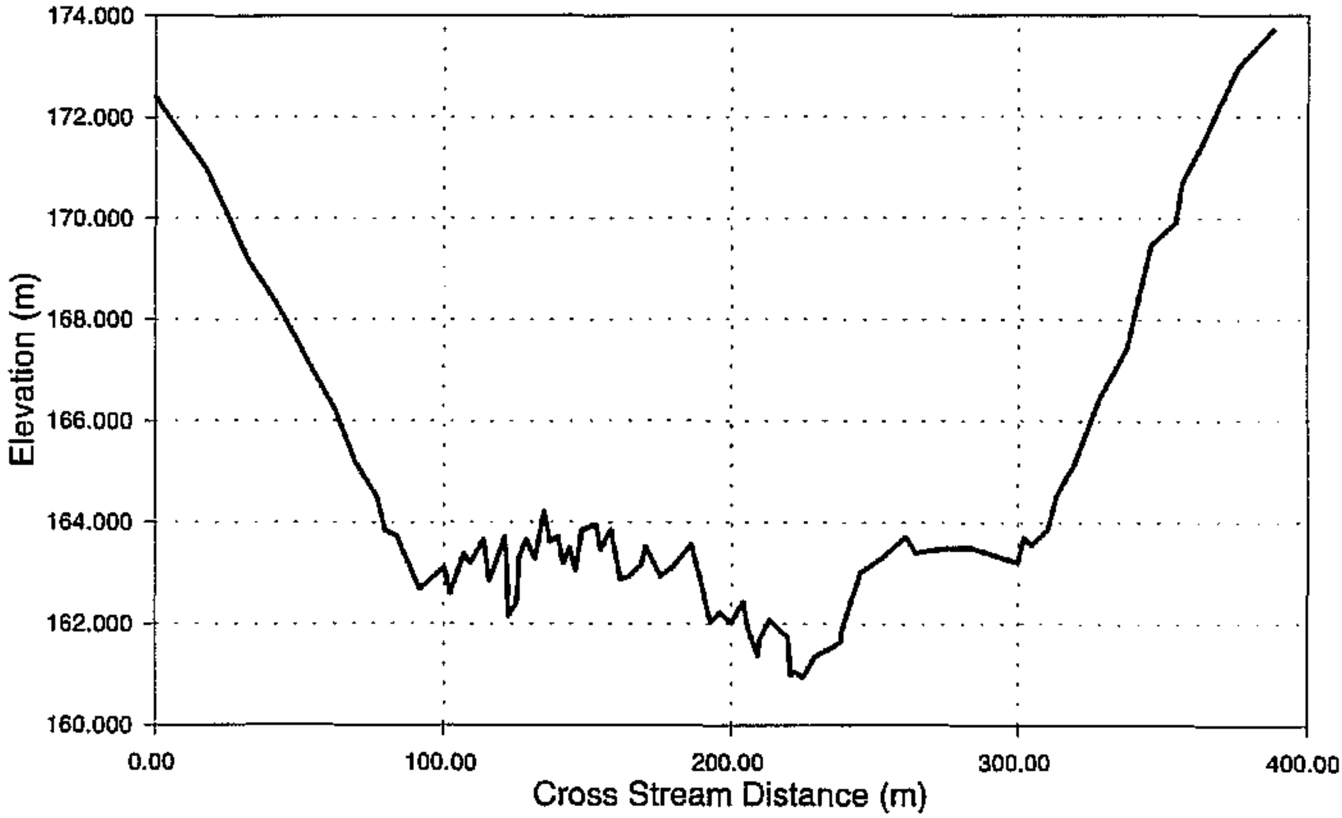

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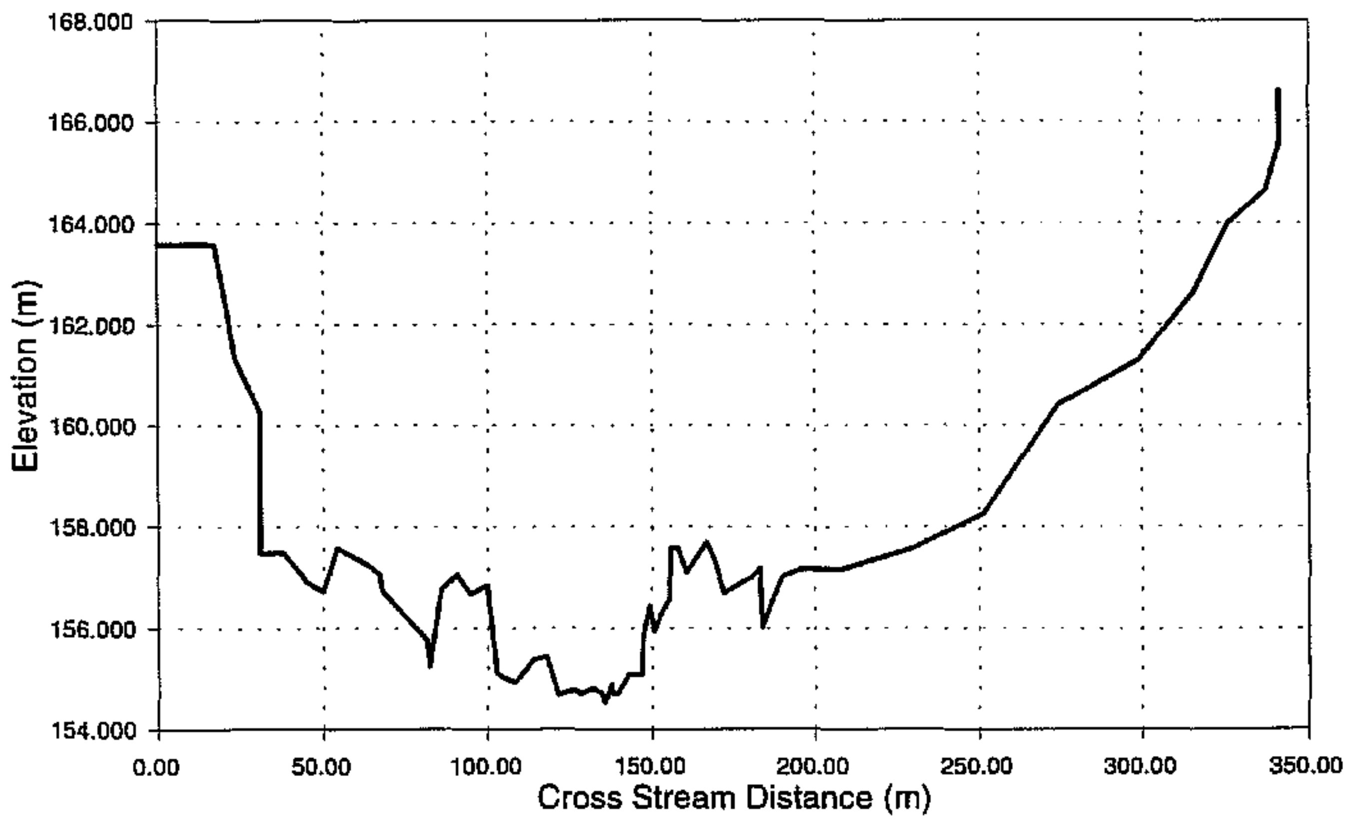

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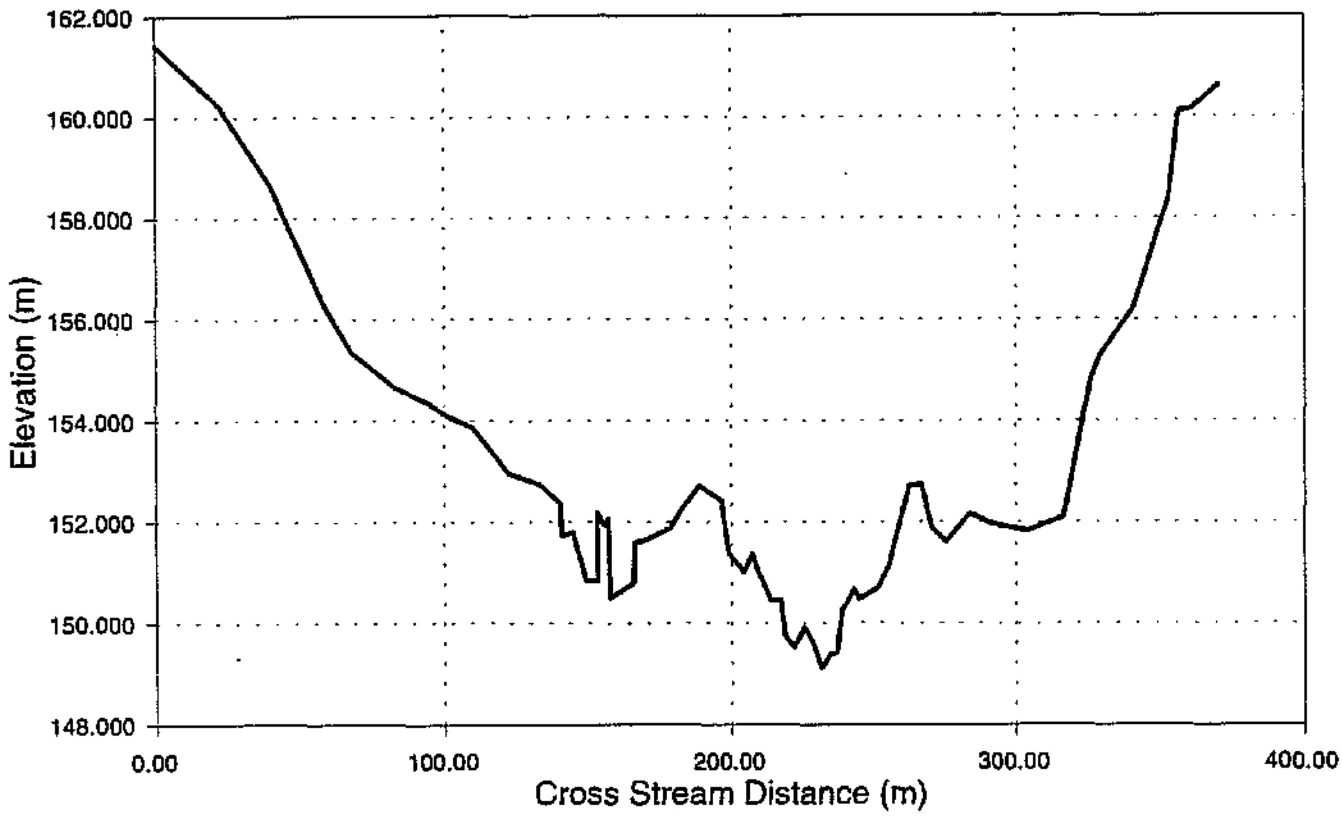

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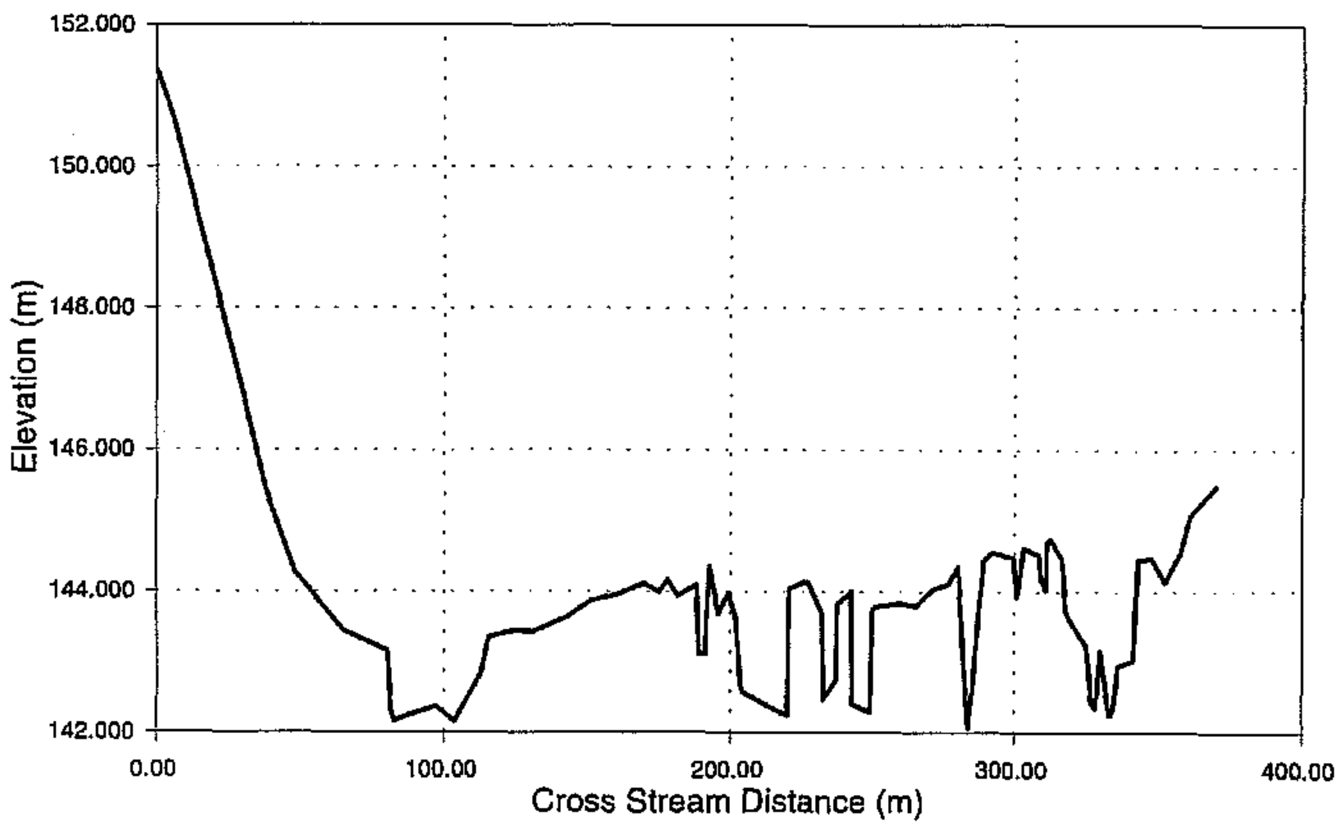

APPENDIX C: SABIE RIVER RATING CURVES

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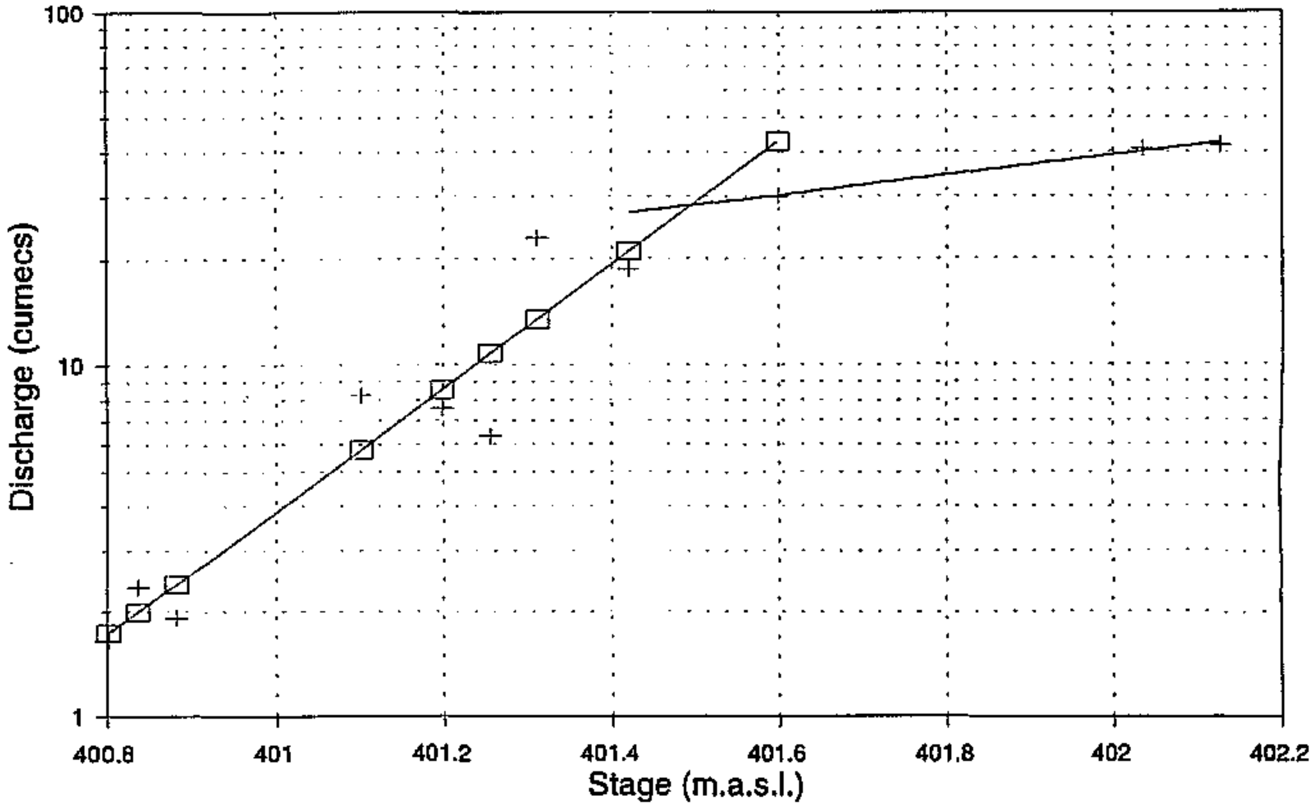

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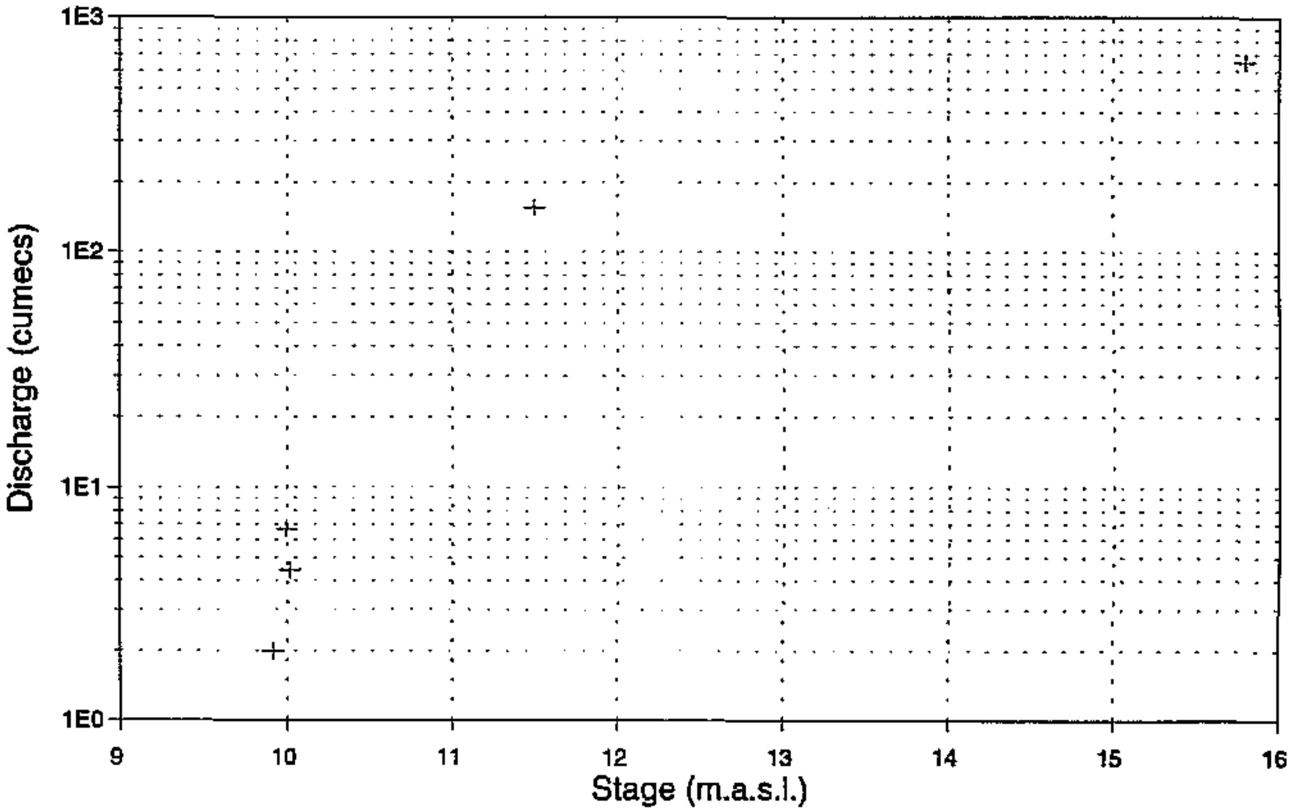

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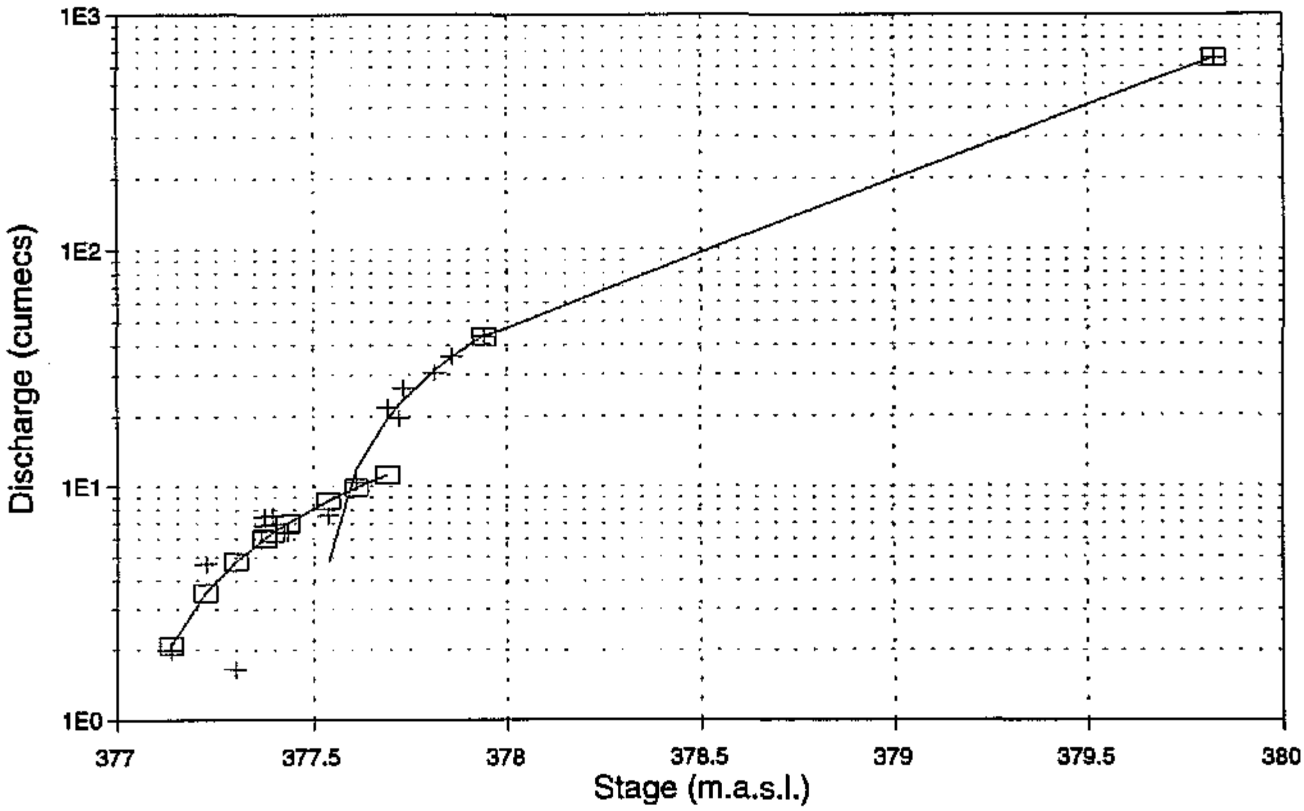

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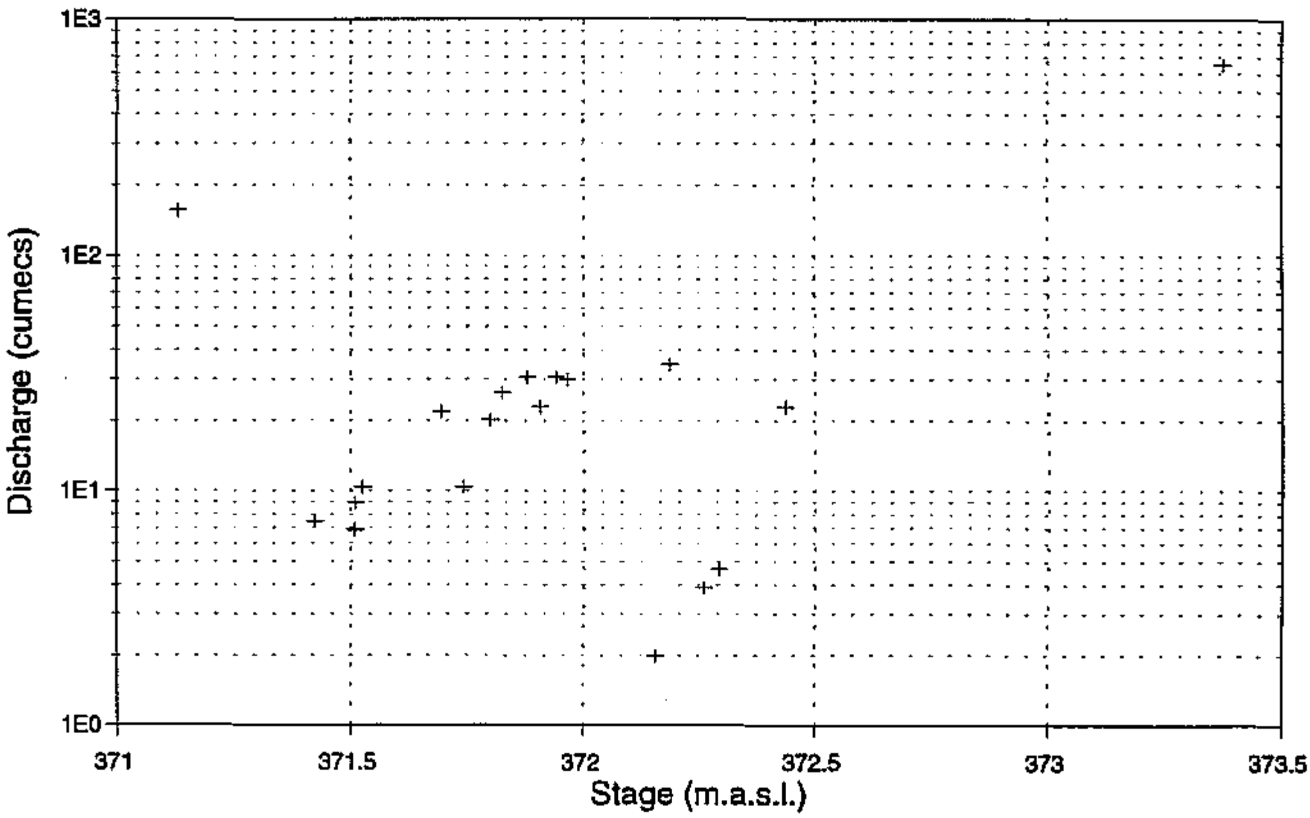

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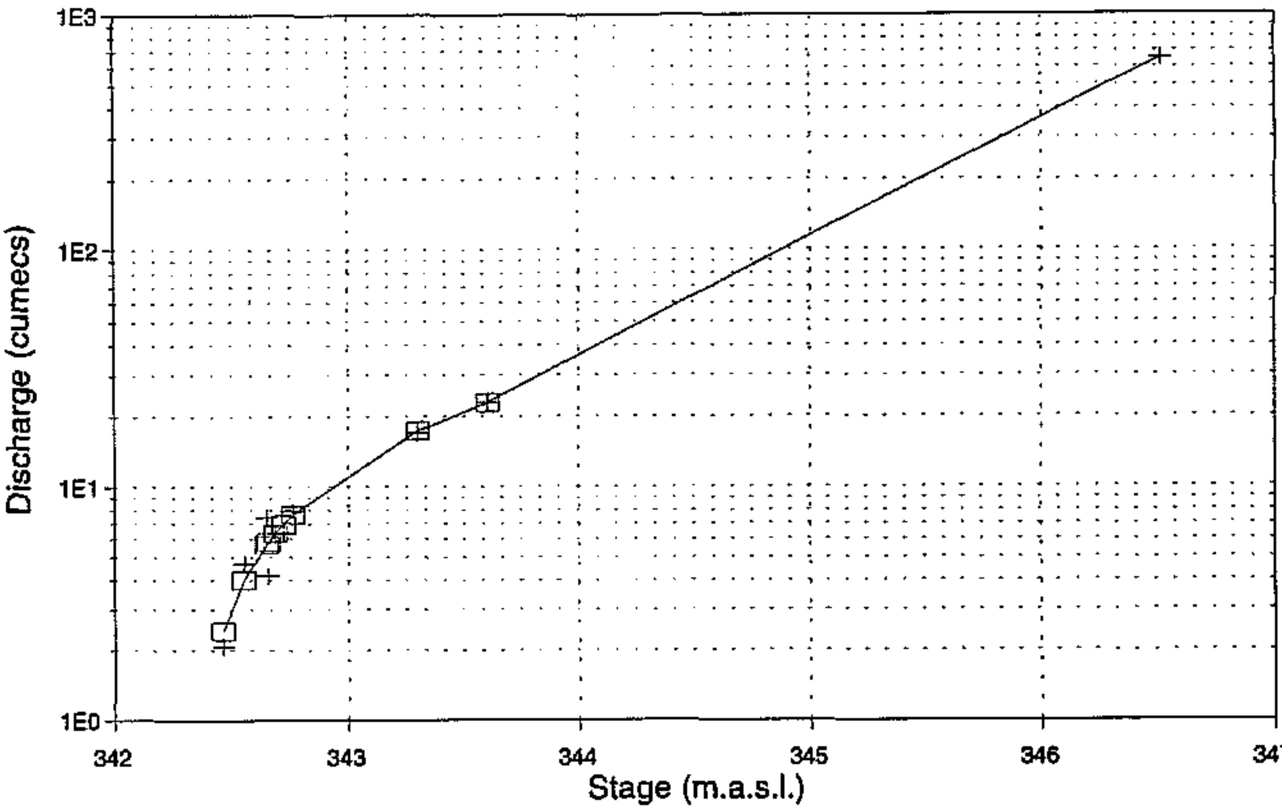

