ASSESSMENT OF THE GEOMORPHOLOGICAL REFERENCE CONDITION

AN APPLICATION FOR RESOURCE DIRECTED MEASURES AND THE RIVER HEALTH PROGRAMME

L du Preez • KM Rowntree

WRC Report No. 1306/1/06

Water Research Commission

ASSESSMENT OF THE GEOMORPHOLOGICAL REFERENCE CONDITION

AN APPLICATION FOR RESOURCE DIRECTED MEASURES AND THE RIVER HEALTH PROGRAMME

L. du Preez & K.M. Rowntree
Geography Department
Rhodes University
PO Box 94
Grahamstown
6140, South Africa

WRC Report: 1306/1/06
ISBN: 1-77005-445-6

MAY 2006

This Report is obtainable from:

Water Research Commission
Private Bag X03
00310 Gezina Pretoria

This report emanates from the WRC research project K5/1306 titled:
"Assessment of the geomorphological reference condition:
Application to resource directed measures and the river health programme

EXECUTIVE SUMMARY

INTRODUCTION

Initiatives have been set in place world-wide to develop river classifications that can be used as the basis of determining a reference condition against which resource protection measures can be evaluated (eg. Apfelbeck, 2001; Rosgen, 1998; Environment Canada, 1999). In South Africa, the present ecological state (PES) of a river reach is an expression of the degree of modification from the reference condition (RC), the condition of the river in its natural state. Whilst methods have been established for the derivation of PES and reference condition for biological components (e.g.Dallas, 2000; Dallas & Fowler, 2000), there has not, to date, been an established method for the derivation of the geomorphological reference condition or the present geomorphological state (PGS). As the geomorphology of a river channel provides the physical template for river ecosystems, the geomorphology is a critical component of the integrated reference condition and the PES of a river.

PROJECT AIMS

The aims, as listed in the project proposal, are as follows:

- to establish a geomorphological database for South African rivers.
- to develop a method to determine the geomorphological reference condition (GRC) for a river reach. This is defined as the channel morphology that would be characteristic of a river reach under natural conditions and would provide habitat to support the natural fauna and flora. It is recognised that this morphology can change in response to the inherent variability of natural systems.
- to develop guidelines for classification of the present geomorphological state (PGS).
- to refine the geomorphological index for the biomonitoring programme.

CHAPTER ONE: INTRODUCTION AND CONTEXT

This chapter provides a general introduction to the project. The project aims are listed and a brief description of the approaches taken is presented.

In terms of the reference condition, the initial approach of this project was to classify river reaches in terms of their zonal gradient classes (see Rowntree *et al.*, 2000) and assess whether channel morphology and dominant bed material could be accurately predicted using channel gradient. If common groupings could be found for undisturbed 'reference' sites, it would then be possible to gauge how far a 'disturbed' reach was removed from its reference condition. If the gradient did not accurately predict the morphology and/or bed material of the reach, it would be assumed that an alteration from reference had occurred. However, while using the data collected at available sites within the RHP, convincing relationships that could be used to define reference condition remained elusive. It was decided that a different approach with more of a systems focus would be taken.

Guidelines for assessing the present geomorphological state were developed in association with a project initiated in 2003/2004 (Project no 2003-046) as a DWAF/RQS study in collaboration with IWR S2S (Thirion & Kleynhans, 2003). The approach to assessing the PES for geomorphology crystallised as a result of collaborative model development. One output from this project has been a series of rule-based models that are collectively known as Assessment Indices. The model for Geomorphology is termed the geomorphology driver assessment index (GAI). The framework for the database is now in place, but data input is an ongoing process.

CHAPTER TWO:CONCEPTUAL BASIS FOR THE GEOMORPHOLOGICAL REFERENCE CONDITION – A REVIEW OF RELEVANT LITERATURE

This chapter reviews literature regarding geomorphological change and the reference condition concept. A brief overview of some of the approaches (both local and international) to the challenge of deriving a reference condition in natural systems is presented.

Internationally, there are two main approaches to deriving ecological reference conditions, namely the multimetric approach and the multivariate approach (Dallas, 2000). If the multimetric approach is selected, sites are classified according to geographic and physical attributes such as climate, physiography, geology, soils and vegetation, as well as additional variables, e.g. stream size, hydrologic regime, elevation and natural riparian vegetation.