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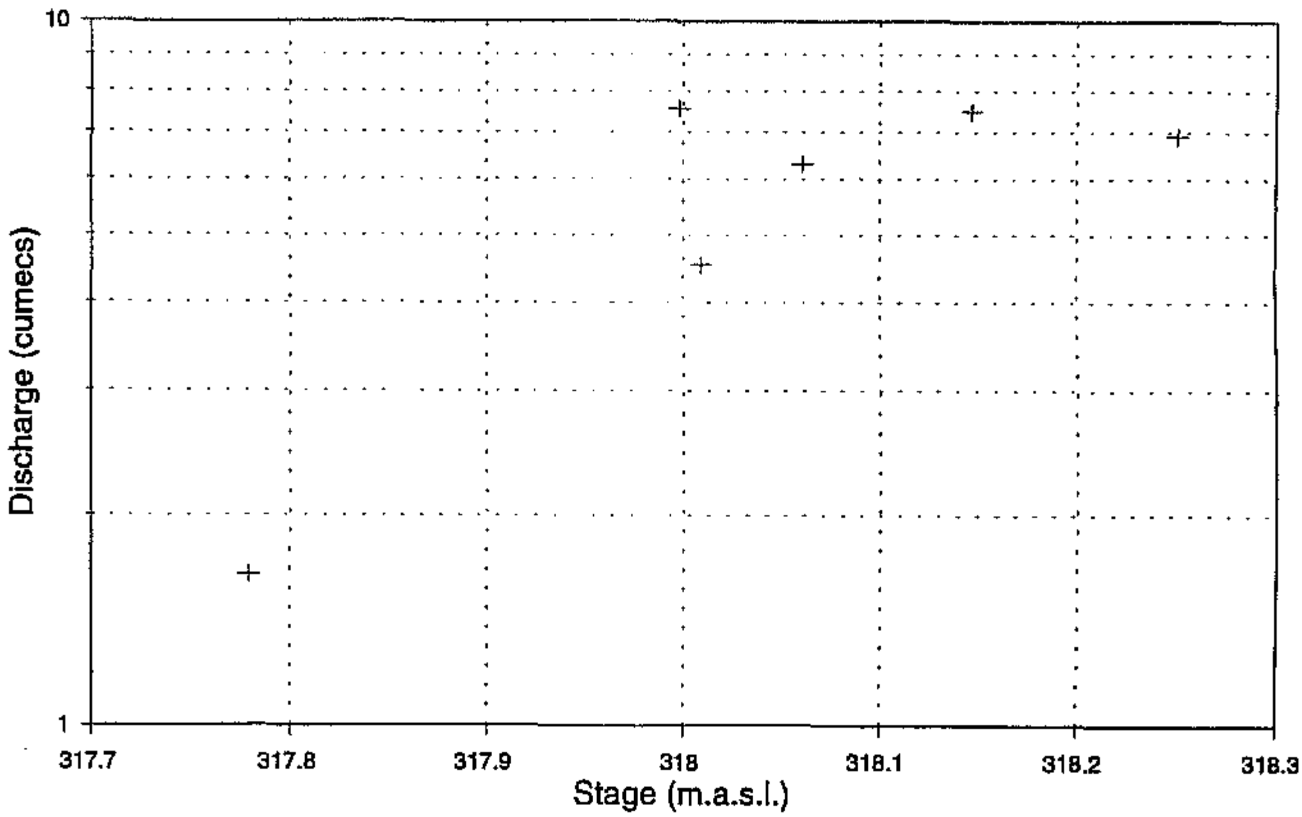

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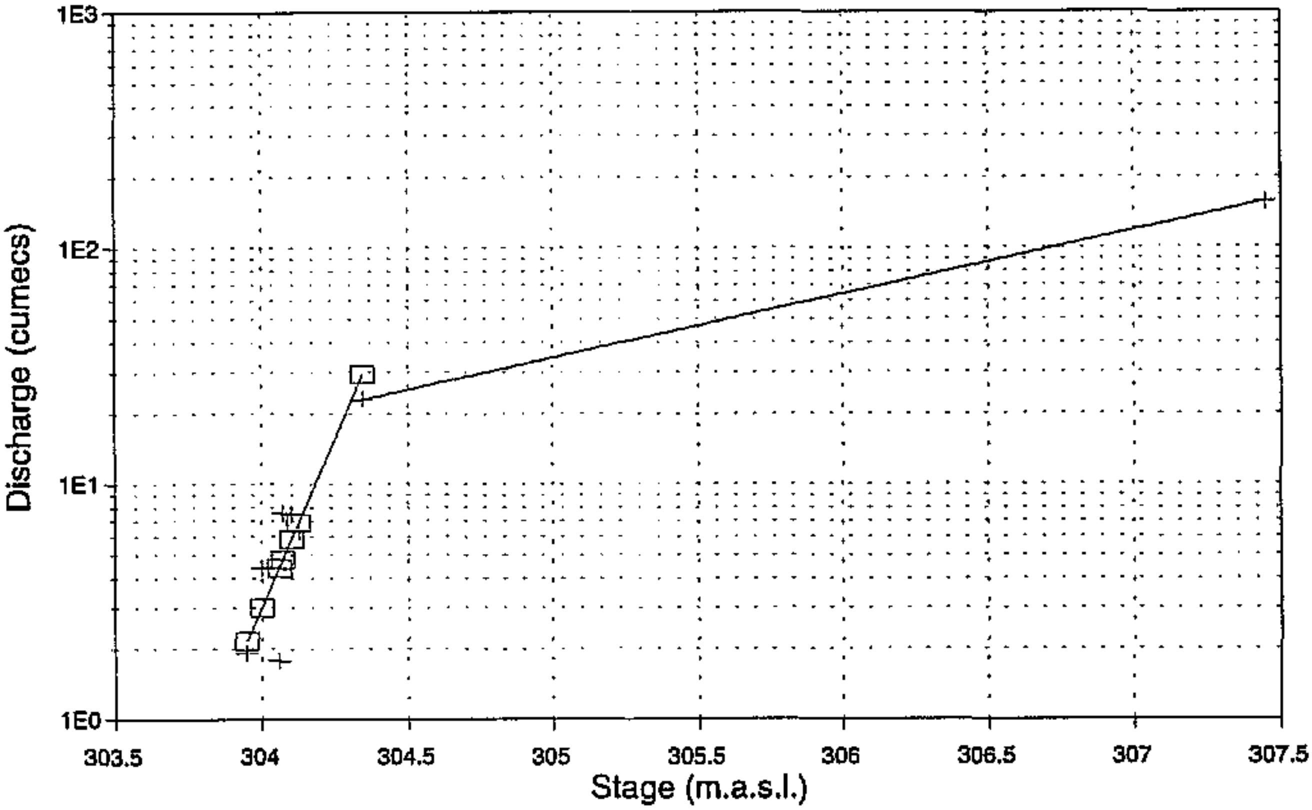

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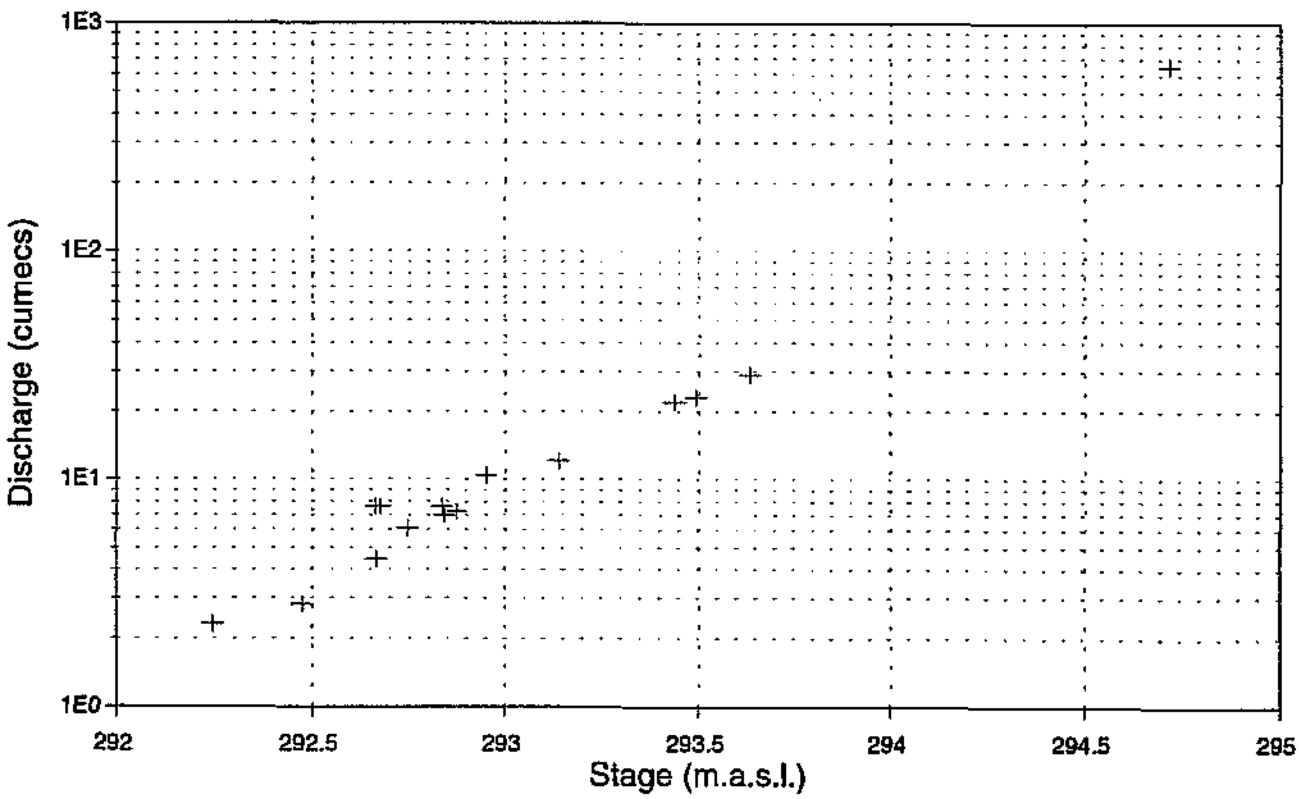

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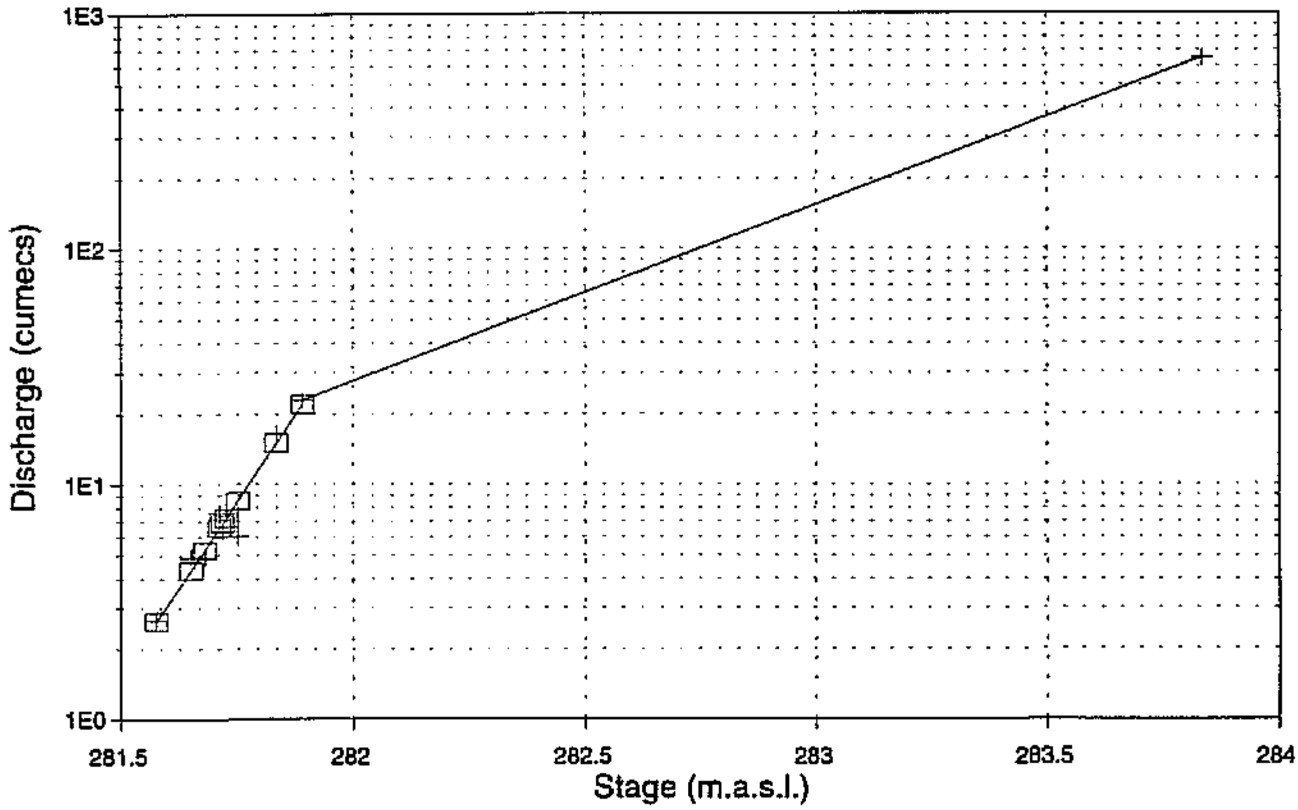

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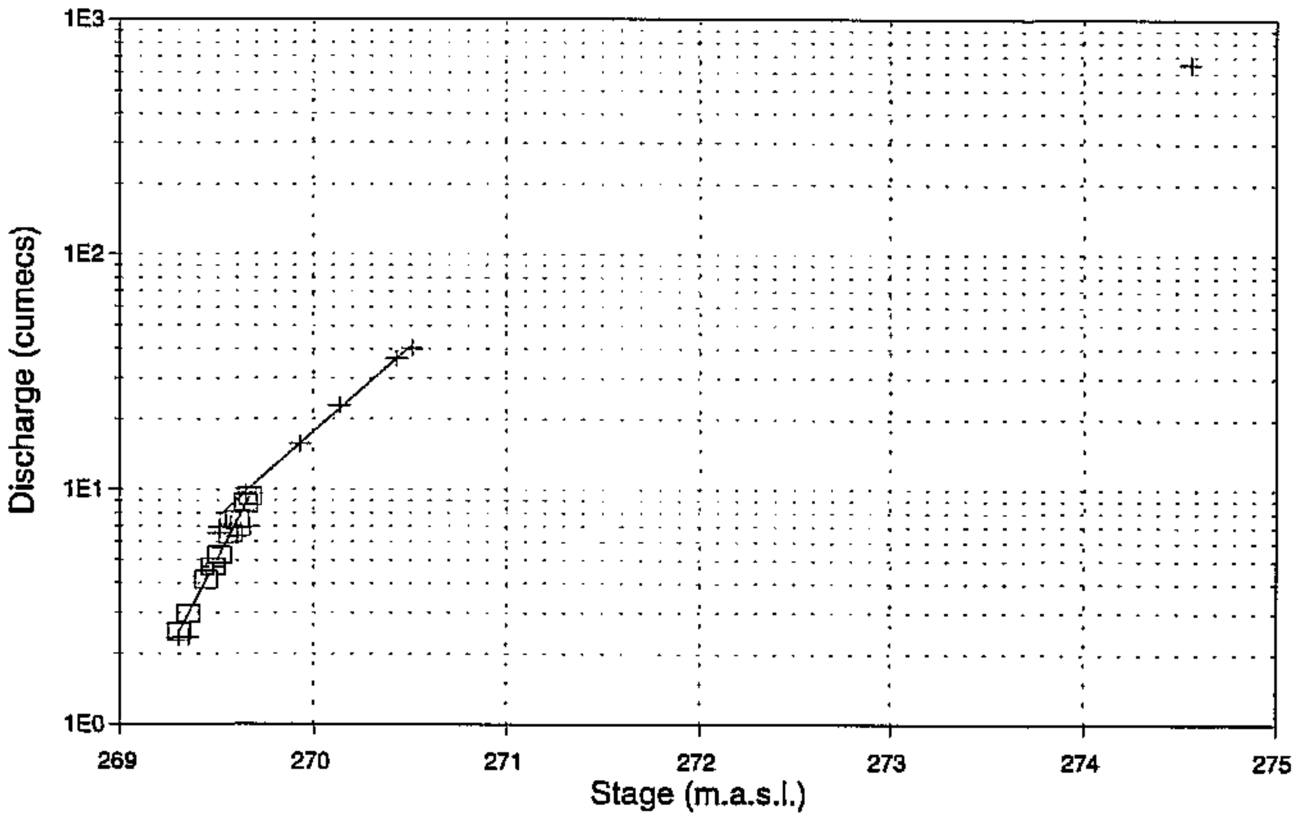

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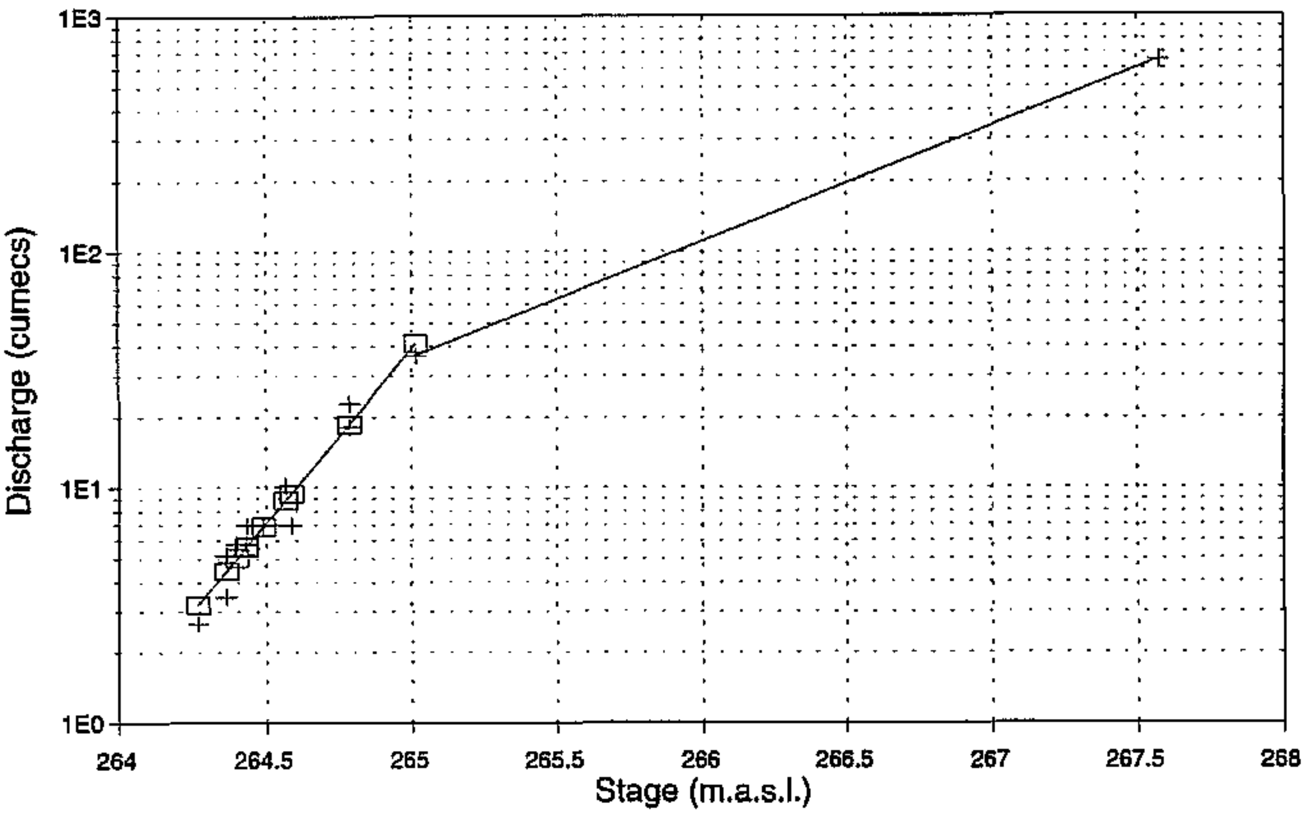

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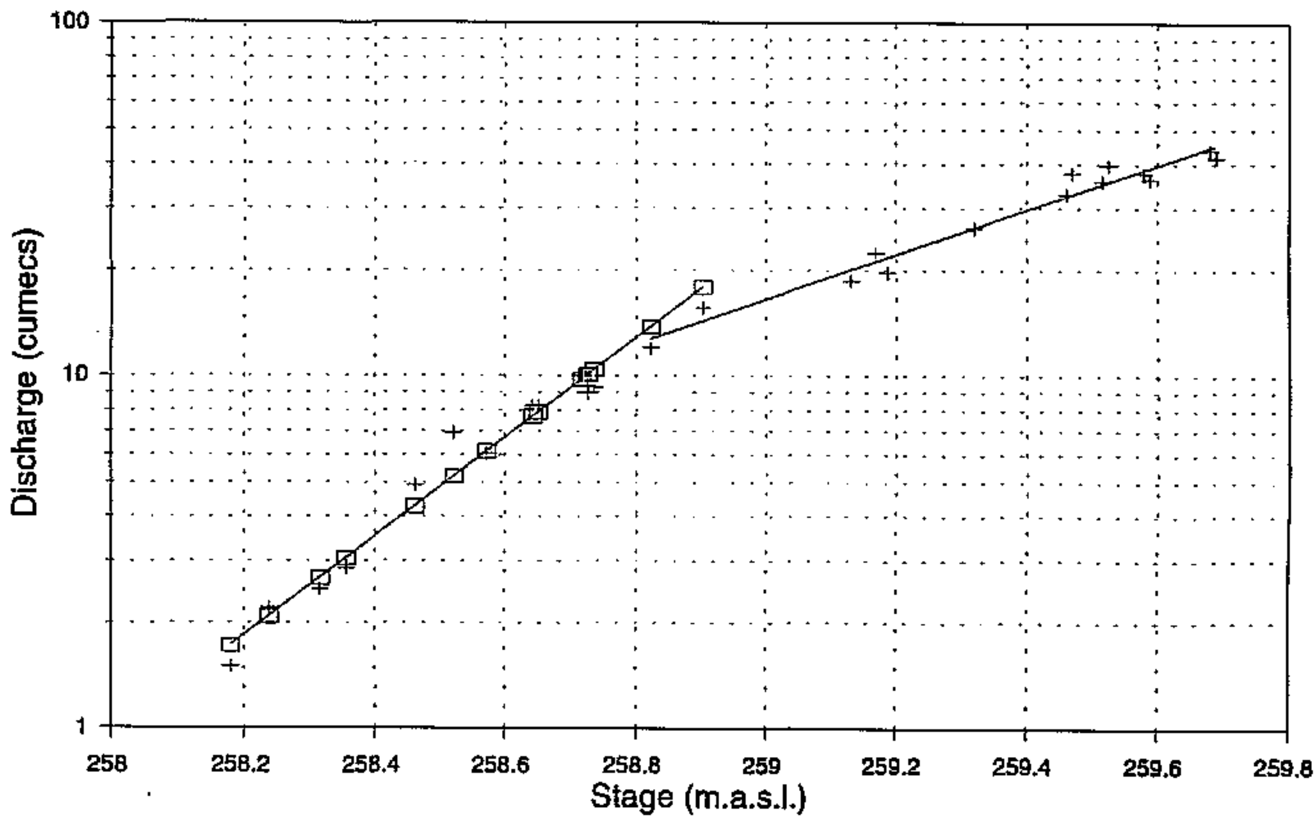

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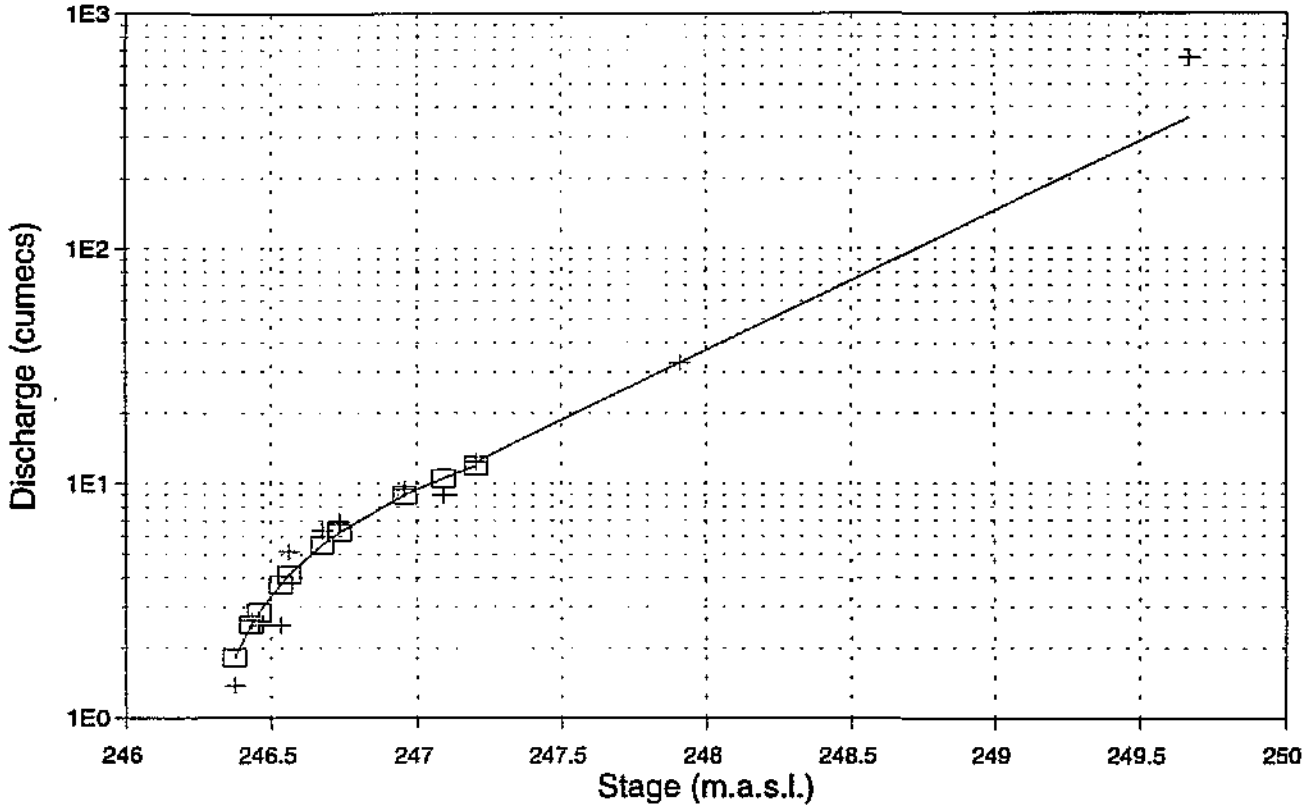

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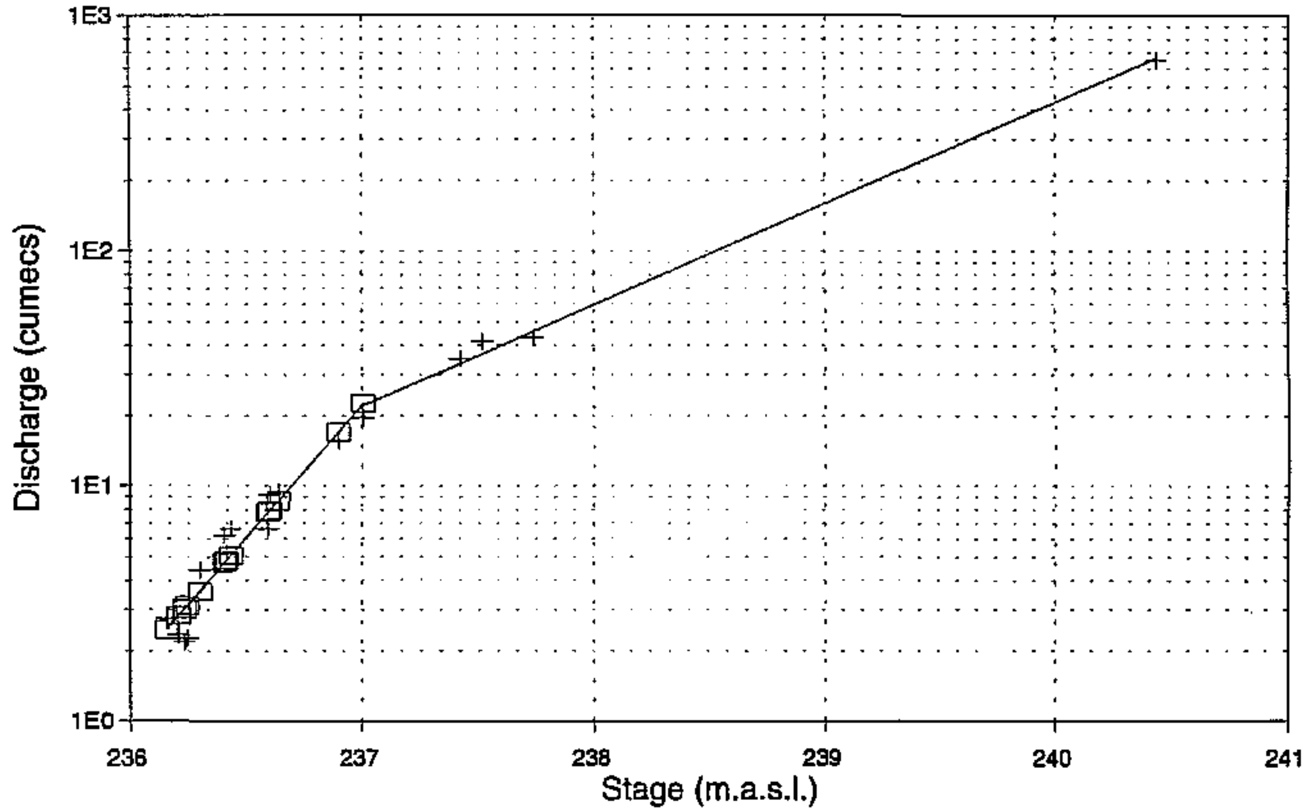

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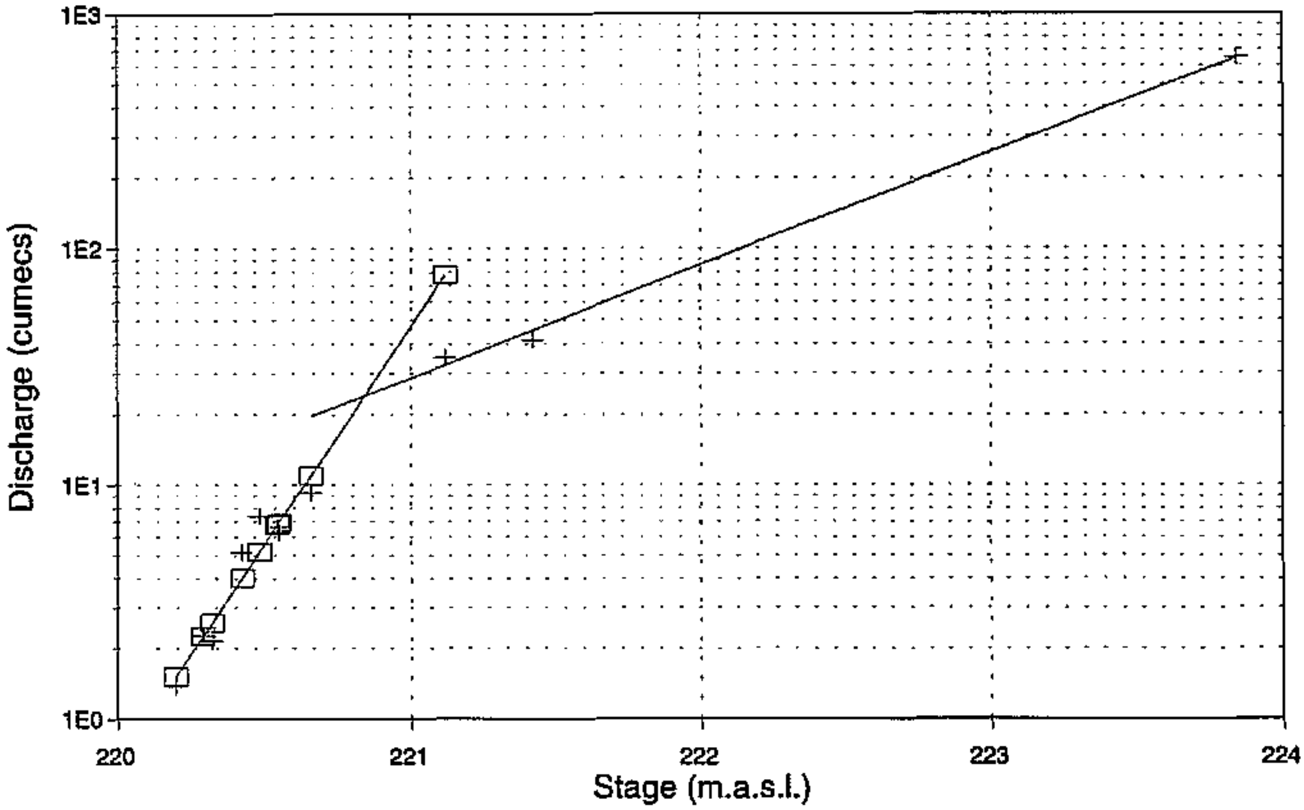