Table E.1 Geomorphological Zonation of River Channels (after Rowntree and Wadeson, 1999)

Longitudinal zone	*Macro-reach characteristics*			*Characteristic channel features*
	Valley form	*Gradient class*	*Zone class*	
A. Zonation associated with a 'normal' profile				
Source zone	*V10*	*not specified*	*S*	*Low gradient, upland plateau or upland basin able to store water. Spongy or peaty hydromorphic soils.*
Mountain headwater stream	*V1, V3*	*> 0.1*	*A*	*A very steep gradient stream dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades.*
Mountain stream	*V1, V3*	*0.04 - 0.99*	*B*	*Steep gradient stream dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool. Approximate equal distribution of 'vertical' and 'horizontal' flow components.*
Transitional	*V2, V3, V4, V6*	*0.02 - 0.039*	*C*	*Moderately steep stream dominated by bedrock or boulder. Reach types include plain-bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.*
Upper Foothills	*V4, V6*	*0.005 - 0.019*	*D*	*Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plain-bed, pool-riffle or pool-rapid reach types. Length of pools and riffles/rapids similar. Narrow flood plain of sand, gravel or cobble often present.*
Lower Foothills	*V8, V10*	*0.001 - 0.005*	*E*	*Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool- riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.*
Lowland river	*V4, V8, V10*	*0.0001- 0.001*	*F*	*Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks.*
B. Additional zones associated with a rejuvenated profile				
Rejuvenated bedrock fall / cascades	*V1, V4*	*>0.02*	*A/B/Cr*	*Moderate to steep gradient, confined channel (gorge) resulting from uplift in the middle to lower reaches of the long profile, limited lateral development of alluvial features, reach types include bedrock fall, cascades and pool-rapid.*
Rejuvenated foothills:	*V2, V3, V4, V6*	*0.001 - 0.02*	*D/Er*	*Steepened section within middle reaches of the river caused by uplift, often within or downstream of gorge; characteristics similar to foothills (gravel/cobble bed rivers with pool-riffle/ pool-rapid morphology) but of a higher order. A compound channel is often present with an active channel contained within a macro channel activated only during infrequent flood events. A limited flood plain may be present between the active and macro-channel.*
Upland flood plain	*V8, V10*	*< 0.005*	*Fr*	*An upland low gradient channel, often associated with uplifted plateau areas as occur beneath the eastern escarpment.*

Sites are then designated to homogenous zones and it is assumed that test site characteristics should, ideally, match the conditions of the reference sites in that zone (Dallas, 2000). The multivariate approach, by comparison, does not make assumptions regarding the similarities of biological communities at different sites based on either physical or chemical attributes. Instead, sites are classified by multivariate analysis of fauna and then probabilities of sites belonging to each of the groups of reference sites are calculated.

The approach used in South Africa to date (i.e. for biotic components) is a regional, multimetric one whereby homogenous zones are delineated and test site conditions are assessed against reference conditions established for each zone. Initially, it was thought that this would be the approach most suitable for identifying the geomorphological reference condition.

Progress has been made in terms of geomorphological classification and zonation (see Rowntree & Wadeson, 1999; Rowntree *et al.*, 2000). It is thus possible to group rivers and river reaches in a regional or longitudinal manner (see table E.1) according to their morphological similarities. By making use of available historical data and empirical data, it was thought that reference sites could be identified, and reference conditions (which, it was thought, would be in the form of ranges) established in terms of form and process.

CHAPTER THREE:AN EMPIRICAL APPROACH TO DETERMINING THE REFERENCE CONDITION FOR SOUTH AFRICAN RIVERS

For the purpose of this chapter, the definition of reference reach that was adopted was "the channel morphology that would be characteristic of a river reach under natural conditions and that would provide habitat to support the natural fauna and flora."

The following objectives were adopted to arrive at the geomorphological reference conditions for South African river sites:

1. Define what is meant by "reference condition" in terms of geomorphology.
2. Collect data for a wide range of field sites and compile into a geomorphological database.
3. Categorise channel characteristics according to the zone classes proposed by Rowntree *et al.* (2000).
4. Test the hypothesis that reach characteristics can be predicted from the reach drivers gradient and stream power.
5. Assess the effect of human induced disturbance on the above relationships.
6. Make recommendations for determining the reference condition of a river reach.

In this chapter, the methods that were adopted to address each objective are presented with results and discussions.

The chapter concludes that the findings obtained by taking the approach outlined above were not conclusive with respect to reference conditions. However, the data that has been collected has suggested areas that may be worthy of further investigation. It was proposed that a different approach be taken in the endeavour to define and describe geomorphological reference conditions for South African river sites. An alternative approach was suggested. This new approach is presented in the chapters that follow.

CHAPTER FOUR: DEVELOPMENT AND APPLICATION OF THE GEOMORPHOLOGY DRIVER ASSESSMENT INDEX

At the start of the present reference condition project there was no standard set of methods in place to derive the EcoClassification for a river reach. To meet this need a study was initiated in 2003/2004 (Project no 2003-046) as a DWAF/RQS study in collaboration with IWR S2S (Thirion & Kleynhans, 2003). The aim of this project was "to devise a set of rule-based models to determine the present ecological state (PES) for various components and an integrated ecological river state (referred to as the Ecostatus)" (Kleynhans *et al*., 2005). The rule-based models focussed on developing a reliable and consistent method to determine the ecological categories (ECs) for the present and the future condition of the river reach.

The EC for each component is assessed using a rule-based model; the model output is an assessment index that can be related directly to the ecological category as indicated in Table E.2. The Geomorphology EC is assessed using the Geomorphology Driver Assessment Index (GAI). This chapter describes the process of developing the GAI rule based model.

Figure E.1 provides a framework within which a driver-driven assessment of change can be placed. Aerial photographs or anecdotal evidence can be used to assess historical changes to channel morphology. A field assessment of the present channel will provide evidence of ongoing change in terms for example of bank erosion, bar development, loss or gain of secondary channels. Finally the river zone, classified in terms of reach gradient and stream power, can be used to get a first approximation of expected channel morphology. These four aspects can then be compared to derive an assessment of the change rating.

Table E.2 Generic ecological categories for EcoStatus components (Kleynhans *et al.*, 2005)

ECOLOGICAL CATEGORY	DESCRIPTION	SCORE (% OF TOTAL)
A	Unmodified, natural.	100
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.	80-99
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem functions are still predominantly unchanged.	60-79
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions have occurred.	40-59
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions are extensive.	20-39
F	Criticall/Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.	0-19

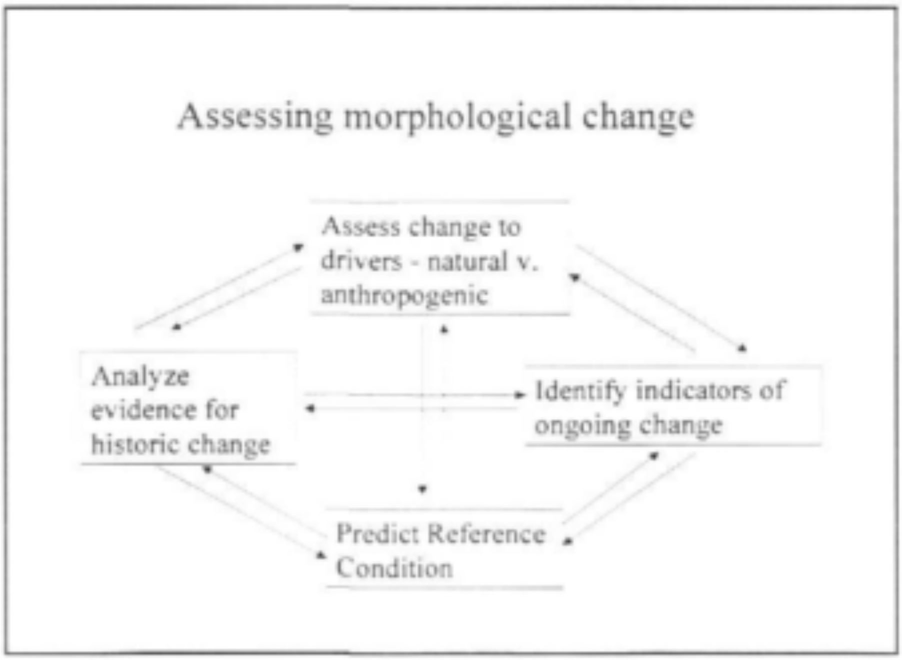

Figure E.1 Framework for assessing morphological change

A fundamental difference between the GAI as presented here and earlier assessment methods is a change to the conceptualisation of the reference condition. Rather than seeing the reference condition as being a deterministic channel morphology that can be predicted from reach and catchment controls, the reference condition is conceptualised as a geomorphological system composed of flows, storages and responses that are dynamic and indeterminate. This thinking is in line with the system paradigm that is being applied increasingly to fluvial geomorphology. This paradigm is explored further in Chapter 5.