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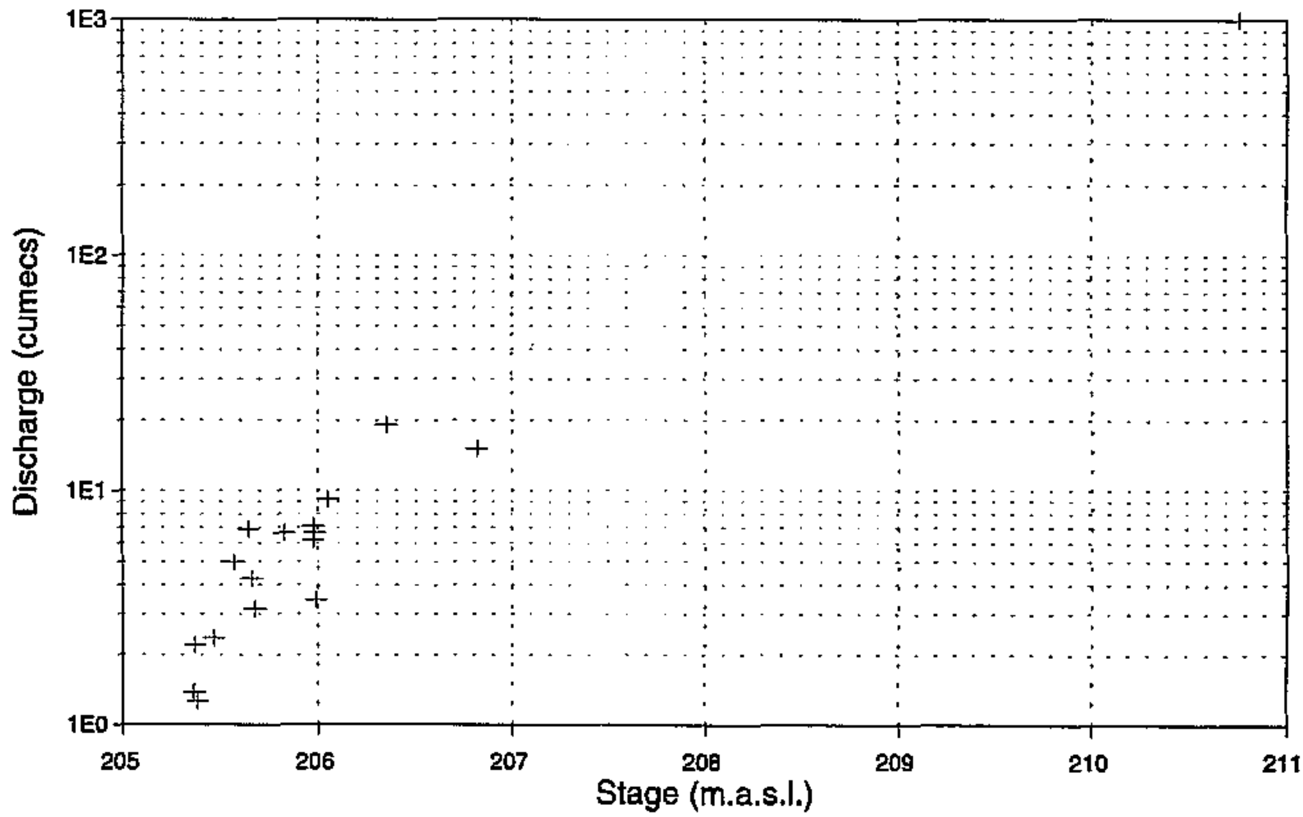

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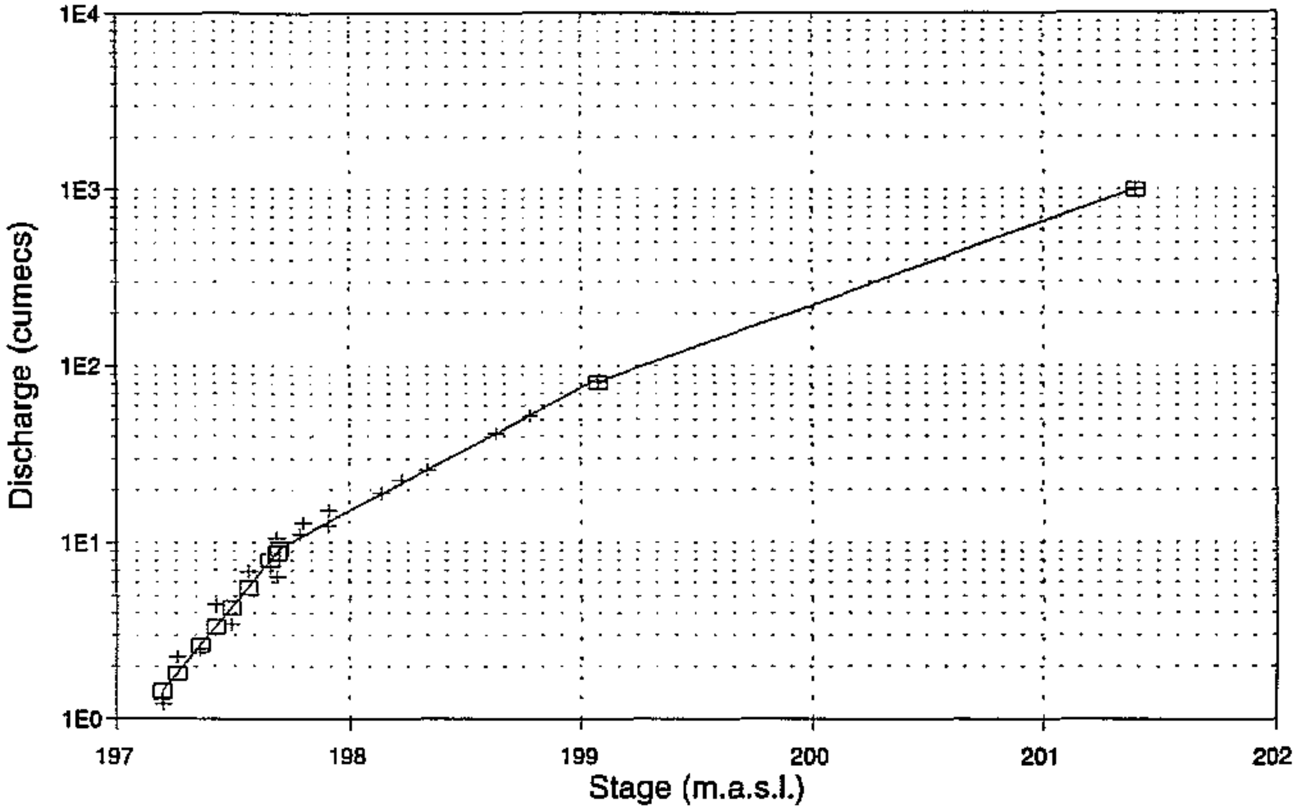

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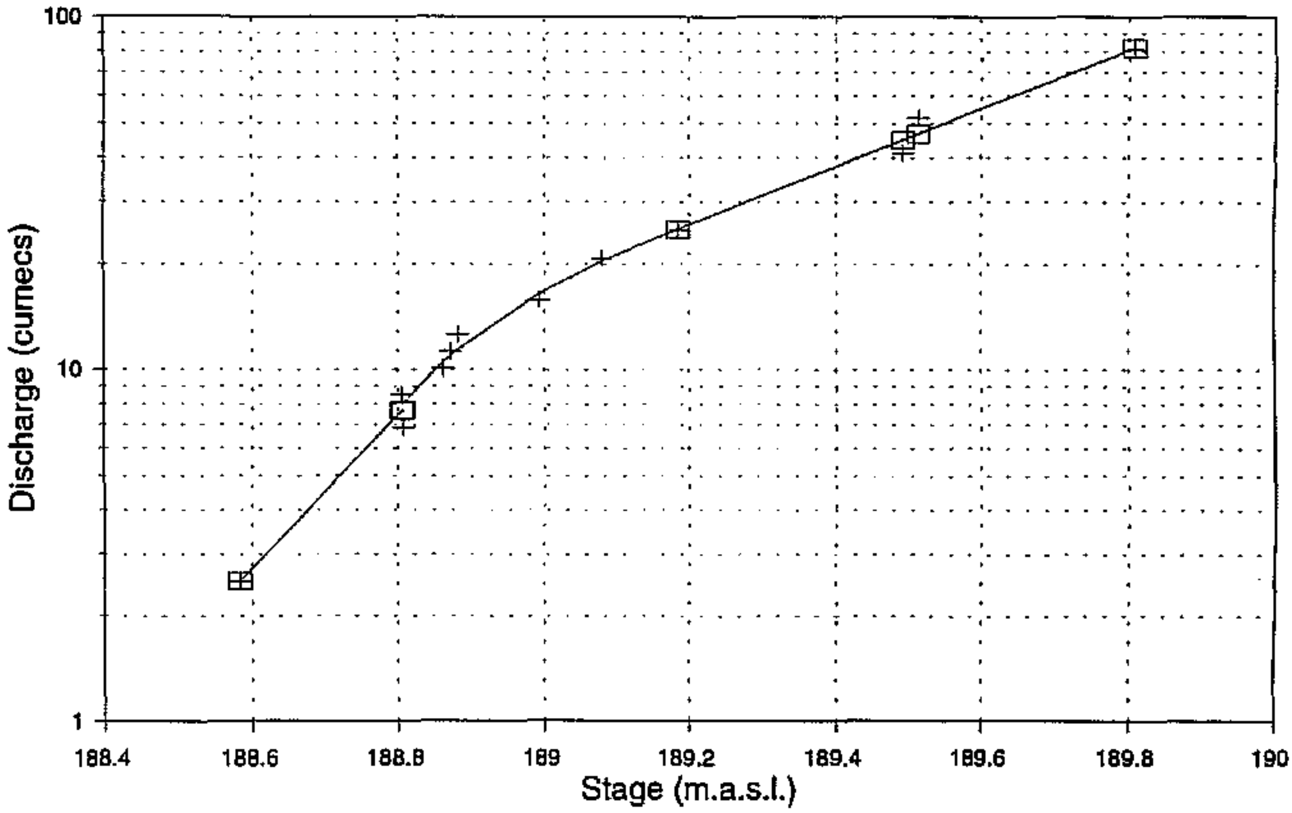

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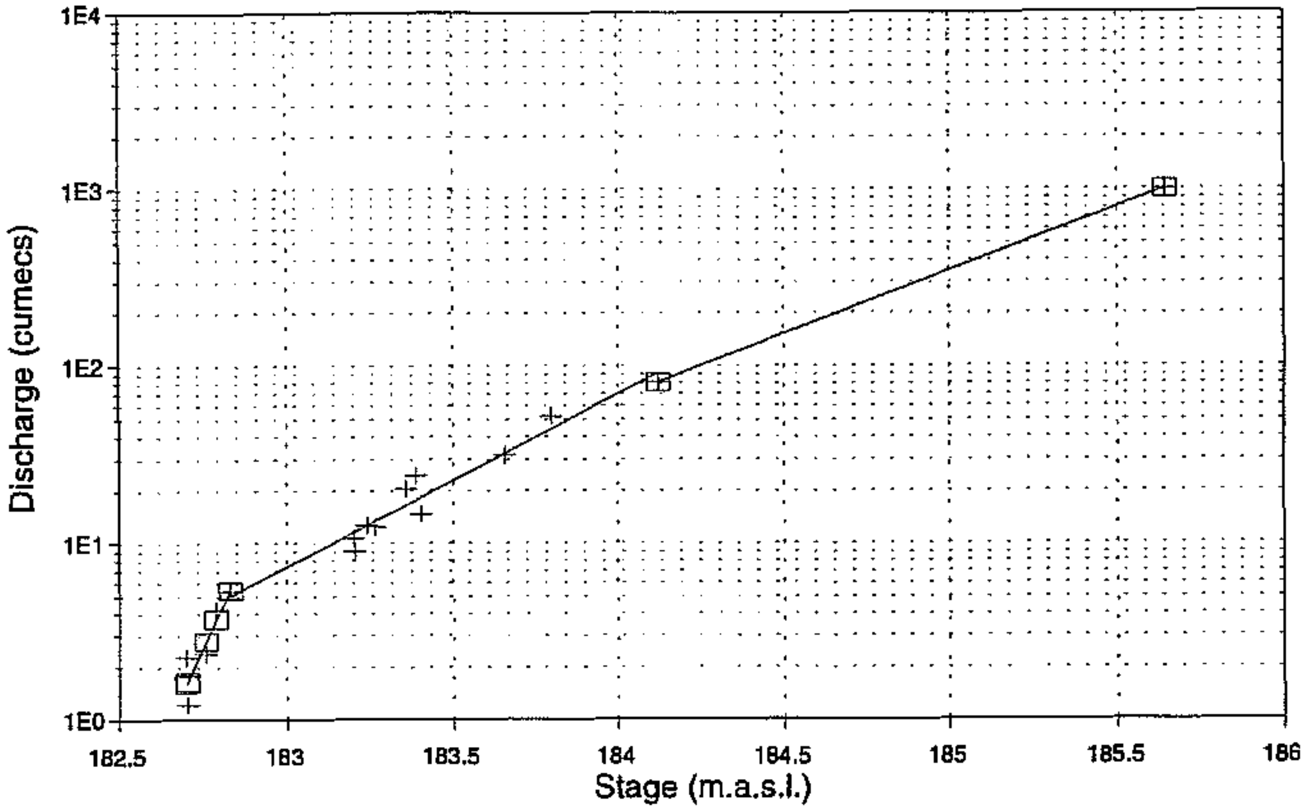

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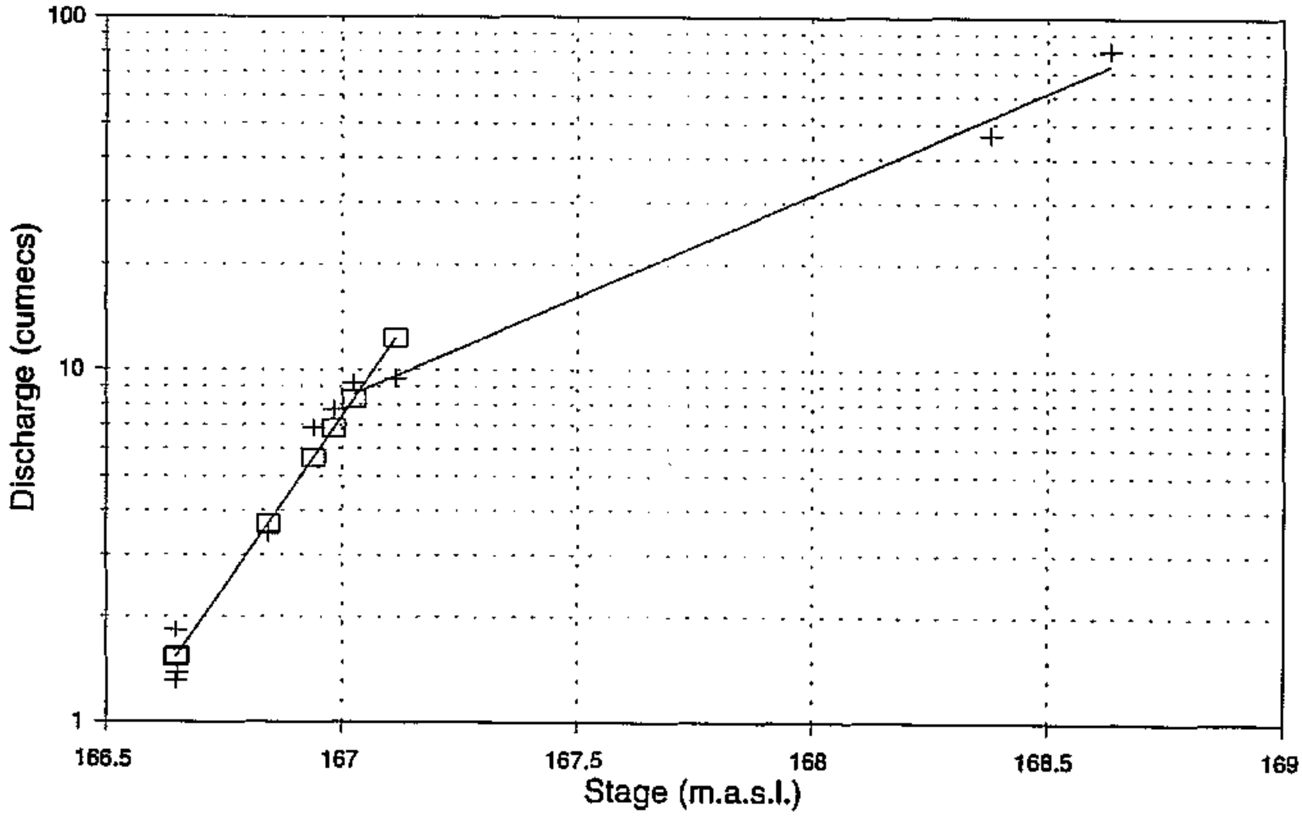

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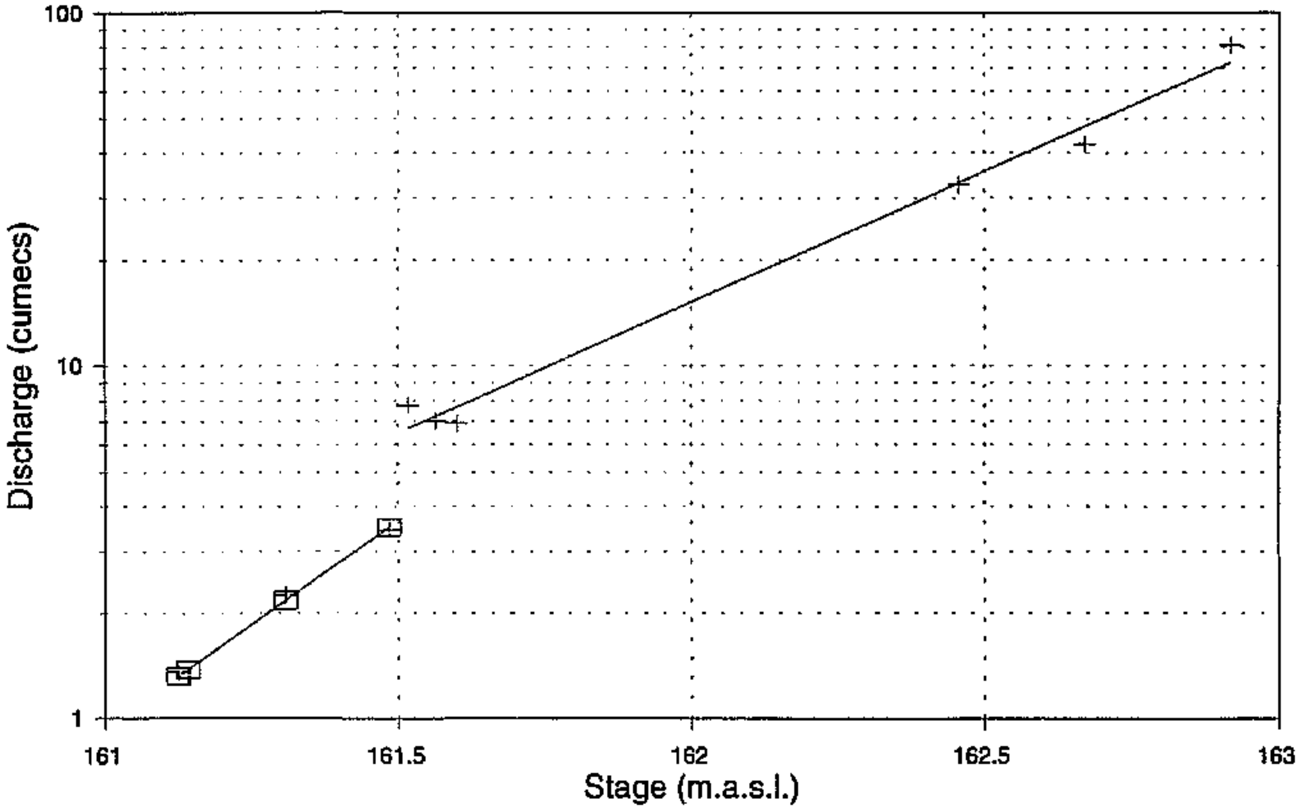

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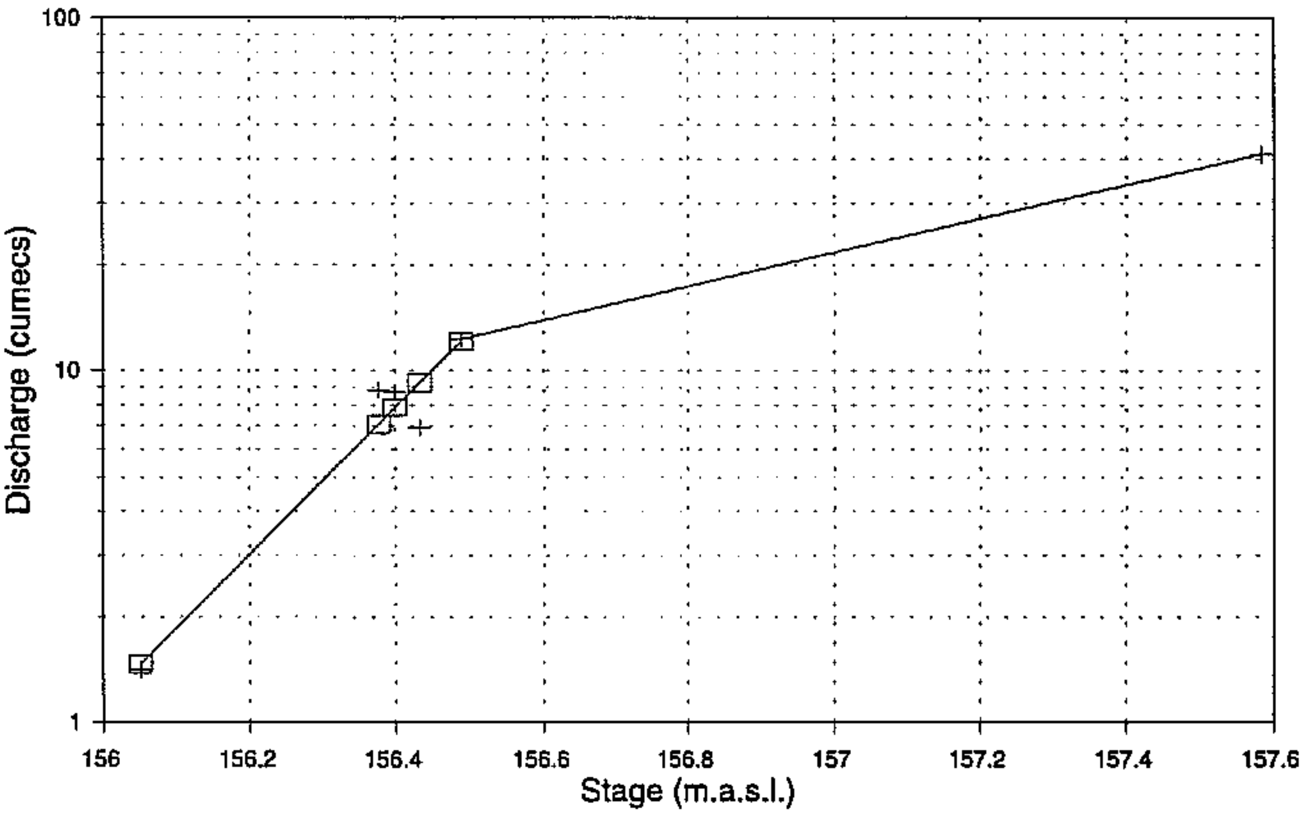

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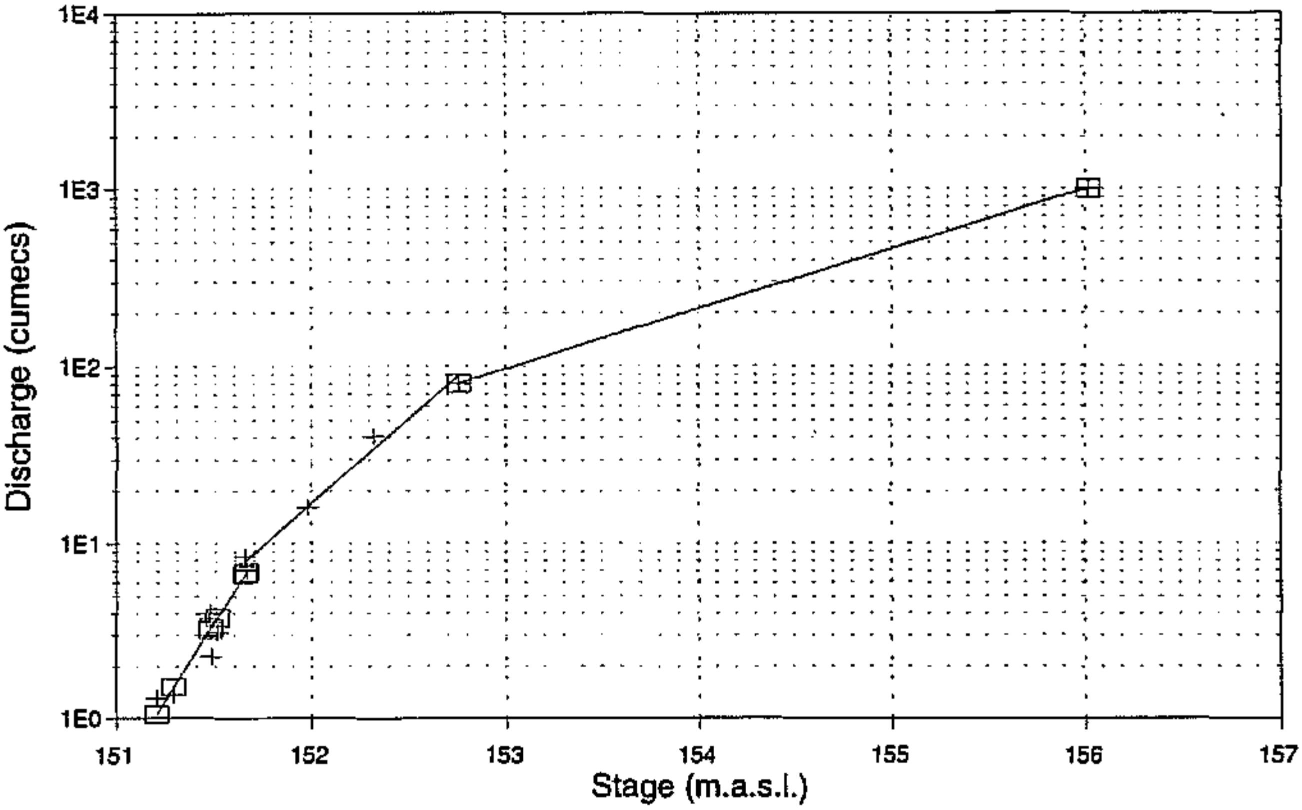

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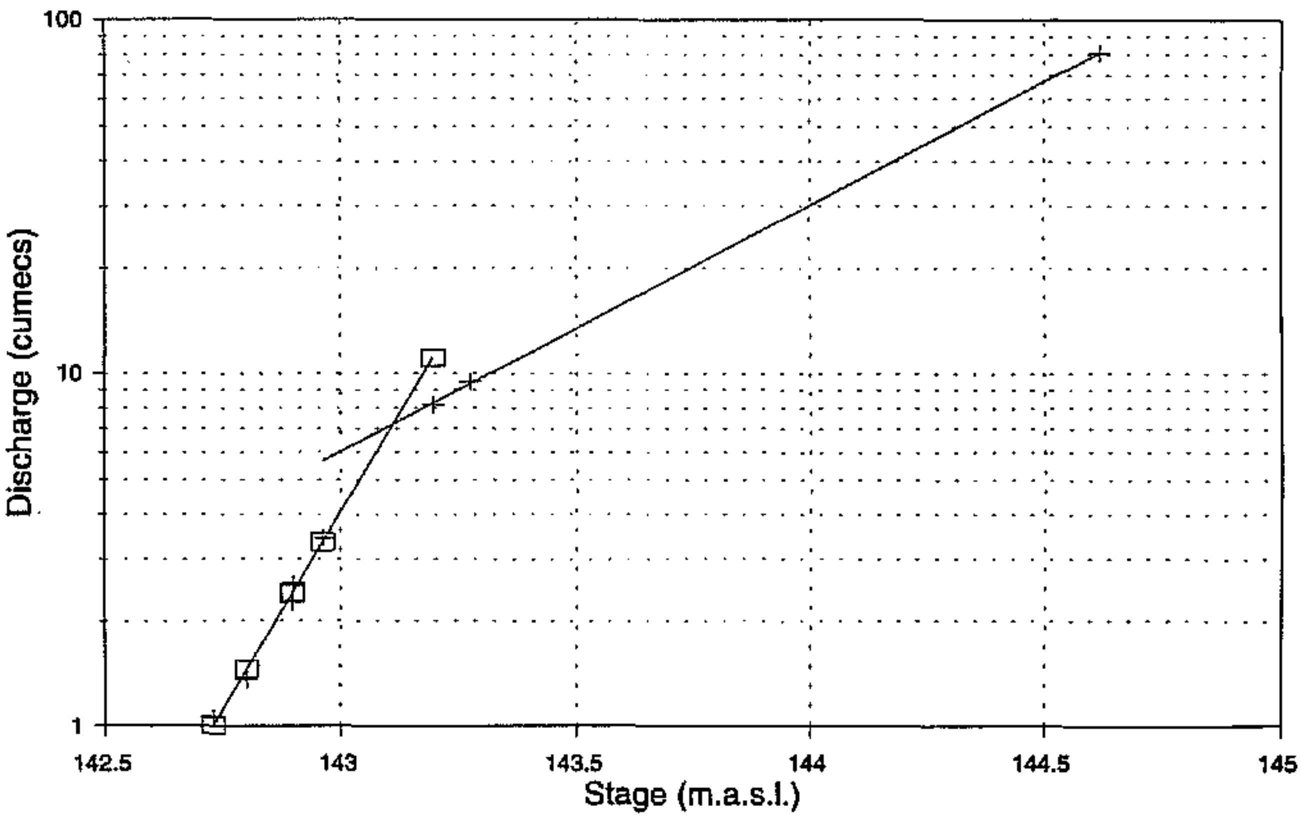

APPENDIX D: SABIE RIVER SIMULATED LOCAL CHANNEL HYDRAULICS

SITE 1

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	400.666	27.479	0.834	0.534	27.816	14.687	0.068	0.030	0.0000390
1.5	400.767	27.713	0.935	0.630	28.125	17.469	0.086	0.035	0.0000500
2.0	400.838	27.878	1.006	0.698	28.344	19.457	0.103	0.039	0.0000630
2.5	400.894	28.007	1.062	0.750	28.514	21.007	0.119	0.044	0.0000770
3.0	400.939	28.112	1.107	0.792	28.652	22.278	0.135	0.048	0.0000910
3.5	400.978	28.201	1.146	0.828	28.770	23.357	0.150	0.053	0.0001070
4.0	401.011	28.278	1.179	0.859	28.871	24.295	0.165	0.057	0.0001230
4.5	401.040	28.346	1.208	0.886	28.961	25.124	0.179	0.061	0.0001400
5.0	401.066	28.406	1.234	0.911	29.041	25.867	0.193	0.065	0.0001570
6.0	401.112	28.512	1.280	0.952	29.180	27.157	0.221	0.072	0.0001930
7.0	401.150	28.630	1.318	0.987	29.324	28.252	0.248	0.080	0.0002320
8.0	401.183	28.785	1.351	1.015	29.496	29.205	0.274	0.087	0.0002740
9.0	401.212	28.921	1.380	1.039	29.647	30.049	0.300	0.094	0.0003170
10.0	401.239	29.043	1.407	1.061	29.783	30.808	0.325	0.101	0.0003630
20.0	401.411	29.845	1.579	1.202	30.673	35.882	0.557	0.162	0.0009070
30.0	401.595	30.702	1.763	1.350	31.624	41.452	0.724	0.199	0.0013140
40.0	402.040	33.152	2.208	1.677	34.268	55.599	0.719	0.177	0.0009770
50.0	402.338	35.393	2.506	1.860	36.588	65.831	0.760	0.178	0.0009490
60.0	402.599	37.346	2.767	2.016	38.609	75.297	0.797	0.179	0.0009380
70.0	402.889	43.065	3.057	2.020	44.386	86.991	0.805	0.181	0.0009500
80.0	403.094	45.038	3.262	2.131	46.409	95.991	0.833	0.182	0.0009490
90.0	403.281	46.792	3.449	2.235	48.209	104.574	0.861	0.184	0.0009500
100.0	403.646	61.558	3.814	2.013	63.084	123.912	0.807	0.182	0.0009530
200.0	404.809	80.457	4.977	2.600	82.223	209.179	0.956	0.189	0.0009480
300.0	405.628	89.976	5.796	3.101	91.885	279.006	1.075	0.195	0.0009470
400.0	406.298	96.867	6.466	3.525	98.954	341.431	1.172	0.199	0.0009480
650.0	407.716	118.399	7.884	4.181	120.872	495.014	1.313	0.205	0.0009470

SITE 3

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	377.072	39.492	0.884	0.219	40.119	8.644	0.116	0.079	0.000210
1.5	377.103	41.470	0.915	0.238	42.144	9.882	0.152	0.099	0.000323
2.0	377.133	43.280	0.945	0.258	43.999	11.170	0.179	0.113	0.000404
2.5	377.164	45.467	0.976	0.275	46.231	12.523	0.200	0.121	0.000461
3.0	377.194	47.655	1.006	0.293	48.463	13.941	0.215	0.127	0.000494
3.5	377.225	49.843	1.037	0.310	50.695	15.427	0.227	0.130	0.000509
4.0	377.255	51.951	1.067	0.327	52.847	16.979	0.236	0.132	0.000511
4.5	377.285	53.324	1.097	0.348	54.265	18.583	0.242	0.131	0.000496
5.0	377.316	54.697	1.128	0.370	55.682	20.228	0.247	0.130	0.000477
6.0	377.377	57.442	1.189	0.412	58.517	23.646	0.254	0.126	0.000436
7.0	377.438	60.188	1.250	0.452	61.352	27.230	0.257	0.122	0.000395
8.0	377.499	62.934	1.311	0.492	64.188	30.982	0.258	0.118	0.000357
9.0	377.560	64.979	1.372	0.537	66.323	34.879	0.258	0.112	0.000318
10.0	377.595	66.157	1.407	0.562	67.553	37.185	0.269	0.115	0.000325
20.0	377.700	69.665	1.512	0.636	71.215	44.294	0.452	0.181	0.000778
30.0	377.804	71.670	1.616	0.721	73.361	51.693	0.580	0.218	0.001088
40.0	377.909	71.805	1.721	0.825	73.618	59.203	0.676	0.238	0.001236
50.0	378.021	71.935	1.833	0.935	73.877	67.230	0.744	0.246	0.001270
60.0	378.131	72.063	1.943	1.044	74.134	75.211	0.798	0.249	0.001264
70.0	378.236	72.232	2.048	1.145	74.415	82.740	0.846	0.252	0.001258
80.0	378.332	72.502	2.144	1.237	74.766	89.710	0.892	0.256	0.001263
90.0	378.428	72.773	2.240	1.329	75.118	96.707	0.931	0.258	0.001252
100.0	378.515	73.017	2.327	1.411	75.435	103.047	0.970	0.261	0.001258
200.0	379.272	76.267	3.084	2.089	79.090	159.342	1.255	0.277	0.001254
300.0	379.884	79.769	3.696	2.596	82.803	207.085	1.449	0.287	0.001252
400.0	380.414	83.040	4.226	3.013	86.245	250.234	1.599	0.294	0.001250
650.0	381.538	91.686	5.350	3.798	95.182	348.268	1.866	0.306	0.001251

SITE 5

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	342.392	52.694	1.619	0.915	55.016	48.235	0.021	0.007	0.000001
1.5	342.420	53.486	1.647	0.930	55.828	49.727	0.030	0.010	0.000002
2.0	342.448	54.278	1.675	0.944	56.640	51.241	0.039	0.013	0.000004
2.5	342.476	55.071	1.703	0.958	57.452	52.778	0.047	0.015	0.000005
3.0	342.504	55.863	1.731	0.973	58.264	54.336	0.055	0.018	0.000007
3.5	342.532	56.656	1.759	0.987	59.076	55.917	0.063	0.020	0.000009
4.0	342.560	57.448	1.787	1.001	59.888	57.521	0.070	0.022	0.000010
4.5	342.589	58.346	1.816	1.014	60.805	59.148	0.076	0.024	0.000012
5.0	342.617	59.253	1.844	1.026	61.732	60.800	0.082	0.026	0.000014
6.0	342.673	61.069	1.900	1.051	63.586	64.181	0.093	0.029	0.000017
7.0	342.729	62.884	1.956	1.076	65.440	67.665	0.103	0.032	0.000021
8.0	342.785	64.699	2.012	1.101	67.294	71.250	0.112	0.034	0.000024
9.0	342.842	65.808	2.069	1.139	68.439	74.929	0.120	0.036	0.000026
10.0	342.898	66.003	2.125	1.191	68.668	78.633	0.127	0.037	0.000027
20.0	343.460	68.847	2.687	1.692	71.823	116.459	0.172	0.042	0.000031
30.0	343.950	71.631	3.177	2.106	74.864	150.866	0.199	0.044	0.000031
40.0	344.406	75.572	3.633	2.437	79.056	184.164	0.217	0.044	0.000031
50.0	344.903	92.922	4.130	2.443	96.604	227.008	0.220	0.045	0.000031
60.0	345.215	95.792	4.442	2.676	99.541	256.367	0.234	0.046	0.000031
70.0	345.502	98.492	4.729	2.887	102.302	284.322	0.246	0.046	0.000031
80.0	345.792	102.535	5.019	3.055	106.400	313.285	0.255	0.047	0.000031
90.0	346.075	108.741	5.302	3.157	112.648	343.287	0.262	0.047	0.000032
100.0	346.311	111.015	5.538	3.325	114.971	369.117	0.271	0.047	0.000031
200.0	348.169	127.080	7.396	4.647	131.552	590.516	0.339	0.050	0.000031
300.0	349.593	138.896	8.820	5.619	143.763	780.486	0.384	0.052	0.000031
400.0	350.767	147.014	9.994	6.453	152.106	948.626	0.422	0.053	0.000031
650.0	352.970	149.182	12.197	8.559	154.310	1276.801	0.509	0.056	0.000031

SITE 9

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	303.835	25.261	1.453	0.829	25.959	20.935	0.048	0.017	0.000006
1.5	303.897	25.351	1.515	0.887	26.112	22.483	0.067	0.023	0.000011
2.0	303.940	25.415	1.558	0.928	26.221	23.584	0.085	0.028	0.000017
2.5	303.974	25.465	1.592	0.960	26.305	24.440	0.102	0.033	0.000023
3.0	304.001	25.505	1.619	0.986	26.374	25.141	0.119	0.038	0.000031
3.5	304.024	25.539	1.642	1.008	26.432	25.734	0.136	0.043	0.000039
4.0	304.044	25.569	1.662	1.027	26.483	26.249	0.152	0.048	0.000048
4.5	304.062	25.595	1.680	1.043	26.527	26.703	0.169	0.053	0.000057
5.0	304.078	25.619	1.696	1.058	26.567	27.110	0.184	0.057	0.000067
6.0	304.106	25.659	1.724	1.084	26.636	27.815	0.216	0.066	0.000089
7.0	304.129	25.745	1.747	1.104	26.746	28.412	0.246	0.075	0.000113
8.0	304.149	26.329	1.767	1.099	27.361	28.937	0.276	0.084	0.000144
9.0	304.167	26.844	1.785	1.096	27.903	29.409	0.306	0.093	0.000177
10.0	304.183	27.305	1.801	1.093	28.388	29.839	0.335	0.102	0.000213
20.0	304.287	30.256	1.905	1.086	31.499	32.850	0.609	0.187	0.000710
30.0	304.787	47.736	2.405	1.091	49.753	52.063	0.576	0.176	0.000633
40.0	305.253	63.464	2.871	1.251	65.891	79.376	0.504	0.144	0.000401
50.0	305.614	96.102	3.232	1.123	98.906	107.875	0.463	0.140	0.000387
60.0	305.910	97.820	3.528	1.396	100.810	136.581	0.439	0.119	0.000261
70.0	306.159	99.129	3.777	1.626	102.215	161.173	0.434	0.109	0.000208
80.0	306.376	100.263	3.994	1.823	103.432	182.740	0.438	0.104	0.000182
90.0	306.567	101.264	4.185	1.994	104.506	201.967	0.446	0.101	0.000167
100.0	306.737	102.159	4.355	2.147	105.466	219.328	0.456	0.099	0.000159
200.0	307.936	109.887	5.554	3.150	113.574	346.128	0.578	0.104	0.000153
300.0	308.879	117.156	6.497	3.868	121.086	453.133	0.662	0.107	0.000153
400.0	309.745	129.733	7.363	4.319	133.872	560.260	0.714	0.110	0.000153
650.0	311.366	144.715	8.984	5.410	149.350	782.902	0.830	0.114	0.000153

SITE 10

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	291.740	7.088	0.137	0.087	7.128	0.618	1.617	1.748	4.254408
1.5	291.965	12.821	0.362	0.223	12.963	2.862	0.524	0.354	0.128687
2.0	292.124	15.594	0.521	0.329	15.785	5.126	0.390	0.217	0.042614
2.5	292.248	17.720	0.645	0.405	17.948	7.185	0.348	0.174	0.025648
3.0	292.349	18.373	0.746	0.491	18.646	9.017	0.333	0.152	0.018227
3.5	292.434	19.643	0.831	0.541	19.971	10.630	0.329	0.143	0.015706
4.0	292.508	21.319	0.905	0.569	21.704	12.136	0.330	0.139	0.014741
4.5	292.573	23.778	0.970	0.572	24.224	13.605	0.331	0.140	0.014757
5.0	292.632	26.126	1.029	0.576	26.622	15.061	0.332	0.140	0.014723
6.0	292.733	30.639	1.130	0.585	31.238	17.918	0.335	0.140	0.014706
7.0	292.818	36.186	1.215	0.573	36.886	20.746	0.337	0.142	0.015325
8.0	292.892	41.122	1.289	0.574	41.919	23.611	0.339	0.143	0.015424
9.0	292.957	45.073	1.354	0.586	45.965	26.423	0.341	0.142	0.015171
10.0	293.015	47.786	1.412	0.610	48.769	29.134	0.343	0.140	0.014635
20.0	293.399	71.459	1.796	0.720	73.079	51.445	0.389	0.146	0.015084
30.0	293.624	79.900	2.021	0.857	81.899	68.439	0.438	0.151	0.015257
40.0	293.812	88.208	2.209	0.955	90.513	84.228	0.475	0.155	0.015515
50.0	293.988	98.487	2.385	1.021	101.165	100.588	0.497	0.157	0.015561
60.0	294.152	109.900	2.549	1.071	112.923	117.700	0.510	0.157	0.015369
70.0	294.288	119.283	2.685	1.117	122.590	133.240	0.525	0.159	0.015437
80.0	294.415	129.554	2.812	1.151	133.113	149.099	0.537	0.160	0.015468
90.0	294.522	138.198	2.919	1.182	141.966	163.391	0.551	0.162	0.015722
100.0	294.629	144.507	3.026	1.235	148.474	178.490	0.560	0.161	0.015348
200.0	295.383	197.328	3.780	1.553	202.530	306.461	0.653	0.167	0.015323
300.0	295.940	251.853	4.337	1.710	257.575	430.600	0.697	0.170	0.015290
400.0	296.341	287.397	4.738	1.877	293.363	539.554	0.741	0.173	0.015244
650.0	296.997	302.318	5.394	2.431	308.420	734.897	0.884	0.181	0.015363

SITE 11

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	281.435	54.697	1.227	0.547	57.050	29.892	0.033	0.014	0.000166
1.5	281.495	58.635	1.287	0.568	61.299	33.302	0.045	0.019	0.000286
2.0	281.537	61.432	1.329	0.584	64.316	35.865	0.056	0.023	0.000423
2.5	281.571	64.050	1.363	0.592	67.104	37.937	0.066	0.027	0.000581
3.0	281.598	66.637	1.390	0.596	69.835	39.713	0.076	0.031	0.000757
3.5	281.620	67.627	1.412	0.610	70.947	41.249	0.085	0.035	0.000927
4.0	281.640	68.485	1.432	0.622	71.910	42.598	0.094	0.038	0.001108
4.5	281.658	69.241	1.450	0.633	72.759	43.802	0.103	0.041	0.001298
5.0	281.673	69.918	1.465.	0.642	73.519	44.890	0.111	0.044	0.001497
6.0	281.700	71.143	1.492	0.658	74.889	46.798	0.128	0.050	0.001923
7.0	281.723	72.404	1.515	0.669	76.278	48.440	0.145	0.056	0.002391
8.0	281.743	73.688	1.535	0.677	77.662	49.887	0.160	0.062	0.002900
9.0	281.761	74.821	1.553	0.684	78.883	51.185	0.176	0.068	0.003440
10.0	281.776	75.834	1.568	0.691	79.975	52.363	0.191	0.073	0.004009
20.0	281.879	82.257	1.671	0.736	86.949	60.502	0.331	0.123	0.011076
30.0	282.083	108.046	1.875	0.737	113.968	79.605	0.377	0.140	0.014323
40.0	282.280	137.868	2.072	0.752	144.795	103.731	0.386	0.142	0.014498
50.0	282.439	161.985	2.231	0.786	169.613	127.384	0.393	0.141	0.014105
60.0	282.566	186.855	2.358	0.801	195.037	149.618	0.401	0.143	0.014313
70.0	282.677	208.548	2.469	0.823	217.202	171.549	0.408	0.144	0.014254
80.0	282.766	229.636	2.558	0.832	238.619	190.994	0.419	0.147	0.014755
90.0	282.854	242.449	2.646	0.874	251.716	211.975	0.425	0.145	0.014168
100.0	282.926	257.398	2.718	0.893	266.871	229.741	0.435	0.147	0.014459
200.0	283.443	297.627	3.235	1.253	308.267	372.859	0.536	0.153	0.013954
300.0	283.815	314.989	3.607	1.546	326.055	486.983	0.616	0.158	0.013893
400.0	284.134	329.076	3.926	1.792	340.337	589.582	0.678	0.162	0.013827
650.0	284.755	338.315	4.547	2.357	350.073	797.468	0.815	0.169	0.013853

SITE 12

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	267.805	4.243	0.131	0.072	4.253	0.307	3.254	3.859	0.712067
1.5	267.916	6.218	0.242	0.143	6.243	0.886	1.692	1.431	0.078318
2.0	267.995	7.672	0.321	0.187	7.707	1.433	1.396	1.031	0.037181
2.5	268.056	8.800	0.382	0.220	8.842	1.936	1.292	0.879	0.025607
3.0	268.106	9.721	0.432	0.247	9.770	2.397	1.251	0.804	0.020640
3.5	268.148	10.439	0.474	0.270	10.495	2.823	1.240	0.761	0.017931
4.0	268.184	11.046	0.510	0.291	11.108	3.215	1.244	0.736	0.016369
4.5	268.217	11.581	0.543	0.309	11.649	3.580	1.257	0.722	0.015431
5.0	268.245	12.060	0.571	0.325	12.133	3.920	1.275	0.714	0.014855
6.0	268.295	12.888	0.621	0.352	12.970	4.543	1.321	0.710	0.014310
7.0	268.337	13.588	0.663	0.375	13.678	5.101	1.372	0.715	0.014207
8.0	268.371	14.142	0.697	0.393	14.237	5.563	1.438	0.732	0.014659
9.0	268.433	16.635	0.759	0.392	16.742	6.527	1.379	0.703	0.013518
10.0	268.489	19.020	0.815	0.394	19.142	7.503	1.333	0.677	0.012538
20.0	268.857	22.693	1.183	0.679	22.938	15.419	1.297	0.502	0.005786
30.0	269.072	23.358	1.398	0.873	23.798	20.391	1.471	0.503	0.005386
40.0	269.224	23.475	1.550	1.021	24.128	23.963	1.669	0.528	0.005694
50.0	269.409	23.618	1.735	1.199	24.527	28.324	1.765	0.515	0.005209
60.0	269.556	23.731	1.882	1.340	24.845	31.806	1.886	0.520	0.005184
70.0	269.693	23.836	2.019	1.471	25.140	35.053	1.997	0.526	0.005184
80.0	269.823	23.936	2.149	1.594	25.421	38.163	2.096	0.530	0.005176
90.0	269.948	24.094	2.274	1.708	25.722	41.158	2.187	0.534	0.005174
100.0	270.075	24.291	2.401	1.820	26.047	44.222	2.261	0.535	0.005113
200.0	271.620	89.353	3.946	1.237	92.411	110.494	1.810	0.520	0.005228
300.0	272.070	120.524	4.396	1.314	124.545	158.386	1.894	0.528	0.005273
400.0	272.354	127.397	4.680	1.518	131.863	193.334	2.069	0.536	0.005204
650.0	272.932	146.693	5.258	1.867	151.741	273.838	2.374	0.555	0.005193

SITE 14

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	263.929	21.810	1.144	0.811	22.071	17.687	0.057	0.020	0.000009
1.5	264.048	22.803	1.263	0.892	23.133	20.336	0.074	0.025	0.000013
2.0	264.132	23.511	1.347	0.948	23.891	22.286	0.090	0.029	0.000018
2.5	264.198	24.085	1.413	0.990	24.503	23.840	0.105	0.034	0.000023
3.0	264.251	24.554	1.466	1.024	25.004	25.139	0.119	0.038	0.000029
3.5	264.296	24.950	1.511	1.052	25.427	26.256	0.133	0.041	0.000034
4.0	264.335	25.459	1.550	1.070	25.958	27.240	0.147	0.045	0.000041
4.5	264.370	25.965	1.585	1.083	26.483	28.127	0.160	0.049	0.000048
5.0	264.401	26.417	1.616	1.095	26.953	28.935	0.173	0.053	0.000055
6.0	264.454	27.199	1.669	1.116	27.765	30.366	0.198	0.060	0.000070
7.0	264.499	27.861	1.714	1.135	28.453	31.608	0.221	0.066	0.000086
8.0	264.538	29.610	1.753	1.105	30.223	32.730	0.244	0.074	0.000109
9.0	264.573	30.334	1.788	1.113	30.968	33.769	0.267	0.081	0.000128
10.0	264.604	30.520	1.819	1.137	31.172	34.708	0.288	0.086	0.000146
20.0	264.806	32.710	2.021	1.256	33.453	41.081	0.487	0.139	0.000365
30.0	264.925	33.533	2.140	1.342	34.320	45.013	0.666	0.184	0.000627
40.0	265.173	44.853	2.388	1.221	45.742	54.758	0.730	0.211	0.000850
50.0	265.410	46.200	2.625	1.419	47.187	65.565	0.763	0.204	0.000760
60.0	265.588	47.208	2.803	1.565	48.268	73.862	0.812	0.207	0.000758
70.0	265.755	48.151	2.970	1.699	49.279	81.805	0.856	0.210	0.000754
80.0	265.906	49.003	3.121	1.820	50.195	89.182	0.897	0.212	0.000757
90.0	266.055	49.838	3.270	1.937	51.092	96.532	0.932	0.214	0.000754
100.0	266.199	50.777	3.414	2.043	52.089	103.732	0.964	0.215	0.000751
200.0	267.699	111.378	4.914	1.921	113.575	213.909	0.935	0.215	0.000761
300.0	268.262	115.091	5.477	2.414	117.974	277.805	1.080	0.222	0.000754
400.0	268.747	119.002	5.962	2.812	122.016	334.586	1.196	0.228	0.000754
650.0	269.772	129.927	6.987	3.571	133.307	463.922	1.401	0.237	0.000754

SITE 15

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	258.013	33.621	0.488	0.371	33.944	12.472	0.080	0.042	0.000088
1.5	258.138	34.753	0.613	0.482	35.177	16.756	0.090	0.041	0.000078
2.0	258.227	34.990	0.702	0.567	35.497	19.851	0.101	0.043	0.000079
2.5	258.296	35.174	0.771	0.633	35.746	22.266	0.112	0.045	0.000085
3.0	258.352	35.325	0.827	0.686	35.949	24.249	0.124	0.048	0.000093
3.5	258.399	35.452	0.874	0.731	36.121	25.932	0.135	0.050	0.000102
4.0	258.441	35.562	0.916	0.770	36.269	27.395	0.146	0.053	0.000112
4.5	258.477	35.686	0.952	0.804	36.427	28.689	0.157	0.056	0.000122
5.0	258.509	35.921	0.984	0.831	36.688	29.853	0.167	0.059	0.000133
6.0	258.566	36.328	1.041	0.878	37.140	31.885	0.188	0.064	0.000156
7.0	258.613	36.672	1.088	0.917	37.522	33.620	0.208	0.069	0.000181
8.0	258.654	36.969	1.129	0.950	37.853	35.137	0.228	0.075	0.000206
9.0	258.691	37.232	1.166	0.980	38.145	36.485	0.247	0.080	0.000232
10.0	258.723	37.467	1.198	1.006	38.407	37.700	0.265	0.084	0.000260
20.0	259.133	40.427	1.608	1.327	41.696	53.641	0.373	0.103	0.000358
30.0	259.411	42.459	1.886	1.535	43.949	65.156	0.460	0.119	0.000451
40.0	259.608	45.027	2.083	1.638	46.551	73.761	0.542	0.135	0.000573
50.0	259.895	51.898	2.370	1.686	53.480	87.482	0.572	0.141	0.000610
60.0	260.266	71.579	2.741	1.539	73.332	110.178	0.545	0.140	0.000620
70.0	260.499	82.920	2.974	1.546	84.794	128.221	0.546	0.140	0.000618
80.0	260.704	92.714	3.179	1.577	94.695	146.179	0.547	0.139	0.000604
90.0	260.963	121.764	3.438	1.420	123.826	172.949	0.520	0.139	0.000624
100.0	261.073	126.131	3.548	1.480	128.214	186.617	0.536	0.141	0.000627
200.0	261.922	147.539	4.397	2.053	149.709	302.844	0.660	0.147	0.000614
300.0	262.632	180.781	5.107	2.296	183.050	415.155	0.723	0.152	0.000631
400.0	263.117	187.754	5.592	2.689	190.103	504.864	0.792	0.154	0.000614
650.0	264.068	195.810	6.543	3.510	198.380	687.304	0.946	0.161	0.000614

SITE 16

Q	Z	W	D max	D ave	P	A	V	Fr	SI
1.0	246.308	20.910	0.956	0.446	21.424	9.334	0.107	0.051	0.000125
1.5	246.349	21.676	0.997	0.471	22.223	10.208	0.147	0.068	0.000219
2.0	246.390	25.077	1.038	0.444	25.658	11.142	0.180	0.086	0.000353
2.5	246.431	26.965	1.079	0.453	27.593	12.222	0.205	0.097	0.000446
3.0	246.472	28.187	1.120	0.474	28.861	13.355	0.225	0.104	0.000508
3.5	246.514	29.375	1.162	0.495	30.097	14.537	0.241	0.109	0.000551
4.0	246.555	29.711	1.203	0.530	30.476	15.751	0.254	0.111	0.000560
4.5	246.596	30.048	1.244	0.565	30.856	16.978	0.265	0.113	0.000561
5.0	246.637	30.384	1.285	0.600	31.236	18.218	0.274	0.113	0.000556
6.0	246.719	31.057	1.367	0.668	31.995	20.741	0.289	0.113	0.000537
7.0	246.801	31.730	1.449	0.735	32.754	23.320	0.300	0.112	0.000510
8.0	246.883	32.403	1.531	0.801	33.514	25.953	0.308	0.110	0.000481
9.0	246.965	33.076	1.613	0.866	34.273	28.642	0.314	0.108	0.000452
10.0	247.047	34.151	1.695	0.919	35.425	31.390	0.319	0.106	0.000429
20.0	247.557	49.383	2.205	1.089	51.012	53.765	0.372	0.114	0.000464
30.0	247.853	51.934	2.501	1.326	53.665	68.858	0.436	0.121	0.000490
40.0	248.123	54.508	2.771	1.525	56.317	83.119	0.481	0.124	0.000496
50.0	248.413	63.161	3.061	1.588	65.085	100.273	0.499	0.126	0.000503
60.0	248.629	66.848	3.277	1.710	68.875	114.334	0.525	0.128	0.000504
70.0	248.826	70.144	3.474	1.822	72.267	127.830	0.548	0.130	0.000505
80.0	249.030	73.926	3.678	1.928	76.142	142.549	0.561	0.129	0.000491
90.0	249.250	83.750	3.898	1.908	86.082	159.793	0.563	0.130	0.000501
100.0	249.464	95.882	4.112	1.867	98.383	179.036	0.559	0.131	0.000506
200.0	250.630	155.098	5.278	2.116	158.321	328.248	0.609	0.134	0.000506
300.0	251.395	199.912	6.043	2.321	203.698	464.010	0.647	0.135	0.000502
400.0	252.044	271.804	6.692	2.282	276.062	620.174	0.645	0.136	0.000509
650.0	252.900	307.397	7.548	2.845	311.964	874.500	0.743	0.141	0.000503

SITE 17

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	235.816	34.237	1.094	0.433	35.816	14.841	0.067	0.033	0.000053
1.5	235.971	39.634	1.249	0.522	41.516	20.703	0.072	0.032	0.000048
2.0	236.081	40.133	1.359	0.625	42.196	25.099	0.080	0.032	0.000046
2.5	236.167	40.520	1.445	0.705	42.724	28.547	0.088	0.033	0.000047
3.0	236.236	40.837	1.514	0.769	43.156	31.388	0.096	0.035	0.000050
3.5	236.296	41.104	1.574	0.822	43.520	33.808	0.104	0.036	0.000054
4.0	236.347	41.336	1.625	0.869	43.836	35.917	0.111	0.038	0.000058
4.5	236.392	41.541	1.670	0.910	44.115	37.787	0.119	0.040	0.000063
5.0	236.432	41.641	1.710	0.948	44.265	39.466	0.127	0.042	0.000067
6.0	236.502	41.746	1.780	1.015	44.440	42.378	0.142	0.045	0.000077
7.0	236.561	41.834	1.839	1.072	44.588	44.846	0.156	0.048	0.000087
8.0	236.612	41.910	1.890	1.121	44.717	46.988	0.170	0.051	0.000098
9.0	236.657	41.978	1.935	1.164	44.830	48.881	0.184	0.054	0.000109
10.0	236.698	42.038	1.976	1.203	44.932	50.577	0.198	0.058	0.000120
20.0	236.963	44.499	2.241	1.391	47.675	61.898	0.323	0.087	0.000265
30.0	237.323	52.718	2.601	1.501	56.350	79.151	0.379	0.099	0.000329
40.0	237.613	65.560	2.891	1.472	69.472	96.511	0.414	0.109	0.000399
50.0	237.919	73.376	3.197	1.605	77.563	117.805	0.424	0.107	0.000371
60.0	238.300	104.877	3.578	1.440	109.364	151.074	0.397	0.106	0.000369
70.0	238.492	115.903	3.770	1.486	120.564	172.268	0.406	0.106	0.000369
80.0	238.631	119.162	3.909	1.583	123.902	188.658	0.424	0.108	0.000370
90.0	238.769	123.766	4.047	1.659	128.588	205.378	0.438	0.109	0.000370
100.0	238.903	129.238	4.181	1.720	134.149	222.321	0.450	0.109	0.000371
200.0	239.902	169.067	5.180	2.217	174.645	374.753	0.534	0.114	0.000370
300.0	240.556	177.235	5.834	2.753	183.257	488.010	0.615	0.118	0.000369
400.0	241.152	193.359	6.430	3.100	199.640	599.502	0.667	0.121	0.000370
650.0	242.251	202.035	7.529	4.043	208.592	816.794	0.796	0.126	0.000369

SITE 18

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	220.101	43.839	0.474	0.132	43.996	5.790	0.173	0.152	0.000902
1.5	220.196	61.902	0.569	0.177	62.179	10.980	0.137	0.104	0.000381
2.0	220.264	71.499	0.637	0.216	71.922	15.472	0.129	0.089	0.000263
2.5	220.316	78.901	0.689	0.246	79.443	19.396	0.129	0.083	0.000220
3.0	220.358	89.285	0.731	0.257	89.934	22.944	0.131	0.082	0.000214
3.5	220.394	95.092	0.767	0.276	95.834	26.279	0.133	0.081	0.000202
4.0	220.426	99.515	0.799	0.295	100.340	29.317	0.136	0.080	0.000194
4.5	220.453	102.148	0.826	0.314	103.043	32.094	0.140	0.080	0.000189
5.0	220.478	104.486	0.851	0.332	105.445	34.639	0.144	0.080	0.000186
6.0	220.520	108.246	0.893	0.362	109.311	39.178	0.153	0.081	0.000187
7.0	220.556	111.534	0.929	0.387	112.689	43.135	0.162	0.083	0.000192
8.0	220.588	114.695	0.961	0.407	115.928	46.667	0.171	0.086	0.000200
9.0	220.615	117.484	0.988	0.424	118.786	49.864	0.180	0.088	0.000210
10.0	220.640	120.063	1.013	0.440	121.424	52.790	0.189	0.091	0.000221
20.0	220.802	127.269	1.175	0.573	128.927	72.896	0.274	0.116	0.000326
30.0	221.051	140.253	1.424	0.758	142.274	106.304	0.282	0.103	0.000238
40.0	221.313	158.260	1.686	0.917	160.660	145.060	0.276	0.092	0.000176
50.0	221.567	186.994	1.940	1.008	189.793	188.553	0.265	0.084	0.000144
60.0	221.717	199.755	2.090	1.090	202.766	217.756	0.276	0.084	0.000140
70.0	221.839	207.552	2.212	1.169	210.717	242.610	0.289	0.085	0.000140
80.0	221.956	216.866	2.329	1.233	220.164	267.363	0.299	0.086	0.000140
90.0	222.060	222.937	2.433	1.302	226.353	290.318	0.310	0.087	0.000140
100.0	222.165	231.085	2.538	1.359	234.621	314.037	0.318	0.087	0.000139
200.0	222.979	319.641	3.352	1.679	324.165	536.710	0.373	0.092	0.000144
300.0	223.567	381.731	3.940	1.943	386.718	741.548	0.405	0.093	0.000139
400.0	224.032	449.152	4.405	2.086	454.262	936.868	0.427	0.094	0.000141
650.0	224.789	480.697	5.162	2.686	485.900	1291.217	0.503	0.098	0.000139

SITE 19

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	204.897	11.588	0.769	0.323	13.769	3.742	0.267	0.150	0.001461
1.5	205.136	15.710	1.008	0.449	19.319	7.051	0.213	0.101	0.000625
2.0	205.307	19.117	1.179	0.519	23.875	9.924	0.202	0.089	0.000471
2.5	205.439	22.692	1.311	0.561	28.443	12.725	0.196	0.084	0.000406
3.0	205.547	25.503	1.419	0.601	32.020	15.318	0.196	0.081	0.000369
3.5	205.638	28.979	1.510	0.615	35.910	17.830	0.196	0.080	0.000353
4.0	205.717	31.373	1.589	0.644	38.583	20.215	0.198	0.079	0.000334
4.5	205.787	33.484	1.659	0.671	40.941	22.475	0.200	0.078	0.000321
5.0	205.849	35.336	1.721	0.697	43.018	24.622	0.203	0.078	0.000312
6.0	205.957	40.066	1.829	0.716	48.201	28.697	0.209	0.079	0.000314
7.0	206.048	43.845	1.920	0.742	52.373	32.525	0.215	0.080	0.000315
8.0	206.127	46.938	1.999	0.770	55.814	36.121	0.221	0.081	0.000315
9.0	206.197	50.966	2.069	0.775	60.154	39.506	0.228	0.083	0.000327
10.0	206.259	55.635	2.131	0.770	65.106	42.834	0.233	0.085	0.000343
20.0	206.669	102.584	2.541	0.723	113.941	74.157	0.270	0.101	0.000464
30.0	206.801	118.755	2.673	0.746	130.758	88.639	0.338	0.125	0.000693
40.0	206.972	139.096	2.844	0.797	151.943	110.803	0.361	0.129	0.000715
50.0	207.120	149.830	2.992	0.882	163.440	132.160	0.378	0.129	0.000684
60.0	207.246	161.546	3.118	0.939	175.711	151.677	0.396	0.130	0.000685
70.0	207.360	174.550	3.232	0.979	189.119	170.830	0.410	0.132	0.000692
80.0	207.456	184.318	3.328	1.021	199.218	188.127	0.425	0.134	0.000703
90.0	207.553	190.759	3.425	1.081	205.960	206.195	0.436	0.134	0.000685
100.0	207.632	194.771	3.504	1.137	210.107	221.427	0.452	0.135	0.000685
200.0	208.247	218.791	4.119	1.601	234.620	350.218	0.571	0.144	0.000688
300.0	208.727	232.726	4.599	1.969	248.759	458.290	0.655	0.149	0.000683
400.0	209.137	247.083	5.009	2.253	263.210	556.689	0.719	0.153	0.000685
650.0	209.957	264.105	5.829	2.902	280.314	766.322	0.848	0.159	0.000678

SITE 20

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	197.098	22.352	0.476	0.243	22.398	5.432	0.184	0.119	0.000454
1.5	197.208	30.369	0.586	0.274	30.436	8.315	0.180	0.110	0.000372
2.0	197.286	36.377	0.664	0.300	36.458	10.921	0.183	0.107	0.000339
2.5	197.347	41.529	0.725	0.320	41.621	13.276	0.188	0.106	0.000330
3.0	197.397	45.975	0.775	0.336	46.077	15.441	0.194	0.107	0.000328
3.5	197.438	49.735	0.816	0.351	49.844	17.444	0.201	0.108	0.000331
4.0	197.475	52.992	0.853	0.364	53.108	19.306	0.207	0.110	0.000335
4.5	197.507	55.512	0.885	0.379	55.633	21.046	0.214	0.111	0.000338
5.0	197.535	55.897	0.913	0.405	56.023	22.639	0.221	0.111	0.000331
6.0	197.585	56.564	0.963	0.449	56.697	25.422	0.236	0.112	0.000329
7.0	197.627	57.127	1.005	0.487	57.267	27.801	0.252	0.115	0.000336
8.0	197.663	57.616	1.041	0.519	57.761	29.881	0.268	0.119	0.000350
9.0	197.695	58.047	1.073	0.547	58.197	31.731	0.284	0.122	0.000366
10.0	197.751	58.799	1.129	0.595	58.957	34.992	0.286	0.118	0.000332
20.0	198.181	76.224	1.559	0.830	76.469	63.249	0.316	0.111	0.000261
30.0	198.433	89.117	1.811	0.943	89.411	83.997	0.357	0.117	0.000281
40.0	198.611	100.114	1.989	1.009	100.440	100.993	0.396	0.126	0.000315
50.0	198.750	129.887	2.128	0.900	130.249	116.836	0.428	0.144	0.000429
60.0	198.863	148.781	2.241	0.890	149.211	132.455	0.453	0.153	0.000487
70.0	198.958	192.634	2.336	0.773	193.118	148.834	0.470	0.171	0.000634
80.0	199.041	207.772	2.419	0.796	208.304	165.437	0.484	0.173	0.000644
90.0	199.135	223.189	2.513	0.832	223.782	185.702	0.485	0.170	0.000610
100.0	199.200	229.937	2.578	0.872	230.583	200.430	0.499	0.171	0.000608
200.0	199.686	264.777	3.064	1.221	265.709	323.413	0.618	0.179	0.000596
300.0	200.036	270.631	3.414	1.541	271.736	417.108	0.719	0.185	0.000592
400.0	200.356	284.103	3.734	1.780	285.349	505.836	0.791	0.189	0.000590
650.0	200.998	303.662	4.376	2.289	305.040	694.947	0.935	0.197	0.000591

SITE 21

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	188.521	74.166	1.367	0.571	76.070	42.330	0.024	0.010	0.000012
1.5	188.542	75.358	1.388	0.583	77.344	43.932	0.034	0.014	0.000025
2.0	188.563	76.550	1.409	0.595	78.619	45.560	0.044	0.018	0.000040
2.5	188.585	77.742	1.431	0.607	79.893	47.213	0.053	0.022	0.000057
3.0	188.606	81.724	1.452	0.599	83.961	48.919	0.061	0.025	0.000077
3.5	188.628	83.556	1.474	0.607	85.881	50.695	0.069	0.028	0.000096
4.0	188.649	84.887	1.495	0.618	87.301	52.500	0.076	0.031	0.000114
4.5	188.671	86.217	1.517	0.630	88.720	54.333	0.083	0.033	0.000132
5.0	188.692	87.548	1.538	0.642	90.140	56.195	0.089	0.035	0.000149
6.0	188.735	89.658	1.581	0.669	92.428	59.998	0.100	0.039	0.000178
7.0	188.778	91.358	1.624	0.699	94.307	63.878	0.110	0.042	0.000202
8.0	188.806	92.470	1.652	0.719	95.537	66.455	0.120	0.045	0.000235
9.0	188.828	93.353	1.674	0.734	96.512	68.523	0.131	0.049	0.000272
10.0	188.850	94.235	1.696	0.749	97.488	70.610	0.142	0.052	0.000308
20.0	189.073	107.103	1.919	0.865	111.256	92.651	0.216	0.074	0.000595
30.0	189.281	123.011	2.127	0.948	127.979	116.666	0.257	0.084	0.000748
40.0	189.432	130.885	2.278	1.038	136.333	135.920	0.294	0.092	0.000870
50.0	189.549	142.019	2.395	1.069	147.863	151.857	0.329	0.102	0.001046
60.0	189.645	155.004	2.491	1.072	161.177	166.109	0.361	0.111	0.001253
70.0	189.726	169.599	2.572	1.057	175.974	179.289	0.390	0.121	0.001487
80.0	189.796	180.827	2.642	1.059	187.320	191.579	0.418	0.130	0.001692
90.0	189.891	196.302	2.737	1.067	202.962	209.398	0.430	0.133	0.001772
100.0	189.993	209.820	2.839	1.097	216.644	230.097	0.435	0.133	0.001743
200.0	190.607	253.610	3.453	1.482	261.042	375.968	0.532	0.139	0.001740
300.0	191.040	265.150	3.886	1.842	272.791	488.439	0.614	0.144	0.001735
400.0	191.404	272.043	4.250	2.155	279.724	586.276	0.682	0.148	0.001735
650.0	192.186	291.989	5.032	2.762	299.733	806.518	0.806	0.155	0.001736

SITE 22

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	182.651	80.060	1.403	0.576	82.425	46.128	0.022	0.009	0.000010
1.5	182.695	87.092	1.447	0.571	89.676	49.764	0.030	0.013	0.000020
2.0	182.726	92.911	1.478	0.566	95.656	52.555	0.038	0.016	0.000032
2.5	182.750	97.050	1.502	0.565	99.926	54.840	0.046	0.019	0.000046
3.0	182.769	100.033	1.521	0.568	103.016	56.775	0.053	0.022	0.000062
3.5	182.786	102.188	1.538	0.572	105.266	58.455	0.060	0.025	0.000079
4.0	182.800	104.366	1.552	0.574	107.528	59.941	0.067	0.028	0.000097
4.5	182.813	106.286	1.565	0.577	109.524	61.278	0.073	0.031	0.000117
5.0	182.824	108.005	1.576	0.579	111.308	62.494	0.080	0.034	0.000138
6.0	182.913	127.011	1.665	0.573	130.845	72.835	0.082	0.035	0.000148
7.0	182.982	152.031	1.734	0.542	156.277	82.356	0.085	0.037	0.000170
8.0	183.041	175.895	1.793	0.524	180.521	92.129	0.087	0.038	0.000185
9.0	183.094	193.973	1.846	0.525	198.909	101.918	0.088	0.039	0.000190
10.0	183.140	201.276	1.892	0.552	206.477	111.191	0.090	0.039	0.000185
20.0	183.448	236.915	2.200	0.753	243.577	178.449	0.112	0.041	0.000190
30.0	183.629	270.451	2.381	0.829	277.903	224.241	0.134	0.047	0.000238
40.0	183.757	293.914	2.509	0.886	301.920	260.408	0.154	0.052	0.000287
50.0	183.856	307.264	2.608	0.945	315.714	290.246	0.172	0.057	0.000332
60.0	183.937	325.271	2.689	0.971	334.093	315.825	0.190	0.062	0.000389
70.0	184.005	338.307	2.757	1.001	347.427	338.560	0.207	0.066	0.000442
80.0	184.065	351.689	2.817	1.021	361.157	359.023	0.223	0.070	0.000500
90.0	184.117	366.617	2.869	1.031	376.388	377.806	0.238	0.075	0.000565
100.0	184.204	398.315	2.956	1.032	408.551	411.218	0.243	0.076	0.000586
200.0	184.810	523.667	3.562	1.332	535.515	697.664	0.287	0.079	0.000578
300.0	185.221	580.532	3.973	1.593	592.711	924.845	0.324	0.082	0.000581
400.0	185.544	595.047	4.296	1.873	607.347	1114.648	0.359	0.084	0.000573
650.0	186.196	613.428	4.948	2.462	625.914	1510.167	0.430	0.088	0.000572

SITE 25

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	166.555	17.659	0.873	0.481	17.769	8.488	0.118	0.054	0.000372
1.5	166.645	18.865	0.963	0.538	19.001	10.146	0.148	0.064	0.000505
2.0	166.709	19.309	1.027	0.589	19.485	11.368	0.176	0.073	0.000635
2.5	166.759	19.615	1.077	0.629	19.822	12.335	0.203	0.082	0.000773
3.0	166.799	20.885	1.117	0.630	21.130	13.152	0.228	0.092	0.000979
3.5	166.834	22.218	1.152	0.625	22.500	13.892	0.252	0.102	0.001207
4.0	166.863	23.373	1.181	0.623	23.686	14.569	0.275	0.111	0.001441
4.5	166.889	24.392	1.207	0.623	24.732	15.196	0.296	0.120	0.001679
5.0	166.913	25.303	1.231	0.624	25.668	15.779	0.317	0.128	0.001921
6.0	166.954	26.947	1.272	0.625	27.355	16.838	0.356	0.144	0.002425
7.0	166.988	28.384	1.306	0.627	28.827	17.788	0.394	0.159	0.002948
8.0	167.018	30.031	1.336	0.621	30.504	18.655	0.429	0.174	0.003543
9.0	167.044	31.578	1.362	0.616	32.077	19.463	0.462	0.188	0.004163
10.0	167.144	38.238	1.462	0.600	38.858	22.959	0.436	0.179	0.003826
20.0	167.662	88.456	1.980	0.705	89.672	62.391	0.321	0.122	0.001667
30.0	167.965	102.681	2.283	0.883	104.144	90.653	0.331	0.112	0.001318
40.0	168.180	117.090	2.498	0.977	118.692	114.341	0.350	0.113	0.001286
50.0	168.347	129.244	2.665	1.043	130.952	134.831	0.371	0.116	0.001323
60.0	168.483	139.550	2.801	1.098	141.359	153.159	0.392	0.119	0.001379
70.0	168.599	146.381	2.917	1.159	148.278	169.627	0.413	0.122	0.001423
80.0	168.705	152.717	3.023	1.215	154.697	185.607	0.431	0.125	0.001457
90.0	168.814	159.059	3.132	1.273	161.122	202.477	0.444	0.126	0.001457
100.0	168.921	165.167	3.239	1.331	167.319	219.856	0.455	0.126	0.001437
200.0	169.669	207.726	3.987	1.754	210.230	364.353	0.549	0.132	0.001447
300.0	170.180	216.561	4.498	2.183	219.145	472.760	0.635	0.137	0.001445
400.0	170.623	224.836	4.941	2.538	227.468	570.553	0.701	0.141	0.001442
650.0	171.547	241.597	5.865	3.251	244.345	785.437	0.828	0.147	0.001444

SITE 27

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	161.024	3.932	0.086	0.038	3.953	0.148	6.742	0.084	0.188681
1.5	161.173	6.914	0.235	0.150	6.992	1.036	1.448	1.194	0.267423
2.0	161.279	8.142	0.341	0.225	8.261	1.835	1.090	0.733	0.088304
2.5	161.362	9.334	0.424	0.273	9.483	2.546	0.982	0.600	0.055694
3.0	161.429	12.198	0.491	0.268	12.395	3.267	0.918	0.567	0.049900
3.5	161.486	14.618	0.548	0.276	14.860	4.032	0.868	0.528	0.042903
4.0	161.218	7.436	0.280	0.183	7.532	1.360	2.942	2.196	0.848085
4.5	161.287	8.237	0.349	0.231	8.359	1.902	2.366	1.572	0.402873
5.0	161.349	8.953	0.411	.0.272	9.099	2.434	2.054	1.258	0.244744
6.0	161.457	13.422	0.519	0.270	13.640	3.621	1.657	1.019	0.160937
7.0	161.547	16.719	0.609	0.299	17.009	4.993	1.402	0.819	0.100753
8.0	161.626	19.406	0.688	0.330	19.758	6.410	1.248	0.693	0.069871
9.0	161.695	21.198	0.757	0.369	21.611	7.825	1.150	0.604	0.051259
10.0	161.757	22.591	0.819	0.406	23.057	9.174	1.090	0.546	0.040598
20.0	162.164	42.738	1.226	0.513	43.379	21.907	0.913	0.407	0.020723
30.0	162.402	53.161	1.464	0.631	54.040	33.525	0.895	0.360	0.015134
40.0	162.571	55.510	1.633	0.770	56.604	42.738	0.936	0.341	0.012741
50.0	162.702	58.605	1.764	0.856	59.883	50.168	0.997	0.344	0.012577
60.0	162.809	63.801	1.871	0.889	65.243	56.725	1.058	0.358	0.013482
70.0	162.900	69.781	1.962	0.899	71.375	62.719	1.116	0.376	0.014800
80.0	163.021	83.569	2.083	0.861	85.406	71.968	1.112	0.382	0.015525
90.0	163.138	98.813	2.200	0.837	100.903	82.683	1.088	0.380	0.015451
100.0	163.235	111.065	2.297	0.835	113.379	92.758	1.078	0.377	0.015189
200.0	163.761	216.059	2.823	0.841	219.489	181.671	1.101	0.383	0.015595
300.0	164.014	230.831	3.076	1.034	234.432	238.758	1.257	0.394	0.015408
400.0	164.219	233.989	3.281	1.224	237.689	286.353	1.397	0.403	0.015222
650.0	164.647	239.398	3.709	1.619	243.177	387.477	1.678	0.421	0.015121

SITE 29

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	155.973	60.673	1.444	0.860	62.298	52.176	0.019	0.007	0.000002
1.5	156.057	61.714	1.528	0.929	63.551	57.307	0.026	0.009	0.000003
2.0	156.116	62.639	1.587	0.974	64.646	61.008	0.033	0.011	0.000004
2.5	156.162	63.357	1.633	1.009	65.496	63.916	0.039	0.012	0.000006
3.0	156.200	63.943	1.671	1.037	66.190	66.317	0.045	0.014	0.000007
3.5	156.232	64.438	1.703	1.061	66.777	68.364	0.051	0.016	0.000009
4.0	156.260	64.868	1.731	1.081	67.285	70.151	0.057	0.018	0.000011
4.5	156.284	65.246	1.755	1.099	67.734	71.736	0.063	0.019	0.000013
5.0	156.306	65.579	1.777	1.116	68.129	73.162	0.068	0.021	0.000015
6.0	156.344	66.154	1.815	1.143	68.812	75.646	0.079	0.024	0.000020
7.0	156.376	66.640	1.847	1.167	69.390	77.764	0.090	0.027	0.000025
8.0	156.403	67.061	1.874	1.187	69.890	79.611	0.100	0.029	0.000031
9.0	156.428	67.433	1.899	1.205	70.332	81.250	0.111	0.032	0.000036
10.0	156.449	67.670	1.920	1.222	70.624	82.722	0.121	0.035	0.000043
20.0	156.929	101.593	2.400	1.187	107.203	120.587	0.166	0.049	0.000085
30.0	157.295	150.944	2.766	1.100	158.920	166.060	0.181	0.055	0.000111
40.0	157.554	173.213	3.025	1.201	183.210	208.081	0.192	0.056	0.000112
50.0	157.747	183.893	3.218	1.320	195.201	242.693	0.206	0.057	0.000114
60.0	157.921	189.885	3.392	1.449	202.228	275.204	0.218	0.058	0.000113
70.0	158.083	195.455	3.554	1.567	208.759	306.354	0.228	0.058	0.000113
80.0	158.224	200.338	3.695	1.669	214.484	334.403	0.239	0.059	0.000114
90.0	158.362	202.888	3.833	1.785	217.855	362.132	0.249	0.059	0.000113
100.0	158.485	204.568	3.956	1.893	220.271	387.223	0.258	0.060	0.000113
200.0	159.531	218.841	5.002	2.782	240.800	608.729	0.329	0.063	0.000113
300.0	160.370	230.280	5.841	3.461	256.622	797.041	0.376	0.065	0.000113
400.0	161.121	251.904	6.592	3.882	278.365	977.887	0.409	0.066	0.000113
650.0	162.601	291.517	8.072	4.735	318.128	1380.406	0.471	0.069	0.000113

SITE 30

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	151.189	65.462	2.065	0.839	67.243	54.943	0.018	0.006	0.000002
1.5	151.289	69.360	2.165	0.890	71.422	61.734	0.024	0.008	0.000003
2.0	151.361	72.125	2.237	0.926	74.387	66.791	0.030	0.010	0.000004
2.5	151.416	73.201	2.292	0.968	75.618	70.828	0.035	0.011	0.000005
3.0	151.462	73.773	2.338	1.005	76.318	74.157	0.040	0.013	0.000006
3.5	151.500	74.257	2.376	1.037	76.910	76.992	0.045	0.014	0.000007
4.0	151.533	74.677	2.409	1.064	77.422	79.463	0.050	0.016	0.000009
4.5	151.562	75.047	2.438	1.088	77.874	81.654	0.055	0.017	0.000010
5.0	151.589	75.536	2.465	1.107	78.436	83.623	0.060	0.018	0.000012
6.0	151.634	79.666	2.510	1.094	82.670	87.131	0.069	0.021	0.000016
7.0	151.672	83.200	2.548	1.085	86.294	90.254	0.078	0.024	0.000020
8.0	151.705	85.913	2.581	1.083	89.084	93.059	0.086	0.026	0.000025
9.0	151.735	88.306	2.611	1.083	91.546	95.609	0.094	0.029	0.000030
10.0	151.769	92.976	2.645	1.062	96.312	98.715	0.101	0.031	0.000036
20.0	152.084	143.714	2.960	0.948	147.939	136.276	0.147	0.048	0.000087
30.0	152.269	153.912	3.145	1.066	158.445	164.001	0.183	0.057	0.000115
40.0	152.400	158.232	3.276	1.165	162.892	184.393	0.217	0.064	0.000144
50.0	152.501	165.049	3.377	1.217	169.759	200.785	0.249	0.072	0.000178
60.0	152.584	170.999	3.460	1.256	175.746	214.722	0.279	0.080	0.000215
70.0	152.654	176.029	3.530	1.289	180.808	226.892	0.309	0.087	0.000253
80.0	152.715	180.222	3.591	1.319	185.028	237.718	0.337	0.094	0.000292
90.0	152.814	188.872	3.690	1.356	193.697	256.177	0.351	0.096	0.000306
100.0	152.915	193.906	3.791	1.420	198.746	275.334	0.363	0.097	0.000307
200.0	153.685	209.341	4.561	2.060	214.315	431.314	0.464	0.103	0.000305
300.0	154.322	228.835	5.198	2.492	233.912	570.362	0.526	0.106	0.000303
400.0	154.861	248.215	5.737	2.818	253.372	699.396	0.572	0.109	0.000304
650.0	155.910	275.480	6.786	3.540	280.730	975.176	0.667	0.113	0.000304

SITE 31

Q	Z	W	D max	D ave	P	A	V	Fr	Sf
1.0	141.784	0.000	0.000	0.000	0.000				
1.5	141.863	0.000	0.000	0.000	0.000				
2.0	141.919	0.000	0.000	0.000	0.000				
2.5	141.962	0.000	0.000	0.000	0.000				
3.0	141.998	0.000	0.000	0.000	0.000				
3.5	142.028	0.000	0.000	0.000	0.000				
4.0	142.054	0.000	0.000	0.000	0.000				
4.5	142.077	0.071	0.014	0.007	0.077	0.001			
5.0	142.098	0.175	0.035	0.017	0.188	0.003			
6.0	142.133	0.354	0.070	0.035	0.381	0.012			
7.0	142.163	1.373	0.100	0.021	1.412	0.029			
8.0	142.235	9.886	0.172	0.043	9.964	0.424	0.856	0.061	
9.0	142.308	24.448	0.245	0.067	24.635	1.637	5.498	6.784	0.231556
10.0	142.373	40.788	0.310	0.093	41.131	3.782	2.644	2.772	1.684294
20.0	142.805	71.324	0.742	0.413	73.561	29.442	0.679	0.338	0.015645
30.0	143.057	82.718	0.994	0.588	86.333	48.620	0.617	0.257	0.008186
40.0	143.236	93.070	1.173	0.690	97.741	64.222	0.623	0.239	0.006791
50.0	143.375	107.703	1.312	0.724	113.139	78.003	0.641	0.240	0.006746
60.0	143.488	131.410	1.425	0.697	137.466	91.627	0.655	0.250	0.007365
70.0	143.584	141.302	1.521	0.741	147.883	104.703	0.669	0.248	0.007083
80.0	143.667	148.922	1.604	0.784	155.957	116.771	0.685	0.247	0.006903
90.0	143.746	157.482	1.683	0.819	164.908	128.929	0.698	0.246	0.006766
100.0	143.826	181.525	1.763	0.783	189.293	142.156	0.703	0.254	0.007249
200.0	144.308	275.352	2.245	0.928	284.719	255.611	0.782	0.259	0.007069
300.0	144.601	308.998	2.538	1.101	318.866	340.147	0.882	0.268	0.007137
400.0	144.826	316.722	2.763	1.297	326.668	410.921	0.973	0.273	0.006978
650.0	145.284	326.687	3.221	1.707	336.686	557.755	1.165	0.285	0.006929

APPENDIX E: QUANTITATIVE MEASUREMENT OF SHORT TERM CHANGE ON THE SABIE RIVER

Code #	Sec2.86.1	Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m²	Perimeter (pixel)	Perim (metres)	Sec2.89.1	sq. size (pixel2)	Code #	Morph Un	Chan Typ	Feature	Area (sq.pixel)	AREA ME	Perimeter (pixel)	PERIM M	Sec2.92.1	Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
1		MCB	MA	Sand	685.38	539.1378	158.3	138.5761		3222.75	1	MCB	MA	Sand	101.64	78.84571	53.41	46.99309		3206.93							
2											2	LB	MA	Sand	198.52	153.9989	87.75	77.20734									
3											3	LB	MPR	Sand	208.15	161.4692	82.4	72.50011									
4		LB	MPR	#Sand\Ve	2256	1776.202	289.71	256.8579			4	RC\LB	MPR	Sand	322.58	250.2366	105.8	93.08873									
5				#							5	MCB	MPR	Sand	90.72	70.37468	50.74	44.64388			MPR	MCB	Sand	264.2	205.9602	120.72	106.1135
6				#							6	LB	MPR	Sand	87.1	67.56652	63.59	55.95002							0		0
7				#							7	LB	MPR	Sand	161.71	125.4441	78.81	69.34143			MPR	LB	Gone	198.37	154.6417	92.41	81.22885
8											8	MCB	MA	Sand	272.09	211.0697	74.21	65.29409			MA	MCB	Gone	248.07	193.3859	66.66	58.59447
9											9	MCB	MA	Sand	89.88	69.72306	50.27	44.23035			MA	MCB	Sand	570.32	444.5897	1174	1031.952
10											10	LB	MA	Sand	47.28	36.67675	39.73	34.95667			MA	LB	Sand	55.59	43.33564	30.66	27.12609
12											12	MCB	MA	Gone	144.23	111.8843	66.99	58.94153							0		0
13											13	LB	MA	Gone	162.39	125.9716	62.05	54.59505							0		0
14											14	LB	MA	Gone	214.62	166.4882	62.28	54.78741							0		0
15		MCB	MA	Veg	171.09	132.7205	52.48	46.17483			15	MCB	MA	Gone	171.09	132.7205	52.48	46.17483							0		0
16		MCB/BCE	MA	Sand	705.72	555.1378	705.72	625.6938			16	MCB\BCE	MA	Gone	1035.79	803.4986	127.19	111.9088			MA	MCB\BCE	Sand	1116.99	870.7627	131.66	115.7298
17		MCB	MPR	Sand	1035.79	262.9897	127.19	74.84053			17	LB	MPR	Gone	339.02	262.9897	85.06	74.84053			MPR	LB	Sand	290.88	226.7589	65.33	57.42539
18		LB	MA	Sand	279.89	220.1888	68.62	60.83873			18	TB	MA	Gone	153.05	118.7262	69.71	61.33474			MA	TB	Sand	220.57	171.9479	70	61.53035
19											19					0		0			MPR	MCB	Sand	26.71	20.82209	20.27	17.81743
20											20					0		0			MPR	MCB	Sand	15.23	11.87273	15.73	13.82675
21											21					0		0			MPR	MCB	Sand	39.03	30.4263	24.12	21.2018
22											22					0		0			MPR	LB	Gone	57.85	45.09765	29.48	25.91307
23		BCB	MPR	'Sand	1475.34	1160.541	291.4	258.3562			23	BCB	MPR	Gone	1055.5	816.6799	239.99	211.0823							0		0
24				'							24	BCB	MPR	Sand	57.39	46.36002	29.57	26.01733							0		0
25				•							25	BCB	MPR	Gone	58.25	45.16656	33.27	29.2728							0		0
																0		0							0		0
	Sec2.86.1b								Sec2.89.1b							0		0	Sec2.92.1b						0		0
1										3270.31	1	MCB	MA	Sand	27.19	20.78549	28.94	25.30273		3128.69	MA	MCB	Sand	165.2	132.0041	65.11	58.19888
2		LB	MA	Sand	953.28	727.1396	224.8	196.2976			2	LB	MA	Sand	367.49	280.929	122.82	107.3836			MA	LB	Sand	47.13	37.65953	30.66	27.40559
3		LB	MA	Sand\Veg	1151.69	878.4821	150.29	131.2347			3	LB	MA	Sand	456.44	348.9272	132.88	116.1792							0		0
4		LB	MA	#Sand	2051.84	1565.095	418.79	363.9452			4	LB	MA	Sand	291.77	223.0446	84	73.44262			MA	LB	Gone	329.84	263.5608	78.82	70.45363
5		LB	MA	#							5	LB	MA	Sand	50.36	38.49768	31.66	27.68087							0		0
6		LB	MA	Sand	1483.5	1134.067	219.3	191.7377			6	LB	MA	Gone	1483.5	1134.067	219.3	191.7377			MA	LB	Sand	894.16	714.4843	172	153.743
7											7	LB	MA	Gone	893.25	682.8481	335.94	293.718			MA	LB	Sand	276.34	220.8113	177.81	158.9363
8		LB	MA	#							8	LB	MA	Gone	62.02	47.41141	41.48	38.26667							0		0
9		LB	MA	#							9	LB	MA	Gone	431.72	330.0299	122.23	106.8678							0		0
10											10					0		0			MA	MCB	Sand	1785.28	1410.558	279.37	249.7162
																0		0							0		0
	Sec2.86.2								Sec2.89.2							0		0	Sec2.92.2						0		0
1										3170.91	1	MCB	MA	Sand	381.21	300.5525	88.28	78.36626		3234.2	MA	LB	Sand	591.13	456.9368	148.18	130.2681
a											a	MCB	MA	Sand	45.41	35.80203	28.59	25.38513			MA	MCB	Sand	441.23	341.0858	118.62	102.5231
b											b	MCB	MA	Sand	22.27	17.55805	21.62	19.19645							0		0
c											c	MCB	MA	Sand	16.89	13.31637	17.84	15.6626							0		0
d											d	MCB	MA	Sand	63.91	50.38774	38.19	33.90899							0		0
2		LB	MA	Sand	1938.56	1484.65	228.14	199.2089			2	LB	MA	Sand	653.01	514.8443	155.15	137.758			BA	LB	Sand	358.66	277.2401	198.89	174.8484
											a	LB	MA	Gone	355.7	275.2184	121.98	107.287									
											b	LB	MA	Sand	333.93	258.3742	107.89	94.89423									
											c	LB	MA	Gone	200.93	155.4671	87.28	76.77558									
3		LB	BA	Sand	127.83	96.57978	52.02	45.22495			3	LB	BA	Sand	78.46	61.85921	36.88	32.72808			BA	LB	Sand	51.75	40.00218	30.8	27.07692
4											4	LEB	BA	Sand	124.8	98.47331	50.4	44.75028			BA	LB	Sand	41.12	31.78528	25.18	22.13828
5											5	LB	BA	Sand	90.48	76.06649	58.08	49.79358							0		0
6											6	LB	BA	Sand	1252.16	987.2245	237.27	210.6728							0		0
7											7	MCB	BA	Sand	112.54	88.72847	46.38	41.18091							0		0
8											8	LB	MA	Veg	431.45	340.1626	89.34	79.32519							0		0
9											9	LB	BA	Veg	1350.28	1064.584	305.15	270.9434							0		0
10											10					0		0			MA	LB	Sand	1469.59	1135.976	199.61	175.4813
11											11					0		0			MA	MCB	Sand	225.31	174.1621	102.17	89.81978
12											12					0		0			BA	LEB	Sand	86.58	68.92536	37.04	32.58264
13											13					0		0			BA	MCB	Sand	675.81	522.3935	159.48	140.2022
																0		0							0		0

	Code #	Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m	Perimeter (pixel)	Perim (metres)		sq. size (pixel2)		Code #	Morph Un	Chan Typ	Feature	Area (sq.pixel)	AREA ME	Perimeter (pixel)	PERIM METRES		Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
	Sec3.86.1a								Sec3.89.1a								0		0	Sec3.92.1a						0		0
	1	LB	PR	Sand	1007.63	775.3242	204.29	179.2016		3270.22		1	LB	PR	Sand	304.93	233.1112	111.47	97.46011		3206.39	PR	LB	Sand	731.3	570.1895	274.27	242.1703
a											a		LB	PR	Gone	84.11	64.29996	44.48	38.88962							0		0
	2	MCB	PR	Sand\Roc	91.29	70.24339	41.29	36.2193				2	MCB	PR	Sand	92.89	71.01204	47.09	41.17158							0		0
a											a						0		0			PR	MCB	Gone	60.03	46.80497	33.82	29.88182
b											b						0		0			PR	LEB	Sand	152.84	119.1683	61.64	54.42585
	3											3	MCB	PR	Sand	37.04	28.31614	30.18	26.38689							0		0
	4	LEB	PR	Sand	283.25	217.9477	81.82	36.2193				4	LEB	PR	Sand	146.34	111.8732	49.18	42.99891			PR	LEB	Sand	231.91	180.8186	84.17	74.31901
a											a		LEB	PR	Gone	12.35	9.441261	16.37	14.31257							0		0
b											b		LEB	PR	Gone	44.11	33.72097	34.29	29.97158							0		0
c											c		LEB	PR	Gone	151.98	116.1896	54.04	47.24809							0		0
	5											5	MCB	PR	Sand	35.42	27.07769	23.28	20.3541							0		0
	6	LB	PR	Sand	454.13	349.4318	148.51	128.5175				6	LB	PR	Veg	1074.55	821.4661	247.84	216.6907							0		0
	7	MCB	PR	Sand	71.06	55.40499	37.93	33.4908				7					0		0			PR	MCB	Gone	71.06	55.40499	37.93	33.4908
	8	MCB	PR	Sand	46.74	36.44285	27.89	24.62584				8					0		0			PR	MCB	Gone	46.74	36.44285	27.89	24.62584
	9	MCB	PR	Sand	466.73	359.1269	97.53	85.55263				9					0		0			PR	MCB	Gone	96.74	75.42751	61.58	54.37288
	10											10					0		0			PR	LB	Sand	45.57	35.53061	28.89	25.50881
	11	LEB	PR	Sand\Roc	525.72	404.517	98.64	86.52632				11					0		0			PR	LEB	Sand	150.07	117.0085	60.68	53.57821
	12											12					0		0			PR	MCB	Veg	144.21	112.4395	45.23	39.93643
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
	Sec3.86.1b								Sec3.1b.89								0		0	Sec3.1b.92						0		0
	1	LB	MA	Sand	296.19	230.4572	78.93	69.61852		3168.87		1	LB	MA	Gone	189.18	149.343	98.35	87.36786		3263.25					0		0
	2	MCB	MA	Veg	228.13	177.5016	59.95	52.87762				2					0		0							0		0
a											a		MCB	MA	Sand	326.46	257.715	92.17	81.87794			MA	MCB	Gone	288.44	220.976	85.8	75.09847
b											b		MCB	MA	Sand	74.03	58.44096	37	32.86844			MA	MCB	Gone	67.69	51.85781	37.94	33.20788
c											c						0		0			MA	MCB	Sand	84.88	65.0272	40.46	35.41357
	3	PB	PR	Sand\Veg	1188.27	924.5597	280.63	247.5237				3					0		0							0		0
a											a		PB	PR	Sand	336.14	265.3566	98.11	87.15466			PR	PB	Gone	105.04	80.47192	64.67	56.60394
b											b		PB	PR	Gone	217.57	171.7548	78.29	69.54784							0		0
c											c						0		0			PR	PB	Sand	82.19	62.96637	44.35	38.81838
d											d						0		0			PR	PB	Gone	134.51	103.0491	63.4	55.49234
	4											4	MCB	PR	Veg	391.06	308.7118	87.04	77.32078							0		0
	5											5	LEB	PR	sand	69.54	54.89648	30.93	27.47624			PR	LEB	Sand	143.47	109.9134	50.17	43.91247
	6											6					0		0			MA	LB	Sand	75.28	57.67257	36.94	32.3328
	7											7					0		0			MA	MCB	Sand	26.13	20.01839	19.79	17.32166
	8											8					0		0			MA	MCB	Veg	204.59	156.7379	65.7	57.50547
	9											9					0		0			PR	BCB	Veg	112.68	88.32498	51.61	45.17287
	10											10					0		0			PR	BCB	Veg	49.02	37.55459	28.22	24.70022
	11											11					0		0							0		0
a											a						0		0			PR	BCB	Veg	11.23	8.603388	14.52	12.70897
b											b						0		0			PR	BCB	Sand	18.05	13.82824	18.65	16.32385
	12											12					0		0			PR	BCB	Sand	49.02	37.55459	28.22	24.70022
	13											13					0		0			PR	BCB	Sand	21.98	16.83904	19.17	16.77899
	14											14					0		0			PR	MCB	Sand	32.67	25.02873	21.6	18.90591
	15											15					0		0			PR	MCB	Sand	7.57	5.799433	10.75	9.40919
	16											16					0		0			PR	BCB	Sand	31.26	23.94852	20.8	18.20569
	17											17					0		0			PR	MCB	Sand	17.67	13.53712	17.79	15.57112
	18											18					0		0			PR	BCB	Sand	234.44	179.6062	70.16	61.40919
	19											19					0		0			PR	LEB	Sand	14.91	11.42266	14.92	13.05908
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
																	0		0							0		0
	Sec3.86.2a								Sec3.89.2a								0		0	Sec3.92.2a						0		0
	1	LEB	PR	Sand	124.23	96.95349	51.35	45.36219		3230.79		1	LEB	PR	Sand	148.58	113.4243	76.57	67.34093		3143	PR	LEB	Sand	259.02	206.0293	78	69.55901
	2											2					0		0			PR	MCB	Sand	62.3	49.55457	31.49	28.08222
	3											3					0		0			PR	MCB	Sand	610.71	485.77	132.27	117.958
	4											4					0		0			PR	BCB	Veg	586.82	466.7674	178.13	159.745

	Code #	Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m²	Perimeter (pixel)	Perim (metres)	sq. size (pixel2)		Code #	Morph Un	Chan Typ	Feature	Area (sq pixel)	AREA ME	Perimeter (pixel)	PERIM METRES	Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
	Sec4.88.1a								Sec4.89.1a							0		0	Sec4.92.1a					0		0
	1								3202.85		1	AB	PR	River	2803.23	2188.075	731.36	646.0492	3209.81	PR	AB	Sand	2803.23	2183.33	731.36	645.3836
	2										2	LB	MPR	Sand	134.7	105.1407	73.95	65.32397						0		0
	3										3	LB	MPR	Sand	131.48	102.6273	73.95	65.32397						0		0
	4										4	LEB	MPR	Sand	99.52	77.68082	44.76	39.53889		MPR	LEB	Gone	99.52	77.51236	44.76	39.49876
	5										5	LB	MPR	Sand	281.73	219.9057	75.84	66.99351						0		0
a										a						0		0		MPR	LB	Veg	507.54	305.3038	103.02	90.9107
b										b						0		0		MPR	LB	Gone	75.78	59.02219	36.8	32.47441
	6										6	LB	MPR	Sand	493.47	385.1804	116.25	102.6808						0		0
a										a						0		0		MPR	LB	Veg	642.68	500.5592	192.97	170.2877
b										b						0		0		MPR	LB	Sand	105.77	82.38027	66.2	58.41864
	7	LB	MPR	Sand	845.63	728.3961	130.23	119.5629			7	LB	MPR	Sand	991.53	773.8435	219.98	194.3024						0		0
a										a						0		0		MPR	LB	Sand	3310.06	2585.091	454.2	400.8119
b										b						0		0		MPR	LB	Veg	224.41	174.7845	85.48	75.4324
	8	MCB	MPR	Sand	1462.63	1142.034	185.82	163.0658			8	LB	MPR	Sand	454.16	354.4968	139.71	123.4133		MPR	LB	Sand	642.08	500.5592	192.97	170.2877
	9										9	LEB	MPR	Sand	343.17	267.963	160.09	141.410		MPR	LB	Sand	920.58	718.8895	222.57	196.4084
	10	MCB	MPR	Sand	99.44	77.61837	46.8	41.34093			10	MCB	MPR	Gone	99.44	77.61837	46.8	41.34093						0		0
	11	MCB	PR	Sand/Veg	493.51	385.2116	126.28	111.5498			11	MCB	PR	Gone	493.51	385.2116	126.28	111.5488						0		0
	12	MCB	MPR	Sand	329.39	257.107	100.19	88.50316			12	MCB	MPR	Gone	329.39	257.107	100.18	88.50318						0		0
	13										13	LB	MPR	Gone	338.55	264.2568	122.73	108.4139						0		0
	14	TB	MPR	Sand	2816.26	2016.235	321.16	281.8678			14	TB	MPR	Gone	1073.05	837.5743	252.63	223.1615						0		0
a										a						0		0		MPR	LB	Gone	116.48	90.72188	48.18	43.39922
b										b						0		0		MPR	LB	Sand	429.68	334.6610	105.87	93.24821
	15	LEB	MPR	Sand	1077.75	830.1649	135.09	118.5624			15	LEB disap	MPR	Gone	1073.05	837.5743	44.68	39.46822		MPR	LEB BEDI	Sand	1073.05	835.7582	44.08	39.42817
	16	LEB	MPR	Sand	252.78	197.3086	72.03	63.62793			16	LEB	MPR	Gone	252.78	197.3086	72.03	63.62793		MPR	LEB	Sand	433.09	337.3175	84.01	74.13519
	17	AB	MPR	River	2968.11	2268.264	916.5	804.3707			17					0		0		MPR	AB	Sand	2701.83	2104.431	791.84	696.7040
	18										18					0		0		MPR	AB	River		0		0
																0		0						0		0
	Sec4.88.1b								Sec4.89.1b							0		0	Sec4.92.1b					0		0
	1	LEB	MPR	Sand	282.75	222.8673	87.14	77.35807	3171.73		1	LEB	MPR	Gone	282.75	222.8673	87.14	77.35807	3192.84	MA	LB	Sand	521.58	408.3825	117.04	103.5015
	2	LEB	MPR	Sand	195.49	154.0078	60.16	53.40672			2	LEB	MPR	Gone	195.49	154.0878	60.16	53.40672		MA	LEB	Sand	228.43	178.8611	69.61	61.59359
	4	LB	MA	Sand/Veg	2124.34	1661.52	276.77	244.7867			4					0		0						0		0
a										a		LB	MA	Sand	72.8	57.38193	34.95	31.02668						0		0
b										b		LB	MA	Gone	163.82	128.9875	41.52	36.85916		MA	LB	Sand	59.55	46.02777	33.26	29.42972
c										c		LB	MA	Sand	720.87	568.1804	200.38	177.8863		MA	LB	Sand	204.1	159.8107	60.65	53.84241
d										d						0		0		MA	LB	Sand	107.83	84.4311	44.19	39.09216
	5										5	LB	MA	Sand	417.62	320.1737	130.41	115.7708		MA	LB	Sand	428.13	335.2268	141.55	125.2489
	6										6					0		0		MPR	MCB	Sand	334.24	261.7106	72.68	64.29235
	7										7					0		0		MA	MCB	Sand	87.91	68.8337	40.42	35.76516
	8										8					0		0		MA	LB	Sand	45.92	35.95545	30.58	27.04068
	9										9					0		0		MA	LB	Sand	96.34	75.43441	46.51	41.15383
	10										10					0		0		MA	LB	Gone	204.55	160.1631	72.82	64.43392
																0		0						0		0
	Sec4.88.2a								Sec4.89.2a							0		0	Sec4.92.2a					0		0
	1								3231.05		1					0		0	3158.52					0		0
a										a		LEB	MA	Sand	165.72	126.2248	74.89	65.59367		MA	LEB	Sand	233.05	184.5893	114.47	101.0382
b										b		LEB	MA	Gone	40.55	31.37525	25.55	22.47142		MA	LEB	Gone	176.37	138.369	51.55	45.77137
	2										2	LB	MA	Sand	551.91	427.0361	238.06	207.6105		MA	LB	Sand	208.22	164.2881	123.7	109.8335
	3										3	I	MA	Gone	306.66	238.8233	117.91	103.7027						0		0
	4	LEB	MA	Sand	221.2	168.9323	79.97	69.87331			4					0		0						0		0
a										a		LEB	MA	Gone	83.59	64.67712	41.45	36.45558						0		0
b										b		LEB	MA	Sand	64.74	50.09206	32.2	28.32014						0		0
	5	LEB	MA	Sand	432.59	330.3727	126.25	110.3102			5					0		0						0		0
a										a		LEB	MA	Sand	60.65	46.8501	50.21	44.16007						0		0
b										b		LEB	MA	Gone	225.21	174.2545	101.18	88.96857						0		0
	6										6					0		0						0		0
a										a		LEB	MA	Gone	125.11	96.8029	72.42	63.69383		MA	LEB	Gone	42.34	33.40676	44.53	39.53829
b										b		LEB	MA	Sand	56.19	43.47656	45.83	40.39578		MA	LEB	Sand	201.81	159.3094	91.51	81.25194
	7	PB	MA	Sand	347.18	265.1291	82.03	71.67322			7	PB	MA	Gone	198.8	153.82	60.43	63.14884		MA	LB	Sand	781.13	616.3209	137.89	122.4329
	8										8	I	MA	Veg	74.34	57.52	37.84	33.10486						0		0
	9										9	AB	MA\BR	River	5344.2	4135.034	778.38	684.591						0		0
	10	MCB	BR	Sand/Veg	3909.56	3054.496	453.00	395.6847			10					0		0						0		0
a										a		MCB	BR	Sand	79.02	61.14112	46.73	41.09938						0		0
b										b		MCB	BR	Sand	422.35	326.7901	180.35	158.6192						0		0
c										c		MCB	BR	Sand	55.28	42.77247	35.52	31.24011						0		0
d										d		MCB	BR	Sand	42.29	32.72156	27.85	24.49428						0		0
e										e						0		0		BR	LEB	Gone	422.23	333.1445	121.27	107.6759
f										f						0		0		BR	LEB	Veg	293.23	231.362	85.37	75.90022
g										g						0		0		BR	MCB	Veg	1380.93	1089.57	163.82	145.4562
	11	LEB	BR	Sand	1011.34	772.369	205.56	179.6068			11					0		0						0		0
a										a		LEB	BR	Veg	142.53	110.2815	62.04	54.56484		BR	LEB	Sand	148.18	116.9	51.28	45.51387
b										b		LEB	BR	Veg	192.23	148.7365	56.85	50		BR	LEB	Sand	170.38	134.4318	53.52	47.52053
c										c						0		0		BR	LEB	gone	185.73	148.5432	94.1	83.55181
	12	MCB	BR	Sand	110.38	84.29815	57.28	50.04808			12					0		0						0		0
a										a		MCB	BR	Sand	369.88	286.1915	147.17	129.4371						0		0
b										b		MCB	BR	Sand	60.23	46.6025	35.78	31.46878						0		0
c										c		MCB	BR	Sand	107.07	82.84459	50.18	44.13369						0		0
d										d						0		0		BR	MCB	Sand	57.11	45.06047	33.15	29.43396
e										e						0		0		BR	RC	Gone	1409.25	1111.915	313.21	278.0999
f										f						0		0		BR	MCB	Sand	31	24.45937	24.84	21.87791
	13										13					0		0		MA	LEB	Sand	94.39	74.47483	47.24	41.94451
	14										14					0		0		MA	LB	Sand	183.14	144.4996	68.09	60.48058
	15										15					0		0		MA	LB	Gone	248.46	194.4509	82.85	73.6515
	16										16					0		0		MA	LB	Sand	510.95	403.1456	135.39	120.2131
	17										17					0		0		BR	LB	Sand	530.52	418.5868	115.92	102.9256
	18										18					0		0		BR	LB	Gone	130	102.5716	60.88	54.03774
	19										19					0		0		BR	MCB	Sand	59.2	46.7095	35.19	31.24528
	21										21					0		0		BR	LEB	Sand	124.72	98.40596	54.81	48.66593

Code #		Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m²	Perimeter (pixel)	Perim (metres)
	Sec4.86.2b							
	1							
	2	MCB	BR	Sand	1094.78	851.7462	287.89	253.916
a								
b								
c								
d								
e								
f								
	3							
	4	MCB	BR	Sand	1916.28	1490.879	280.39	247.3011
a								
b								
c								
d								
e								
f								
g								
	5							
	6	MCB	BR	Sand	57.62	44.82875	29.8	26.2833
	7	MCB	BR	Sand	1109.44	863.1517	185.41	163.5297
a								
b								
c								
	8	LB	BR	Sand	152.37	118.5449	55.92	49.32087
a								
b								
	9	LB	BR	Sand	1311	1019.967	247.48	218.2748

	sq. size (pixel2)	Code #		Morph Un	Chan Typ	Feature	Area (sq.pixel)	AREA ME	Perimeter (pixel)	PERIM METRES
Sec4.89.2b								0		0
	3209.81		1	MCB	BR	Sand	188.97	147.1889	58.58	51.67895
			2					0		0
		a		MCB	BR	Sand	161.42	125.7302	50.89	44.91021
		b		MCB	BR	Gone	52.85	41.16492	35	30.88735
		c		MCB	BR	Sand	49.47	38.53224	27.89	24.61281
		d		MCB	BR	Gone	195.48	152.2596	76.7	67.68742
		e		MCB	BR	Gone	37.23	28.99849	26.77	23.62441
		f		MCB	BR	Sand	237.04	184.6307	105.4	93.01505
			3	LB	BR	Sand	255.75	199.204	79.38	70.05251
			4					0		0
		a		MCB	BR	Gone	9.85	7.672176	63.31	55.8708
		b		MCB	BR	Gone	80.54	62.7327	41.21	36.36765
		c		MCB	BR	Gone	245.94	191.5629	107.27	94.66531
		d		MCB	BR	Gone	82.18	63.99452	43.82	38.67096
		e						0		0
		f						0		0
		g						0		0
			5	LEB	BR	Sand	220.91	172.067	75.03	66.21365
			6	MCB	BR	Sand	76.89	59.88971	49.82	43.96594
			7					0		0
		a		MCB	BR	Veg	103.43	80.56174	37.97	33.50836
		b		MCB	BR	Sand	305.04	237.596	125.4	110.665
		c						0		0
			8					0		0
		a		MCB	BR	Sand	195.45	152.2362	76.91	67.87274
		b		LEB	BR	Sand	209.48	163.1642	72.13	63.65441
			9	LEB	BR	Sand	159.64	124.3438	73.58	64.93403

	Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
sec4.92.2b						0		0
	3144.47		MCB	Sand	183.68	146.0182	63.27	56.40546
						0		0
			MCB	Gone	55.15	43.84682	36.73	32.74494
			MCB	Sand	107.11	85.15744	44.4	39.58278
						0		0
			MCB	Sand	334.54	265.9749	89.79	80.04814
			MCB	Gone	33.42	26.57046	21.64	19.29215
						0		0
						0		0
						0		0
						0		0
						0		0
		BR	MCB	Sand	269.69	214.4161	101.41	90.40742
		BR	MCB	Sand	193.62	153.9369	57.2	50.99403
		BR	MCB	Sand	169.61	134.8478	58.74	52.36694
		BR	MCB	Gone	155.39	123.5423	87.79	78.26513
		BR	MCB	Sand	217.09	172.5967	67.83	60.47071
						0		0
		BR	MCB	Sand	113.75	90.43654	74.77	66.65775
						0		0
						0		0
						0		0
		BR	MCB	Sand	95.51	75.9349	44.3	39.49363
		BR	MCB	Sand	67.38	53.57024	39.91	35.57992
		BR	MCB	Gone	147.54	117.3012	71.38	63.61772
		BR	LEB	Veg	108.32	86.11944	40.82	36.39119
		BR	LEB	Sand	183.16	145.6207	97.24	86.68985

	Code #	Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m	Perimeter (pixel)	Perim (metres)
	Sec5.86.2b							
	1	MCB	MPR	Sand	1236.5	952.5196	185.71	162.9678
	2	LB	MPR	Sand	1532.3	1166.546	249.95	218.0399
	3							
a								
b								
c								
	4							
a								
b								
	5	LB	MPR	Sand	2008.72	1547.368	206.32	181.0539
a								
b								
c								
	6							
	7							
a								
b								
c								
	8							
	9							
	10							
	11							
	12							
a								
b								
	13							
	14	MCB	MA	Sand	118.64	91.39258	44.84	39.34887
	15							
	16							
	17							
	18							
	Sec5.86.2a							
	1							
a								
b								
c								
d								
e								
f								
	2							
a								
b								
c								
d								
e								
	3	MCB	MPR	Sand	1873.38	1467.246	290.17	256.7876
a								
b								
	4	LB	MPR	Sand	528.41	413.8549	120.74	106.8496
a								
b								
	5	MCB	MPR	Sand	209.06	163.7375	80.01	70.80531
	6							
	7							
	8	MCB	MPR	Sand	127.66	99.98434	46.71	41.33828
	9							
	10	MCB	MPR	Sand	51.53	40.35871	87.6	77.52212
	11	MCB	MPR	Sand	71.83	56.25783	38.38	33.9646
	12	MCB	MPR	Sand	308.73	241.7998	76.91	68.06195
	13							
	14							
	15							
	16							
	17							

	sq. size (pixel2)	Code #		Morph Un	Chan Typ	Feature	Area (sq.pixel)	AREA ME	Perimeter (pixel)	PERIM METRES
Sec5.89.2a								0		0
	3220.46		1	LB	MPR	Veg	529.18	410.7954	170.28	150.6703
			2	LB	MPR	Gone	190.41	147.8127	91.78	81.21046
			3					0		0
		a		MCB	MPR	Sand	66.22	51.4057	39.24	34.72105
		b		MCB	MPR	Sand	85.16	66.10857	50.81	44.95863
		c						0		0
			4					0		0
		a		LB	MPR	Gone	60.74	47.15165	29.97	26.5186
		b		LB	MPR	Sand	41.51	32.22366	29.55	26.14697
			5					0		0
		a		MCB	MPR	Gone	10.27	7.972464	14.04	12.42313
		b		MCB	MPR	Sand	63.85	49.5659	40.41	35.75632
		c		MCB	MPR	Gone	65.51	50.85454	33.79	29.89869
			6	MCB	MPR	Sand	231.13	179.4231	65.14	57.63837
			7					0		0
		a		RC	MPR	River	770.52	598.1444	151.06	133.6637
		b		RC	MPR	River	169.71	131.7436	57.28	50.68354
		c						0		0
			8	LB	MPR	Sand	339.7	263.7046	132.06	116.8517
			9	LB	MPR	Sand	35.63	27.65909	84.23	74.52993
			10	LB	MPR	Sand	172.22	133.6921	74.98	66.34518
			11	MCB	MPR	Sand	247.9	192.4415	90.19	79.80357
			12	MCB	MPR	Sand	422.82	328.2295	110.42	97.70384
		a						0		0
		b						0		0
			13	MCB	MPR	Sand	53.32	41.3916	30.43	26.92563
			14					0		0
			15					0		0
			16					0		0
			17					0		0
			18					0		0
								0		0
Sec5.89.2b								0		0
	3283.84		1					0		0
		a		LEB	MPR	Sand	109.78	83.56071	60.27	52.57557
		b		MCB	MPR	Sand	430.25	327.551	161.75	141.1
		c						0		0
		d						0		0
		e						0		0
		f						0		0
			2					0		0
		a		RC	MPR	Sand	69.68	53.04765	44.43	38.7578
		b		LB	MPR	Veg	1532.3	1166.546	249.95	218.0399
		c		RC	MPR	Sand	285.64	217.4588	155.48	135.6305
		d						0		0
		e						0		0
			3					0		0
		a		MCB	MPR	Veg	50.64	38.55243	34.01	29.66808
		b		MCB	MPR	Sand	54.38	41.3997	35.59	31.04636
			4					0		0
		a		MCB	MPR	Sand	23.05	17.54805	21.84	19.05177
		b		MCB	MPR	Veg	21.38	16.27688	19.74	17.21987
			5	MCB	MPR	Gone	2083.2	1585.948	285.22	248.8071
			6	MCB	MA	Sand	1037.66	789.9745	311.74	271.9414
			7					0		0
			8					0		0
			9					0		0
			10					0		0
			11					0		0
			12					0		0
			13					0		0
			14					0		0
			15					0		0
			16					0		0

	Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
sec5.92.2a						0		0
	3157.31					0		0
		MPR	LB	Sand	68.12	53.93832	36.95	32.8722
						0		0
		MPR	MCB	Gone	275.87	218.4375	89.12	79.28473
		MPR	MCB	Sand	189.78	150.2703	64.12	57.04373
		MPR	MCB	Gone	109.52	86.71939	53.27	47.39113
		MPR	LB	Sand	214.15	169.5668	80.42	71.54486
						0		0
						0		0
						0		0
						0		0
						0		0
						0		0
		MPR	MCB	Gone	228.34	180.8026	74.28	66.08247
						0		0
						0		0
						0		0
		MPR	LB	Sand	892.07	706.3529	184.54	164.1742
		MPR	LB	Gone	361.06	285.8921	89.22	79.37369
		MPR	LB	Gone	80.66	63.86766	47.89	42.60487
		MPR	LB	Sand	891.28	705.7273	266.62	237.1959
						0		0
						0		0
		MPR	MCB	Gone	81.79	64.76241	35.99	32.01815
		MPR	MCB	Sand	303.45	240.2757	114.35	101.7304
		MPR	MCB	Sand	693.5	549.1225	196.82	175.099
		MPR	LB	Sand	51.27	40.59627	33.04	29.39371
		MPR	MCB	Sand	162.22	128.448	49.79	44.29518
		MPR	LB	Sand	185.88	147.1823	102.45	91.14383
		MPR	LB	Veg	468.82	371.2179	179.59	159.7705
		MPR	LEB	Sand	75.03	59.40975	39.5	35.14079
						0		0
Sec5.92.2b						0		0
	3199					0		0
		MPR	MCB	Gone	116.86	91.32541	67.75	59.8895
		MPR	MCB	Gone	197.15	154.0716	87.72	77.54254
		MPR	MCB	Gone	262.23	204.9312	77.3	68.33149
		MPR	MCB	Sand	325.76	254.5786	151.72	134.1171
		MPR	MCB	Sand	97.71	76.3598	44.16	39.03648
		MPR	LB	Sand	74.93	58.55738	35.55	31.42541
						0		0
		MPR	LB	Veg	197.74	154.5327	118.23	104.5127
		MPR	LB	Sand	1722.72	1346.286	281.74	249.0519
		MPR	LB	Veg	396.67	309.9953	152.48	134.789
		MPR	LB	Gone	215.69	168.5605	100.79	89.09613
		MPR	LB	Sand	36.58	28.58706	23.83	21.06519
						0		0
						0		0
						0		0
						0		0
						0		0
						0		0
		MPR	LB	Sand	2041.22	1595.202	281.39	248.7425
		MA	LB	Sand	989.18	773.0384	242.13	214.0376
		MPR	LB	Sand	140.03	109.4326	53.47	47.2663
		MA	LB	Veg	620.3	484.7609	148.58	131.3414
		MA	RC\LB	Sand	139.87	109.3076	47.57	42.05083
		MA	LEB	Sand	147.09	114.95	51.64	45.64882
		MA	LB	Sand	255.98	200.0469	107.12	94.69171
		MA	RC\LB	Sand	973.47	760.7612	330.52	292.1724
		MA	RC\LB	Sand	345.77	270.2173	128.2	113.326
		MA	LB	Sand	381.21	297.9134	99.45	87.9116
		MA	RC\LB	Sand	1198.17	936.3629	184.99	163.5271
		MA	LB	Sand	191.3	149.4996	85.73	75.78343

Code #		Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m2)	Perimeter (pixel)	Perim (metres)
Sec6.88.1a								
1		*BCB	MPR	Veg	12317.6	9750.87	1144.23	1018.45
	a							
	b							
	c							
2								
3								
4								
5								
6		MCB	MPR	Veg	199.18	157.798	84.14	74.891
	a							
	b							
	c							
	d							
7		*						
	a							
	b							
	c							
	d							
	e							
8		*						
9		*						
10								
11		#BCB	MPR	Sand/Veg	9470.56	7328.62	919.5	804.251
12		#						
13		#						
14		MCB	MPR	Sand	182.00	141.631	57	124.884
	a							
	b							
	c							
	d							
15		#						
16		#						
17								
18								
19		MCB	MPR	Sand/Veg	3053.48	3075.04	356.06	2711.44
	a							
	b							
	c							
20								
	a							
	b							
	c							
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								
35		LB	MPR	Veg/Rock	554.23	446.3	118.12	105.959
36								
37								
38								
Sec6.88.1b								
1		LB	MPR	Veg/Sand				
2								
3		MCB	MPR	Sand	780.1	588.348	112.71	98.5744
	a							
	b							
	c							
4								
5								
6								
7		BCB	MPR	Veg	538.03	411.582	131.75	115.227
8		BCB	MPR	Veg	229.28	173.203	77.84	67.7562
	a							
	b							
	c							
9		LEB	MPR	Sand	282.55	218.145	83.89	73.3689
10		MCB	MPR	Sand	375.85	287.365	92.13	80.5755
11		RCLB	MPR	Sand/Veg	2901.86	2202.18	202.15	176.104
12								
13								
14								
15		LB	MA	Sand	80.1	60.7811	53.05	48.2148
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26		LB	MPR	Sand	420.81	328.2	80.54	78.8745
27								
28								

sq. size (pixel2)	Code #	Morph Un	Chan Typ	Feature	Area (sq pixel)	AREA METRES	Perimeter (pixel)	PERIM METRES	Sq Size (pixel2)			Feature	Area (Pixel2)	AREA METRES	Perimeter (pixel)	PERIM METRES
Sec6.89.1a						0		0	Sec6.92.1a					0		0
3100.78	1	BCB	MPR	Gone	963.4	778.74	188.33	169.095	3104.58					0		0
	a	BCB	MPR	Sand	25.11	20.2449	20.81	18.6846						0		0
	b	BCB	MPR	Sand	47.94	38.6518	29.31	26.3185						0		0
	c	BCB	MPR	Sand	32.38	26.1063	23.35	20.9652						0		0
	2	BCB	MPR	Veg	88.93	71.6997	42.22	37.908						0		0
	3	BCB	MPR	Veg	68.71	55.3974	32.78	29.4411						0		0
	4	MCB	MPR	Veg	22.87	18.4389	16.96	15.2278		MPR	BCB	Veg	1064.4	857.121	348	312.164
	5	MCB	MPR	Veg	21.75	17.5359	18.51	16.6195						0		0
	6					0		0						0		0
	a	MCB	MPR	Gone	167.61	135.135	64.82	58.1096						0		0
	b	MCB	MPR	Sand	34.43	27.7591	23.85	21.4141						0		0
	c	MCB	MPR	Veg	59.48	47.9557	43.72	39.2546						0		0
	d					0		0		MPR	BCB/MCE	Veg	380	306	103.64	92.9873
	7					0		0		MPR	BCB/MCE	Veg	532.47	428.778	129.71	116.353
	a	BCB	MPR	Sand	31.18	25.1388	22.78	20.4624						0		0
	b	BCB	MPR	Gone	381.52	307.6	133.59	119.946						0		0
	c	BCB	MPR	Gone	161.3	130.048	63.38	56.8889						0		0
	d	BCB	MPR	Sand	63.22	50.971	31.79	28.5432						0		0
	e	BCB	MPR	Sand	106.35	85.7448	46.51	41.7598						0		0
	8	RC	MPR	Sand	1714.12	1382.91	343.91	308.786		MPR	RC	Sand	834.71	672.16	141.31	126.758
	9	BCB	MPR	Gone	65.72	52.9867	30.98	27.8159		MPR	BCB	Sand	194.81	156.712	65.2	58.4856
	10	BCB	MPR	Sand	31.74	25.5903	22.36	20.0763						0		0
	11	RC	MPR	Sand	279.11	225.032	92.98	83.4837						0		0
	12	RC	MPR	Sand	70.37	56.7357	37.67	33.8227						0		0
	13	RC	MPR	Sand	146.07	117.769	56.97	51.1515		MPR	RC	Sand	591.03	475.934	172.32	154.575
	14	MCB	MPR	Sand	180.8	145.77	53.41	47.9551						0		0
	a					0		0						0		0
	b					0		0						0		0
	c					0		0						0		0
	d					0		0						0		0
	15	RC	MPR	Sand	511.42	412.332	142.97	128.368						0		0
	16	RC	MPR	Sand	601.63	485.063	123.96	111.3		MPR	RC	Sand	456.39	367.513	95.36	85.54
	17	LB	MPR	Sand	298.68	240.81	92.77	83.2952						0		0
	18	LB	MPR	Sand	464.94	374.857	112.88	101.333						0		0
	19					0		0						0		0
	a	MCB	MPR	Sand	346.60	279.494	85.98	77.1987		MPR	MCB	Gone	178.93	144.098	55.57	49.8475
	b	MCB	MPR	Veg	360.29	290.483	111.38	99.9865		MPR	MCB	Gone	182.49	146.952	60.49	54.2609
	c					0		0		MPR	MCB	Sand	90.63	72.9809	51.18	45.9096
	20					0		0						0		0
	a	LB	MPR	Gone	610.44	492.165	146.1	131.178						0		0
	b	LB	MPR	Sand	34.32	27.6705	24.87	22.33						0		0
	c	LB	MPR	Sand	157.73	127.17	61.52	55.2368						0		0
	21	MCB	MPR	Sand	60.85	48.890	33	29.6296		MPR	BCB	Sand	192.86	155.303	72.08	64.6215
	22					0		0		MPR	RC	Sand	2527.34	2035.17	404.71	363.034
	23					0		0		MPR	BCB	Sand	121.81	97.8279	52.4	47.0039
	24					0		0		MPR	BCB	Sand	48.38	38.9586	29.48	26.4442
	25					0		0		MPR	BCB	Sand	78.88	63.5191	38.2	33.4722
	26					0		0		MPR	BCB	Sand	257.63	207.46	71.91	64.5046
	27					0		0		MPR	MCB	Sand	86.96	70.0256	37.05	33.2347
	28					0		0		MPR	MCB	Sand	92.36	74.3901	44.29	39.7291
	29					0		0		MPR	BCB/MCE	Sand	222.53	179.195	63.11	56.6111
	30					0		0		MPR	BCB/MCE	Sand	49.07	39.5142	28.48	25.5292
	31					0		0		MPR	BCB	Sand	189.6	152.839	57.98	52.0093
	32					0		0		MPR	BCB	Sand	138.03	111.15	49.99	44.8421
	33					0		0		MPR	LB	Sand	184.78	148.798	56.01	50.2422
	34					0		0		MPR	LB	Sand	96.24	78.1089	37.45	33.5935
	35					0		0		MPR	LB	Gone	554.23	446.3	118.12	105.959
	36					0		0		MPR	MCB	Sand	45.40	36.5314	28.08	25.1884
	37					0		0		MPR	LB	Sand	353.03	284.282	88.68	79.53
	38					0		0		MPR	RCLB	Sand	1433.25	1154.14	252.38	226.372
						0		0						0		
Sec6.89.1b						0		0	Sec6.92.1b					0		0
3268.06	1	LB	MPR	Sand	452.92	346.475	127.42	111.44	3184.82	MPR	LB	Sand	195.22	153.252	66.36	58.7959
	2	MCB	MPR	Gone	22.89	17.5104	20.21	17.8754		MPR	LB	Sand	252.1	197.904	73.64	65.2141
	3	MCB	MPR	Gone	780.1	588.348	112.71	98.5744						0		0
	a					0		0		MPR	MCB	Sand	325.56	255.572	99.7	88.3350
	b					0		0		MPR	MCB	Sand	28.83	22.6322	23.42	20.7505
	c					0		0		MPR	MCB	Sand	13.91	10.9197	15.54	13.7487
	4	LEB	MPR	Sand	104.01	79.5658	60.09	52.645		MPR	LB	Sand	2226.74	1748.01	374.32	331.853
	5	LB	MPR	Sand	18.26	13.9685	19.9	17.4042		MPR	RC	Sand	380.1	298.387	105.79	93.7314
	6	AB	MPR	River	439.48	336.178	93.43	81.7124		MPR	RC	Sand	502.54	394.505	98.49	87.2435
	7	BCB	MPR	Gone	538.03	411.582	131.75	115.227						0		0
	8					0		0						0		0
	a	BCB	MPR	Sand	61.53	47.0692	31.27	27.3483		MPR	BCB	Gone	81.59	64.05	34.35	30.4348
	b	BCB	MPR	Gone	117.4	89.8086	44.84	39.0415						0		0
	c	BCB	MPR	Sand	85.87	65.6888	43.75	38.2631		MPR	BCB	Gone	111.21	87.3024	44.83	39.8048
	9	LEB	MPR	Gone	282.55	216.145	83.89	73.3689						0		0
	10	MCB	MPR	Gone	375.85	287.365	92.13	80.5755						0		0
	11	RCLB	MPR	Sand	237.31	181.537	98.89	86.304						0		0
	12	LB	MPR	Gone	137.94	105.521	47.59	41.6215						0		0
	13	LB	MA	Veg	55.15	42.1886	30.32	26.8174						0		0
	14	BCB	MA	Gone	953.77	729.615	140.34	122.738						0		0
	15	LB	MA	Gone	61.97	47.4066	35.18	30.7504		MA	LB	Sand	182.82	143.518	58.96	52.2394
	16					0		0		MPR	RCLB	Sand	668.46	525.542	115.49	102.329
	17					0		0		MPR	LB	Sand	79.84	62.5506	33.31	29.5131
	18					0		0		MPR	LB	Sand	74.14	58.2018	36.72	32.5344
	19					0		0		MPR	LB	Sand	85.59	67.9751	39.51	35.0064
	20					0		0		MPR	MCB	Sand	93.27	73.2181	44.23	39.1884
	21					0		0		MPR	MCB	Sand	27.83	21.8257	20.5	18.1633
	22					0		0		MPR	TC	Sand	351.2	275.7	102.13	90.4888
	23					0		0		MPR	MCB	Sand	51.43	40.3737	33.36	29.5574
	24					0		0		MPR	MCB	Sand	51.8	40.6642	36.29	32.1535
	25					0		0		MPR	LEB	Sand	350.8	275.386	119.82	106.162
	26					0		0		MPR	LB	Sand	375.37	294.674	94.36	83.6043
	27					0		0		MPR	RCLB	Sand	565.76	444.15	218.61	193.692
	28					0				MA	LB	Veg	224.31	176.089	102.18	90.5419

Code #		Morph Un	Chan Typ	Feature	Area (pixel2)	AREA (m'	Perimeter (pixel)	Perim (metres)		sq. size (pixel2)
	Sec7.86.1b								Sec7.89.1b	
1		LB	MA	Sand	1134.47	877.1549	192.71	169.4452		
a										
b										
c										
d										
e										
2										
3		BB	MA	River	502.27	386.3475	104.64	92.00739		
4		BB	MA	River	4223.64	3265.654	1054.73	927.3982		
5		BB	MA	River	1174.46	908.09	227.97	200.4484		
6		BB	MA	River	956.4	739.4739	171.07	150.4177		
7		BB	MA	River	1207.34	933.4968	342.49	301.1431		
8										
9										
10										
11										
12										
13										
	Sec7.86.2a								Sec7.89.2a	
1		BB	MA	River	14457.01	11169.64	2431.64	2136.954		
2		BCB	MA	Sand	100.67	77.91796	40.63	35.70613		
3										

Code #	Morph Un	Chan Typ	Feature	Area (sq.pixel)	AREA ME	Perimeter (pixel)	PERIM METRES		Sq. Size (pixel2)			Feature	Area (Pixel2)	AREA ME	Perimeter (pixel)	PERIM METRES
					0		0	sec7.92.1b						0		0
1					0		0							0		0
a	MCB	MA	Sand	230.68	176.4655	62.2	54.39916			MA	LB	Sand	437.96	343.8087	85.43	75.8922
b	BCB	MA	Sand	21.71	16.60771	18.88	16.51216							0		0
c	BCB	MA	Veg	184.99	141.5136	55.83	48.82806							0		0
d					0		0			MA	BCB	Gone	1284.64	1008.472	203.77	180.5431
e					0		0			MA	MCB	Veg	91.13	71.53915	37.2	32.95973
2	BB	MA	Gone	218.65	167.2628	90.66	79.28984							0		0
3	BB	MA	Gone	502.27	384.2264	104.64	91.51653							0		0
4					0		0			MA	BB	Sand	4223.64	3315.655	1054.73	934.5058
5					0		0			MA	BB	Sand	1174.48	921.9938	227.97	201.9847
6					0		0			MA	BB	Sand	956.4	750.798	171.07	151.5705
7					0		0			MA	BB	Sand	1207.34	947.7897	342.49	303.451
8					0		0			MA	LB	Sand	98.15	77.05001	41.26	36.55895
9					0		0			MA	MCB	Sand	58.47	45.9003	28.95	25.65011
10					0		0			MA	LB	Sand	137.77	108.1526	63.61	56.35937
11					0		0			MA	MCB\BCE	Sand	55.91	43.89064	27.6	24.45399
12					0		0			MA	LB\TB	Sand	121.63	95.48235	63.83	56.55429
13					0		0			MA	MCB	Sand	154.79	121.5137	59.65	52.85075
					0		0							0		0
					0		0	Sec7.92.2a						0		0
1	BB	MA	Sand	14457.01	11059.32	2431.64	2126.675							0		0
2	BCB	MA	Gone	100.67	77.01052	40.63	35.53437			MA	BCB	Sand	311.68	244.676	77.72	68.88103
3					0		0			MA	BCB	Sand	62.89	49.3701	32.58	28.86634
					0									0		0

APPENDIX F: LETABA RIVER CROSS-SECTIONS

(Appendix F)

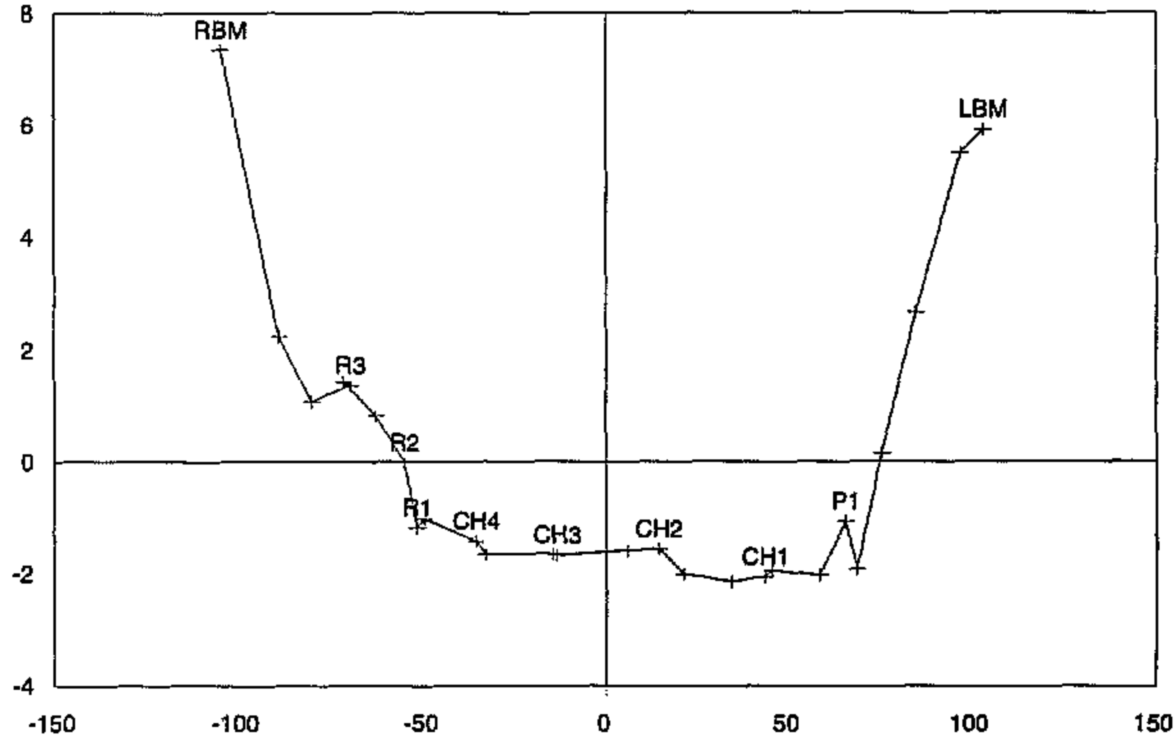

Figure 102. Letaba cross-section: Upstream 11.

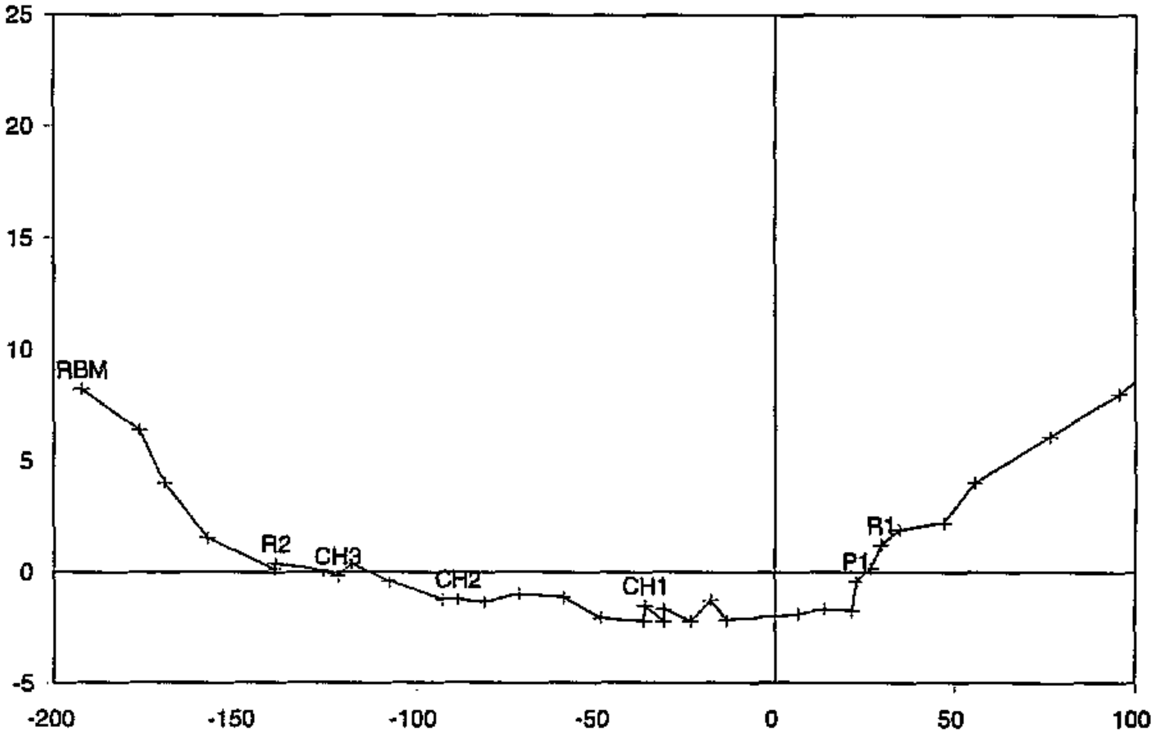

Figure 103. Letaba cross-section: Upstream 10.

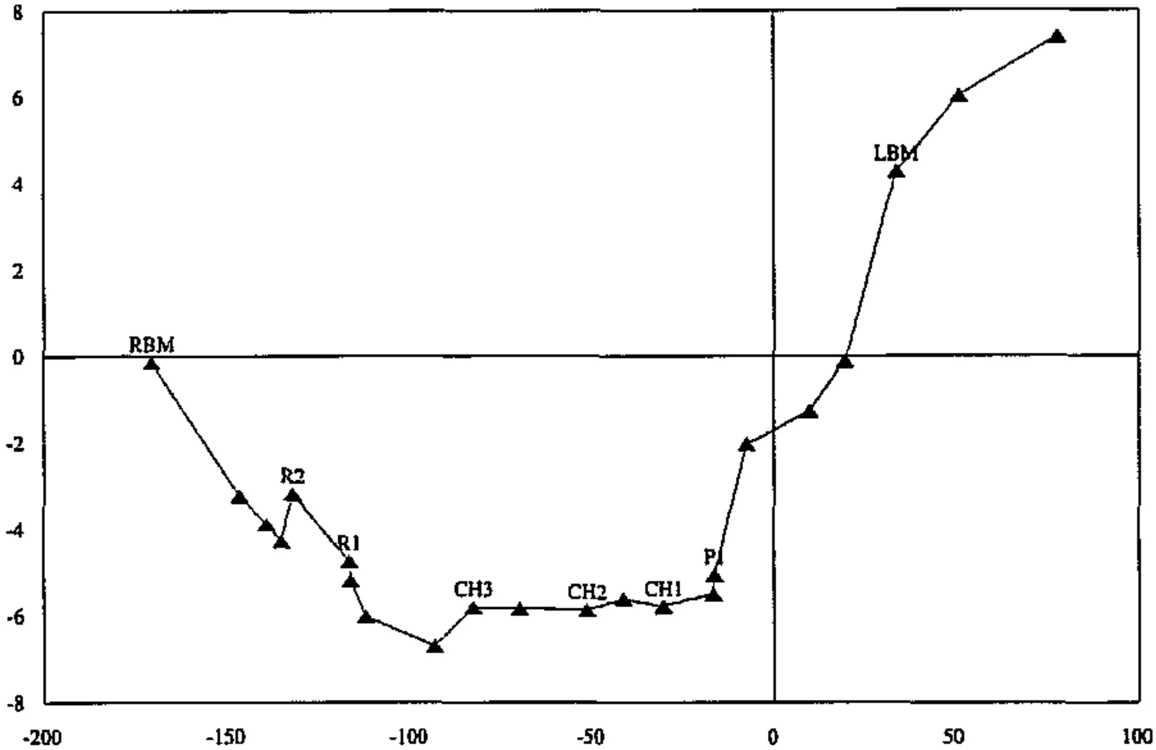

Figure 104. Letaba cross-section: Upstream 9.

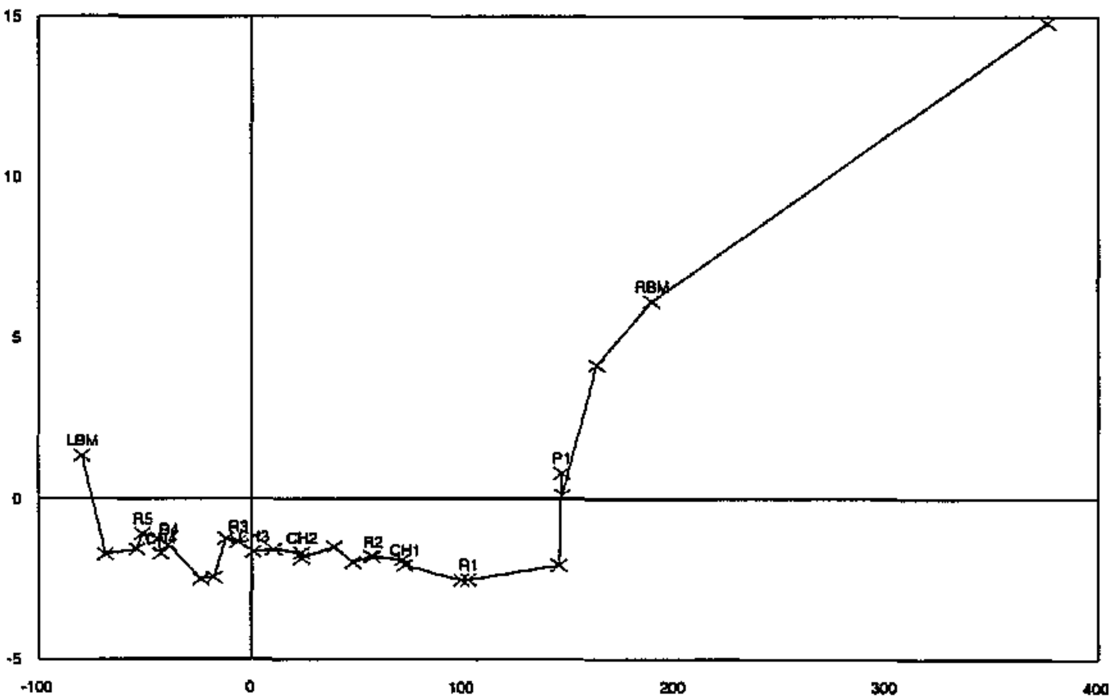

Figure 105. Letaba cross-section: Upstream 8.

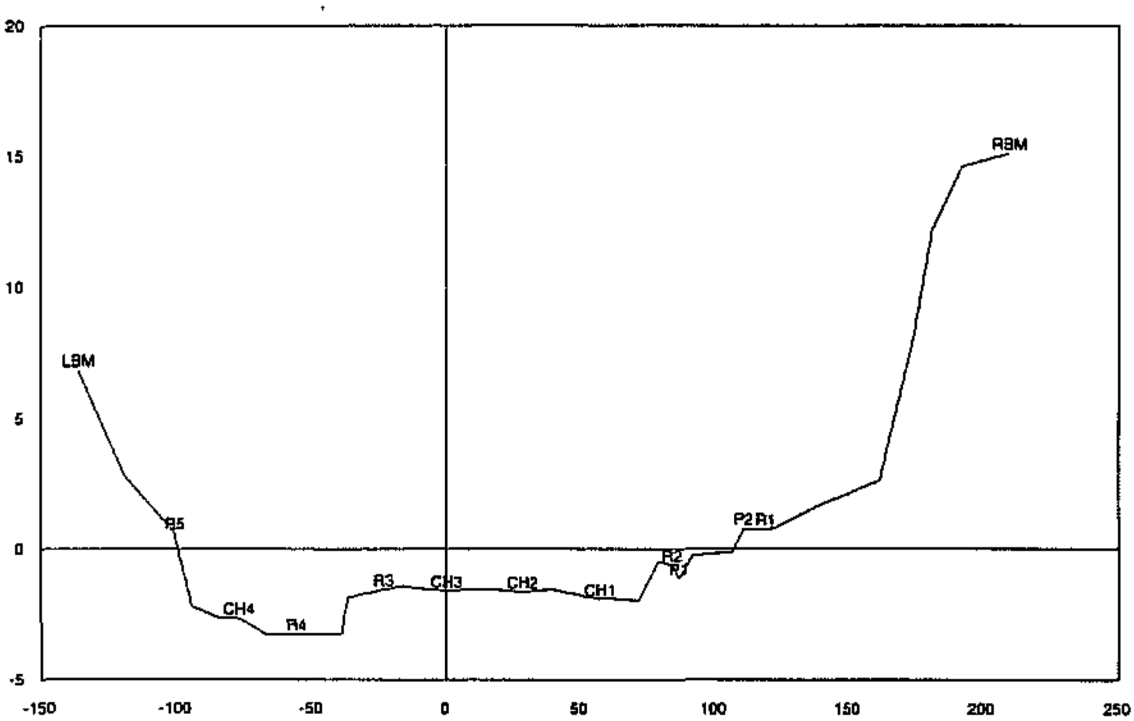

Figure 106. Letaba cross-section: Upstream 7.

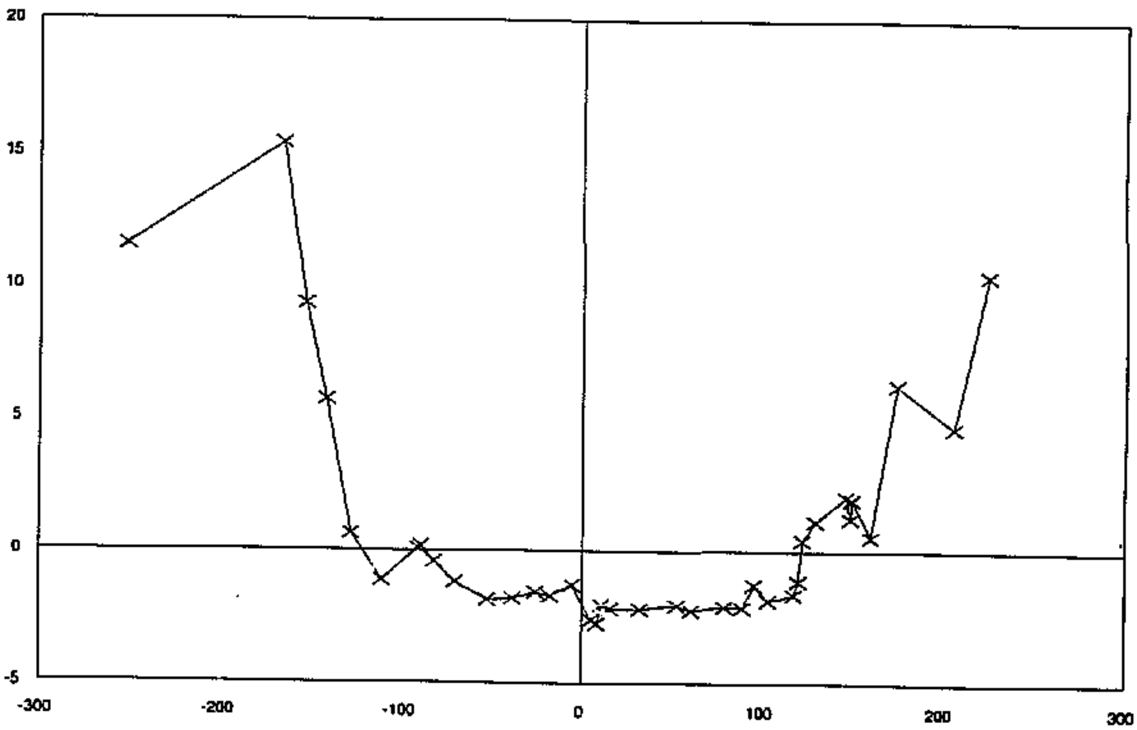

Figure 107. Letaba cross-section: Upstream 6.

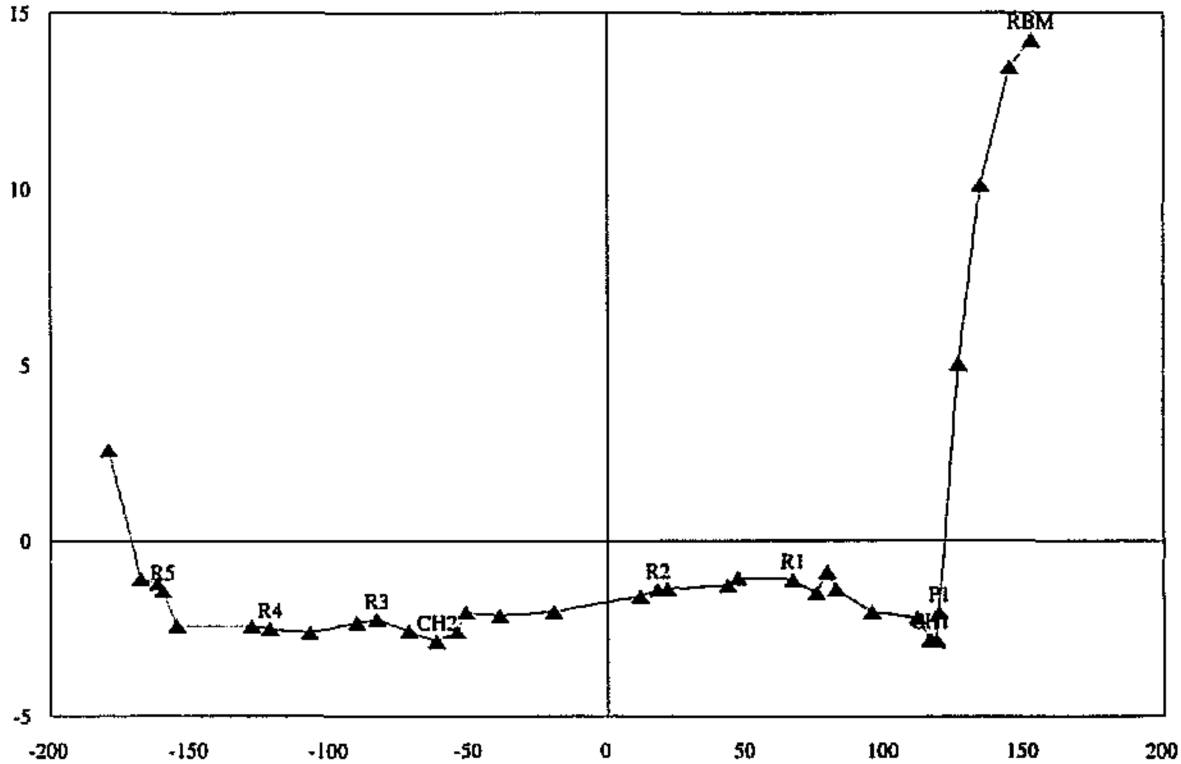

Figure 108. Letaba cross-section: Upstream 5.

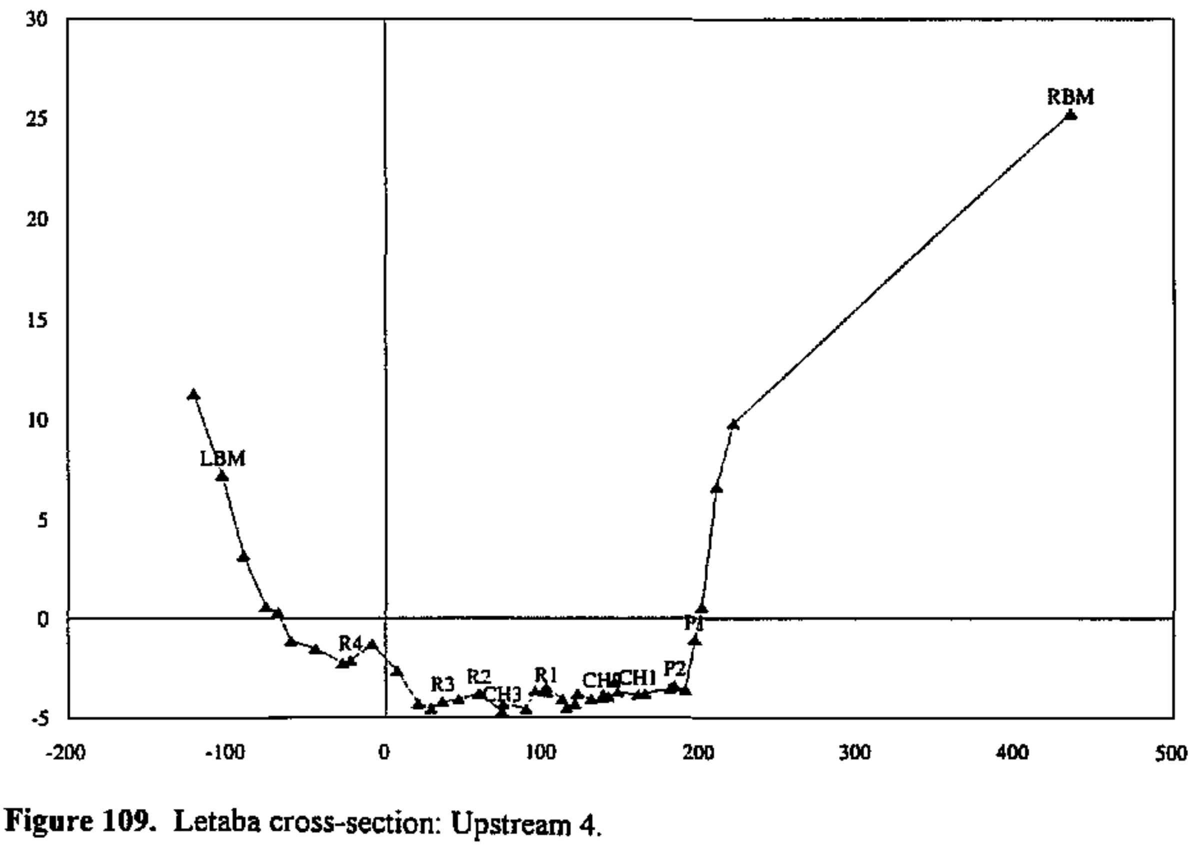

Figure 109. Letaba cross-section: Upstream 4.

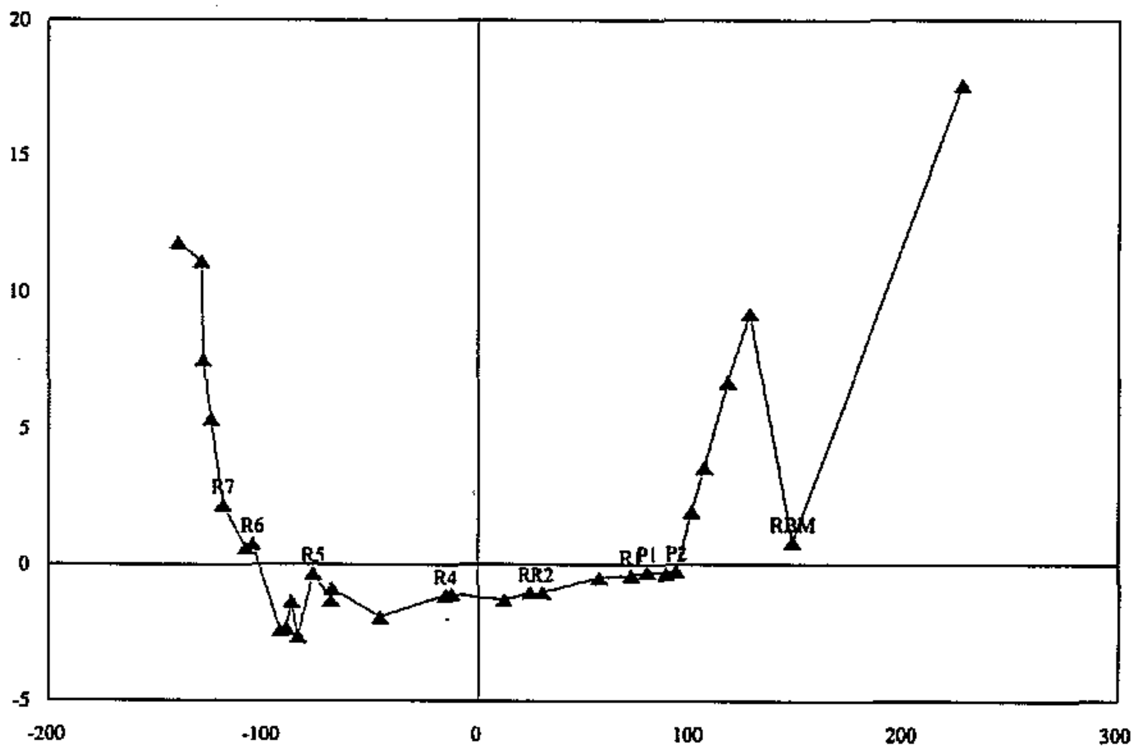

Figure 110. Letaba cross-section: Upstream 3.

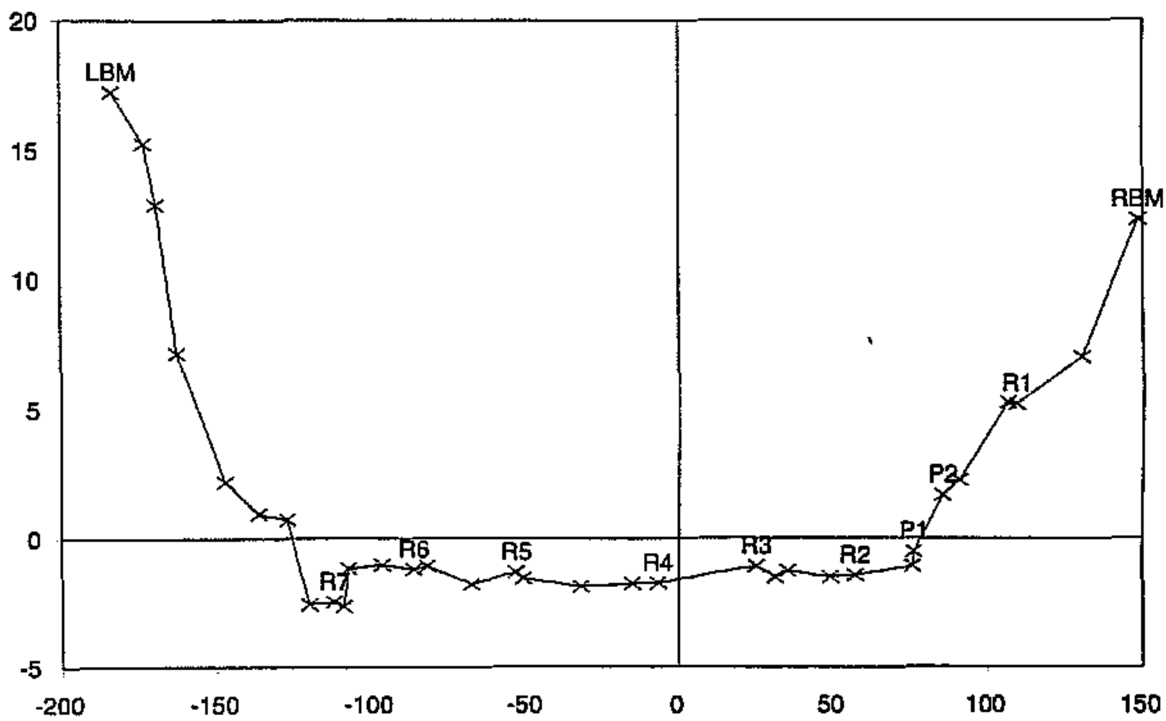

Figure 111. Letaba cross-section: Upstream 2.

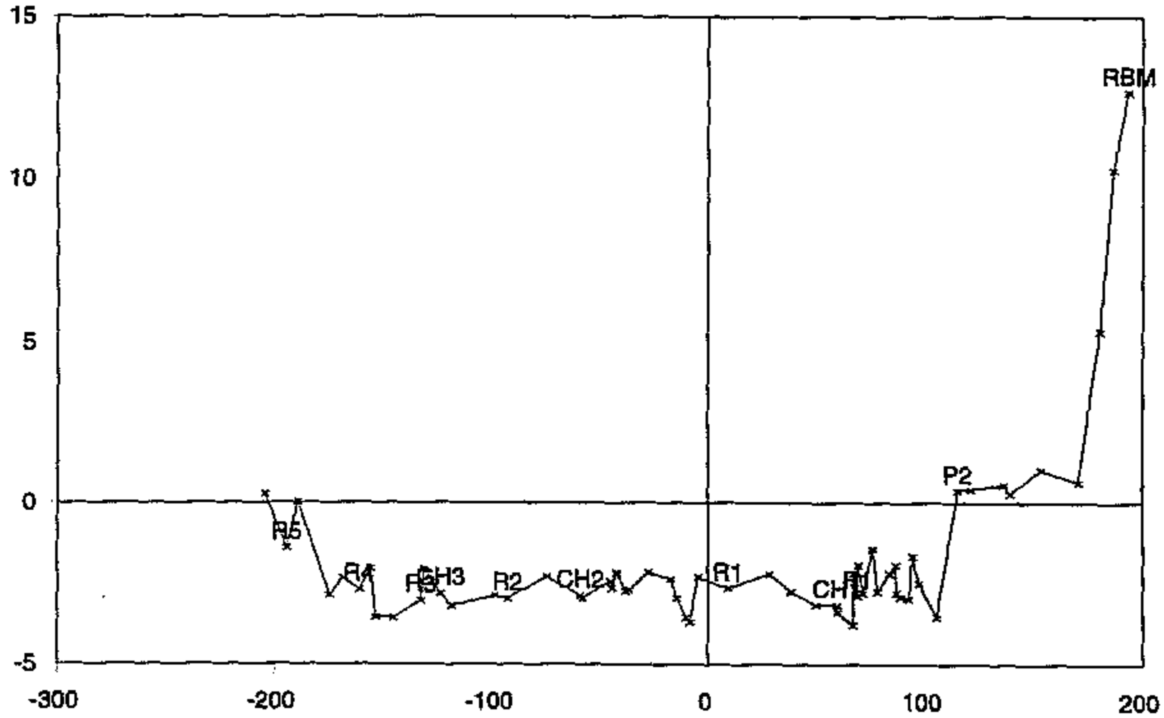

Figure 112. Letaba cross-section: Upstream 1.

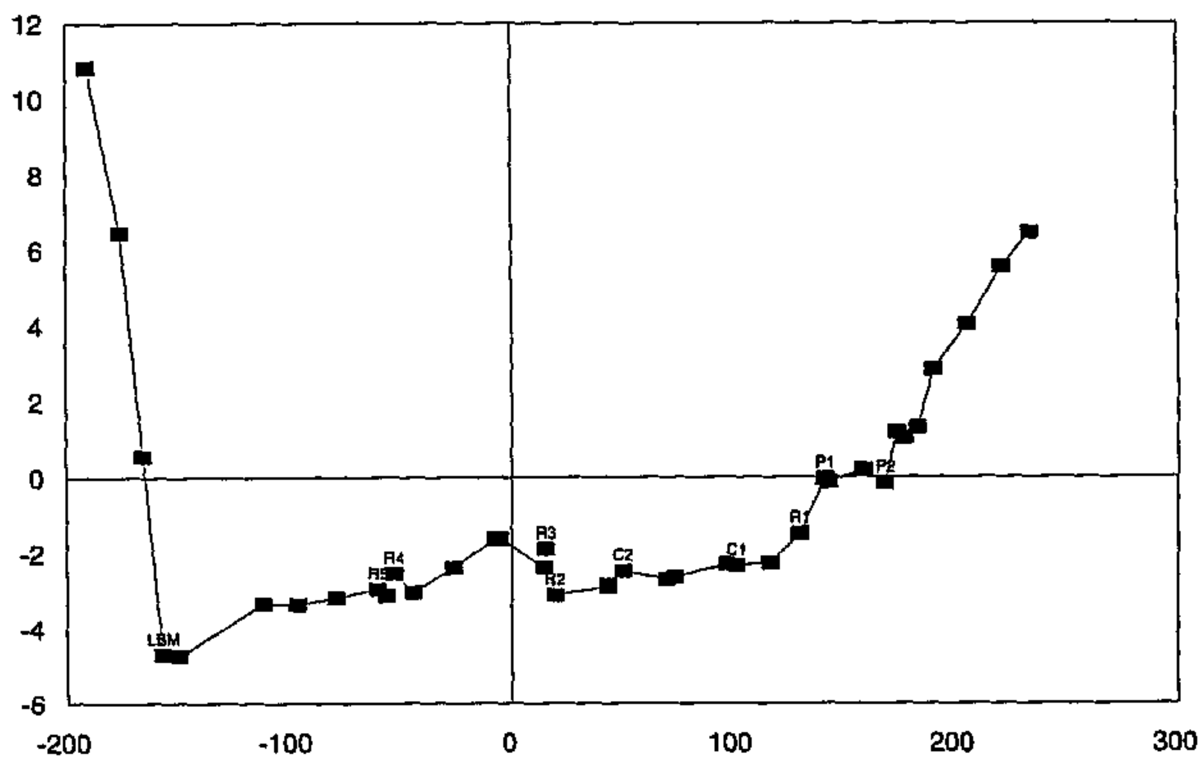

Figure 113. Letaba cross-section: Downstream 1.

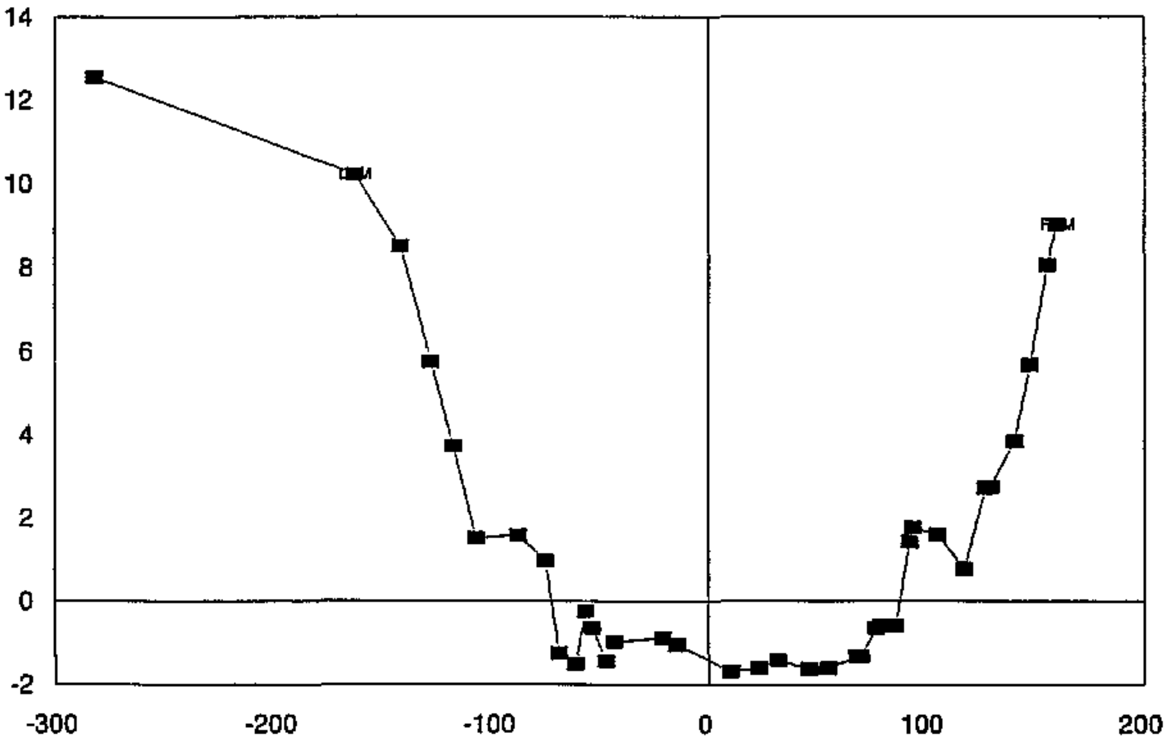

Figure 114. Letaba cross-section: Downstream 2.

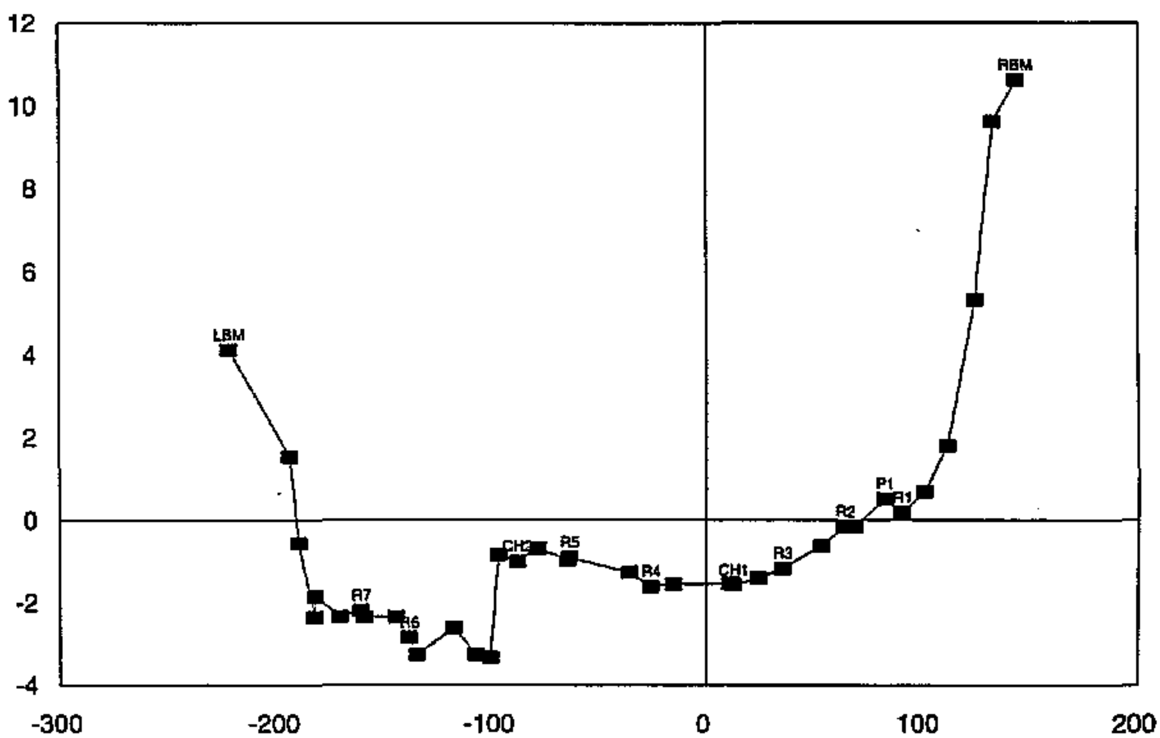

Figure 115. Letaba cross-section: Downstream 3.

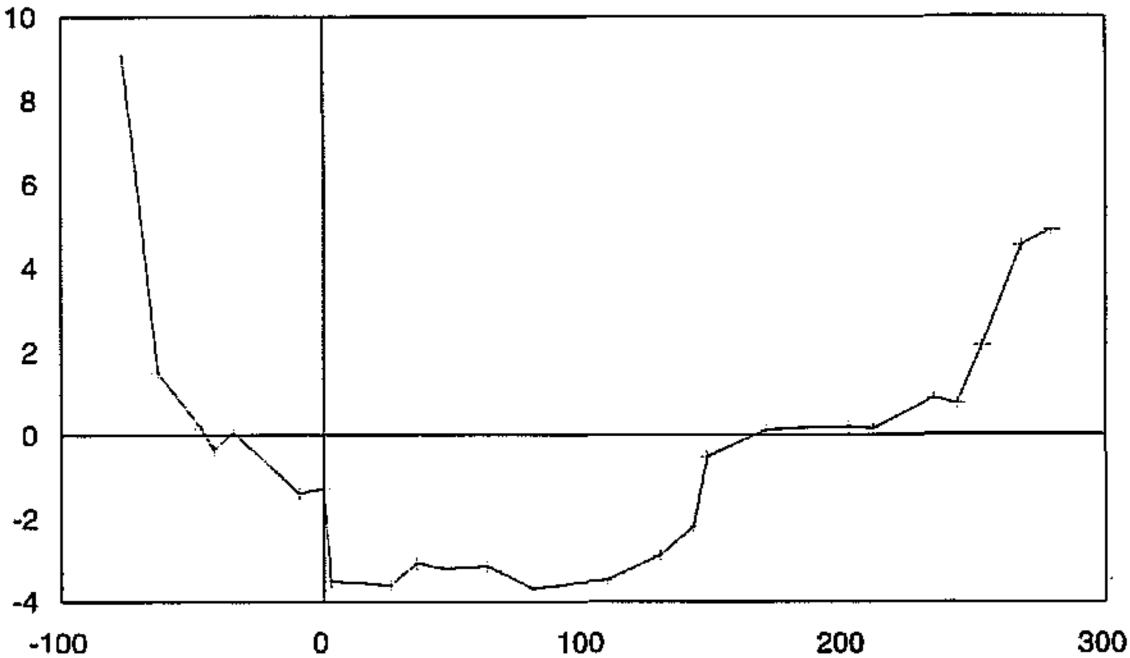

Figure 116. Letaba cross-section: Pump House.

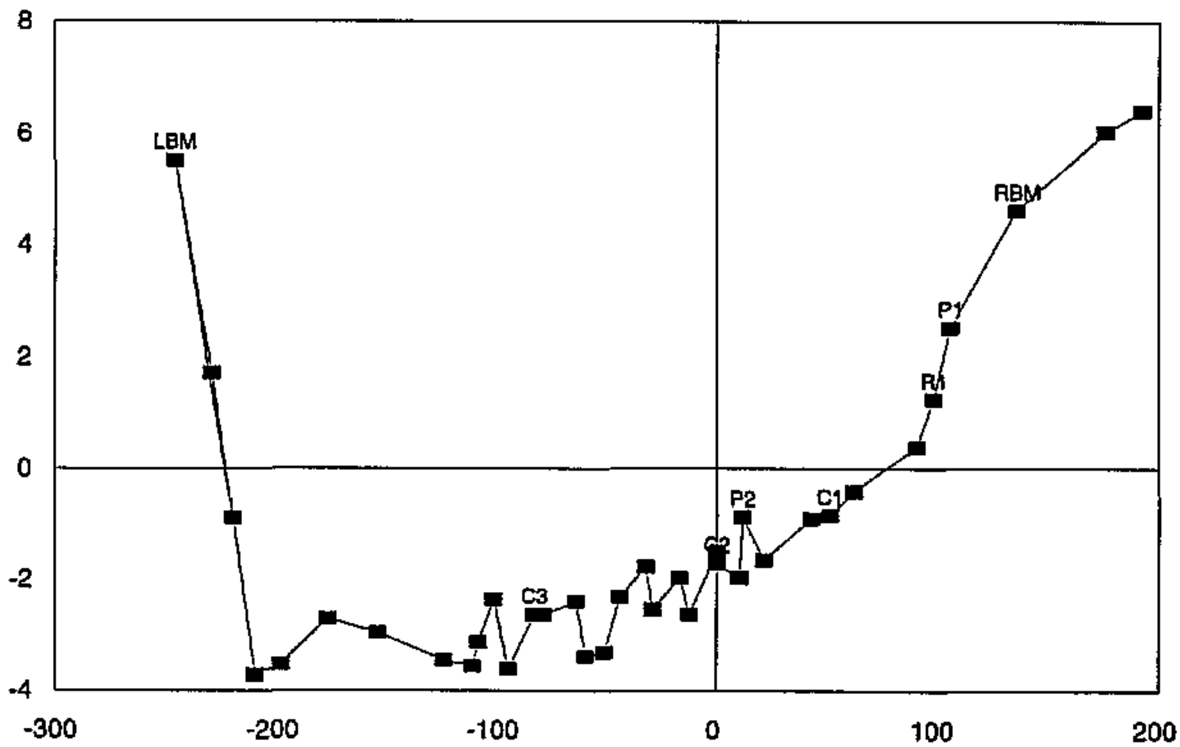

Figure 117. Letaba cross-section: Downstream 4.

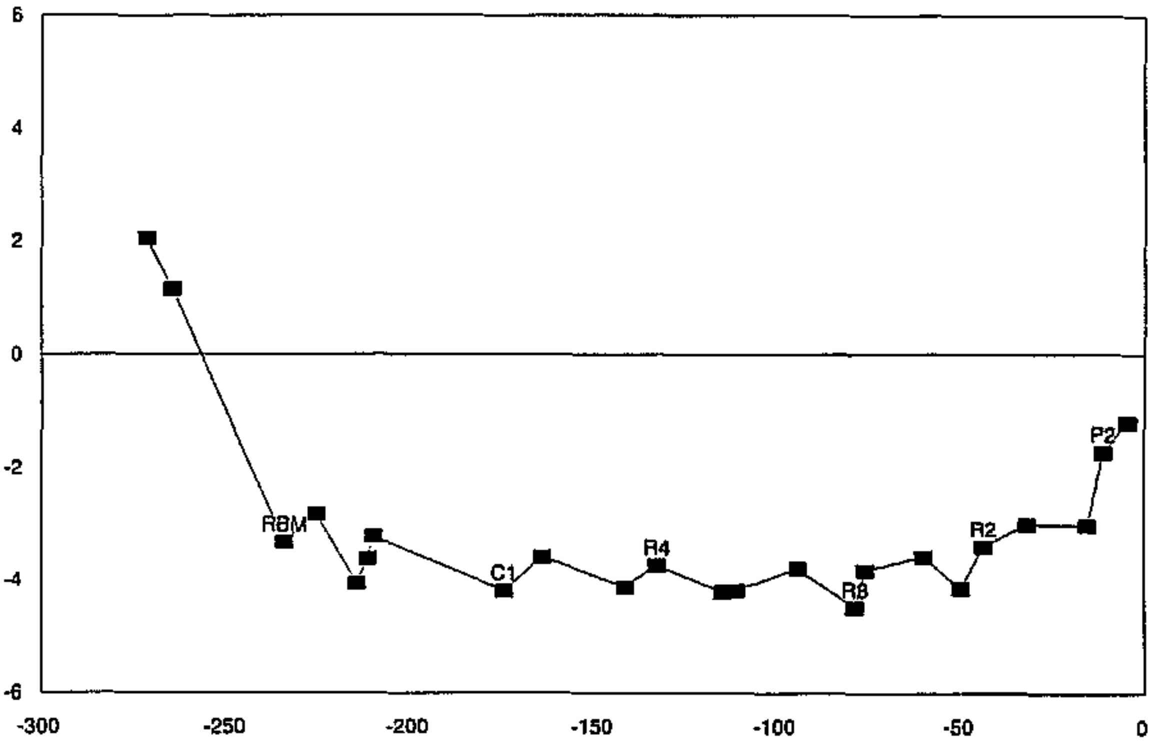

Figure 118. Letaba cross-section: Downstream 5.

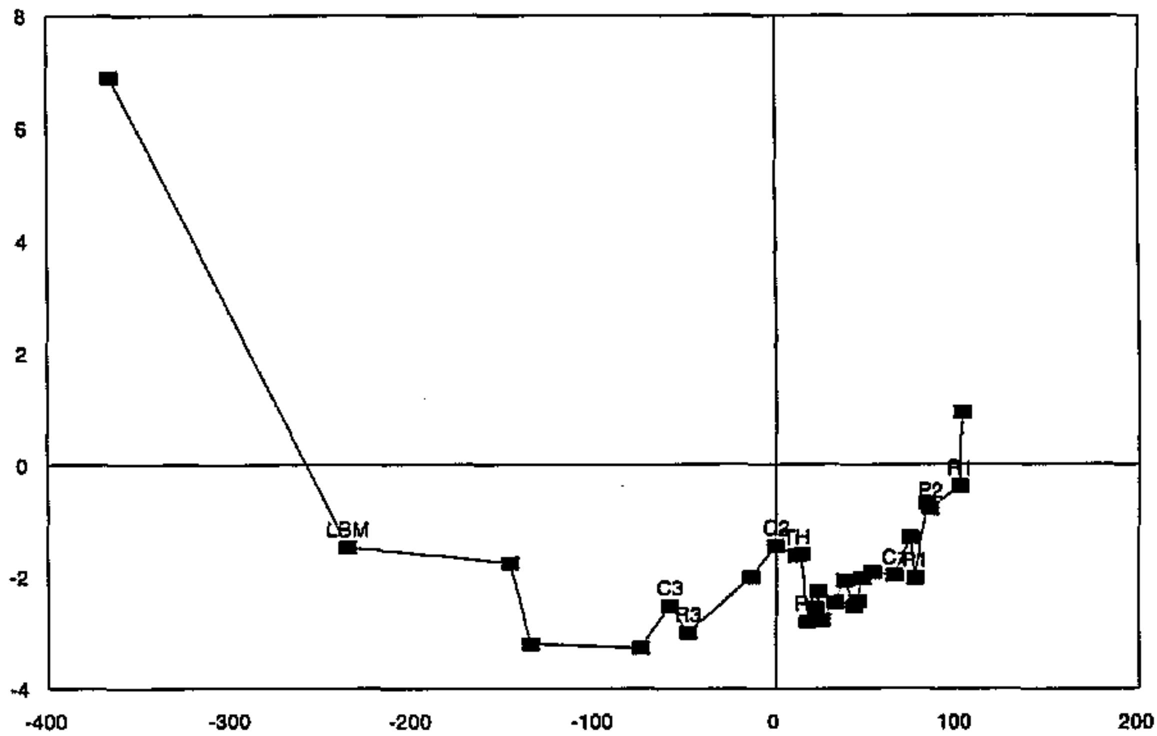

Figure 119. Letaba cross-section: Downstream 6.

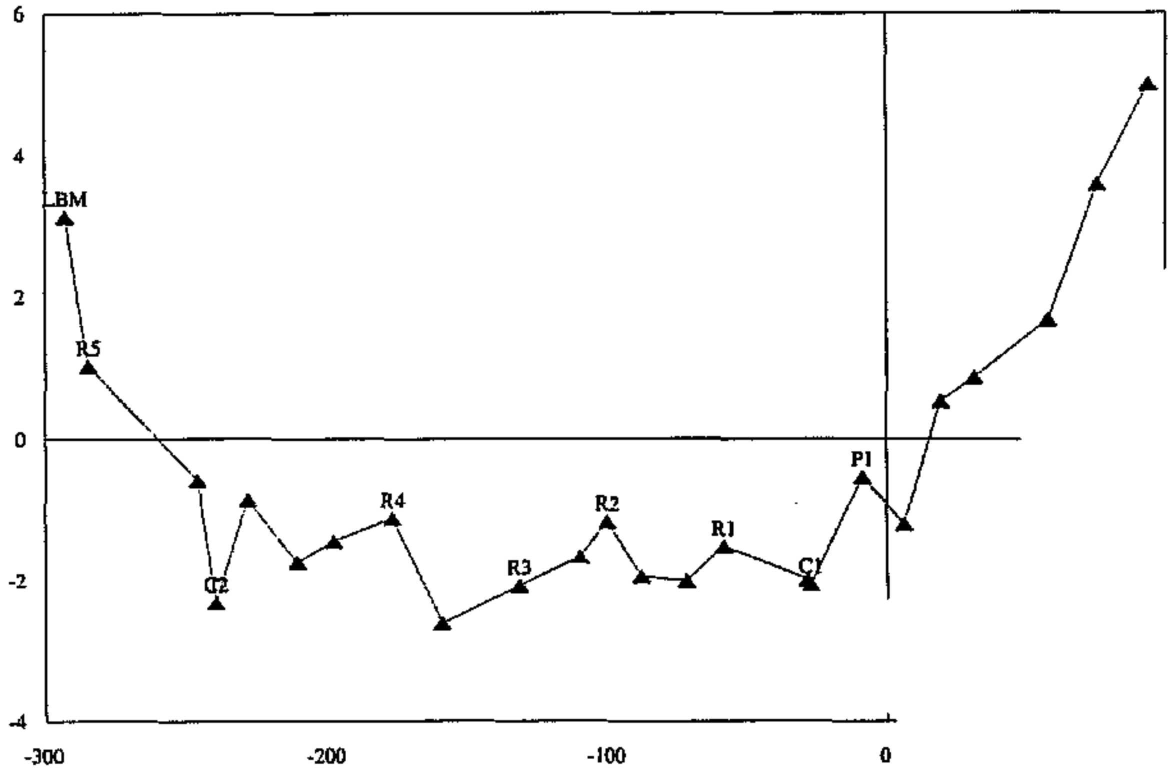

Figure 120. Letaba cross-section: Downstream 7.

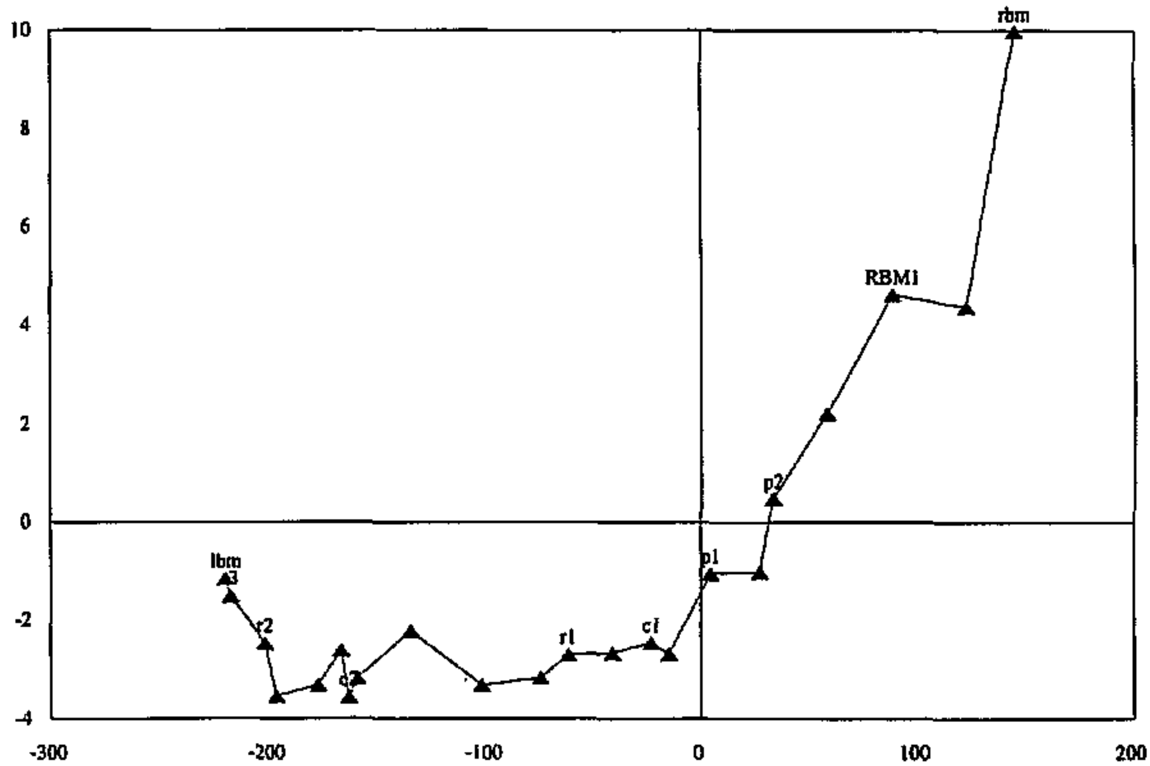

Figure 121. Letaba cross-section: Downstream 8.