CHAPTER FIVE: ADOPTING A SYSTEMS PARADIGM IN FLUVIAL GEOMORPHOLOGY

Despite the long history of the discipline of fluvial geomorphology, cause-effect relationships within river systems are relatively poorly understood, and difficult to unravel. Ways of thinking (dubbed "paradigms" by Kuhn in 1970) in Western science can be broadly broken down into two main classes, namely reductionism and holism (or the "systems approach"). The reductionist approach holds that a complex entity can be understood as a sum of its constituent parts (i.e. if one can fully comprehend each of the parts and its relationship to other parts, one can understand the whole), whilst the holistic approach holds that it is not only impossible to fully understand each part of a system and its relationships with other parts, but that a system can exhibit its own properties independent of the characteristics of its parts, i.e. a system can behave as an entity in its own right (Laszlo, 1972; CALRESCO, 2004).

An holistic outlook is warranted in river science. Rivers are widely recognised as being natural *systems*. A system may be simply defined as "A collection of interacting parts that forms an integrated and consistent whole, isolatable from its surroundings" (CALRESCO, 2005).

In this chapter, certain relevant systems concepts are presented and defined, and the history of systems thinking in fluvial geomorphology is outlined. In addition, the applicability of systems theory concepts to fluvial geomorphology in general is discussed, particularly within the context of this project.

Within the context of this particular project, perhaps the most intriguing systems concept is that of self-organization.

As has been pointed out in Chapter 2 of this report, the original notion of a "reference condition" has been replaced as a systems perspective has been taken. It now seems more important to understand the system that is being dealt with, and to gain some idea of the trajectory that it is on. If systems tend to self-organize after a perturbation, then a measure of a system's type and degree
of self-organization would go a long way towards allowing one to gain an understanding of its trajectory, and hence its potential endpoints.

Self-organization, and particularly self-organized criticality, is a systems concept which needs to be further investigated in the context of managing South African river systems. Self-organisation is a measure of the systems intrinsic adaptation to the current set of external drivers. Self-organised criticality implies a hierarchy of pattern and structure that could be considered to be the optimal ecosystem condition given the current externalities. The 'reference condition' may be better thought of as the *attractor* to which the system is tending, rather than a *past* condition from which it has moved. It is proposed that the degree of self-organisation is a better measure of ecosystem health than a measure that compares the present condition to a historic reference condition.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This chapter reviews the aims of the project and states how each one of these has been addressed. Conclusions that have been reached with regards to each one are presented. Furthermore, the chapter presents the new directions that this project has suggested.

The primary aim of this project was to derive a method by which to gauge the geomorphological reference conditions for South African rivers. If these systems are indeed nonlinear dynamical systems, however, deriving a "reference condition" may be redundant. These systems exhibit chaos and associated unpredictability and although sensitive to initial conditions, these initial conditions become irrelevant to the present condition. It is proposed that the degree of self-organization is a better measure of ecosystem health than a measure that compares the present condition to a historic reference condition and that it would be useful to apply a systems theory framework to understanding and managing trajectories of change in river systems.

Work done abroad has identified self-organization at a variety of scales in geomorphological systems (see Chapter 5). In order to explore this idea further within the South African context, certain research needs can be identified. In this chapter, some of these needs are presented, along with ideas as to how these could be addressed.

ACKNOWLEDGEMENTS

The authors would like to thank the Water Research Commission for its financial support of this project. We also thank the following members of the project steering committee for their much valued guidance and advice:

Dr. S.A. Mitchell	WRC (Chairman)
Dr. S. Liphadzi	WRC
Dr. W.J. Muller	IWR
Mr. H.H. Pienaar	RDM Office
Dr. D.J. Roux	CSIR
Ms. D.M. Schael	NMMU

In addition, we acknowledge the following groups/persons:

- The NRF for providing Masters and PhD funding which supported student participation in the project.
- The technical staff of the Rhodes University Geography Department for their willing assistance, and Ms. Gillian McGregor for her kind assistance with GIS.
- Dr. Roy Wadeson, who helped to put together the initial project proposal and undertook many field surveys in the data collection phase.
- River Health champion Mick Angliss from Limpopo Province and Ms. Denise Schael from NMMU for their assistance with data collection.
- Mr. Jonothan Freeman for the many hours spent behind the computer digitising long profiles and calculating channel gradients.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AusRivAS	-	Australian River Assessment System
BBM	-	Building Block Methodology
CALRESCO	-	Complexity and Artificial Life Research Concept
CWE	-	Center for Water in the Environment
DWAF	-	Department of Water Affairs and Forestry
EC	-	Ecological Category
EMC	-	Ecological Management Class
ER	-	Ecological Reserve
ESS	-	Earth Surface System/s
EU	-	European Union
EWR	-	Environmental Water Requirement
GAI	-	Geomorphology Driver Assessment Index
GRC	-	Geomorphological Reference Condition
IFA	-	Instream Flow Assessment
IFR	-	Instream Flow Requirement
IWR	-	Institute for Water Research
MAF	-	Mean Annual Flood
NDS	-	Nonlinear Dynamical Systems
NRHP	-	National River Health Programme
NWRI	-	National Water Research Institute
PES	-	Present Ecological State
RC	-	Reference Condition
RDM	-	Resource Directed Measures
REC	-	Recommended Ecological Category
RIVPACS	-	River Invertebrate Prediction and Classification
System		
RQS	-	Resource Quality Services
S2S	-	Source to Sea
SPATSIM	-	Spatial and Time Series Information Modelling
WFD	-	Water Framework Directive

CHAPTER 1
INTRODUCTION AND CONTEXT

1.1 BACKGROUND AND TERMS OF REFERENCE

Initiatives have been set in place world-wide to develop river classifications that can be used as the basis for determining a reference condition against which resource protection measures can be evaluated (eg. Apfelbeck, 2001; Rosgen, 1998; Environment Canada, 1999). In South Africa, water resources are protected through Resource Directed Measures and the ecological Reserve (ER), the responsibility of DWAF; the River Health Programme has been set up to monitor the ecological health of South Africa's rivers. Local initiatives have been put in place to rehabilitate highly disturbed rivers. Before an ER can be established, the river must be classified according to an ecological category (EC) that is decided upon in relation to the present ecological state of the river of concern (Kleynhans *et al.*, 2005). The present ecological state (PES) is an expression of the degree of modification from the reference condition (RC), the condition of the river in its natural state. The ecological category has become the benchmark for management decisions regarding water resource protection. Apart from its application to the ecological Reserve, it provides a means of reporting the results of biomonitoring for river health and, together with the RC, also has the potential to provide a benchmark for setting realistic objectives for river rehabilitation projects.

Considerable progress has been made in developing procedures for all the above initiatives (see King *et al.*, 2000; Dallas, 2000; Dallas & Fowler, 2000), but there is no established method for determining the geomorphological reference condition. As the geomorphology of the river channel provides the physical template for river ecosystems, the geomorphology is a critical component of the integrated reference condition and the PES of a river. To date, efforts to establish a geomorphological reference condition (GRC) have been hampered worldwide by the inherently dynamic nature of river channels and, in South Africa, by the lack of geomorphological data for South African rivers. In order to determine the GRC for a river reach it is necessary to distinguish natural processes of change from those that are a result of human disturbance.

Geomorphological data on South African rivers are being collected in a systematic way as input to the River Health Programme and as a routine procedure during ecological Reserve assessments (King *et al.*, 2000; Rowntree & Ziervogel, 1999).

Data collection is based on a classification system developed through the WRC project K/497 (Rowntree & Wadeson, 1999). A geomorphological database is being developed at Rhodes University for storing and managing these data. This database has good potential to allow data analysis for determining the reference conditions for different river types and for classifying the present geomorphological status. Available data need to be collated and additional field data to be collected.

It was thought that the biomonitoring component of the River Health Programme would provide a good opportunity for building up the geomorphological database for rivers across the country. A prototype geomorphological index was developed by Rowntree and Wadeson (2000), but due to limited funding from the River Health Programme it has not been possible to develop the geomorphological index further through an analysis of the field data. Professional geomorphologists needed to be further involved in the River Health Programme in order to refine data collection methods and use the data to develop a geomorphological index that can inform managers as to the state of the nation's rivers. It was anticipated initially that the geomorphological index of river condition would be equivalent to the present ecological state (PES) for geomorphology that needed to be developed for application to the classification of a river reach for Reserve determinations. The parallel development of an integrated EcoStatus model lead to the development of a Geomorphological Driver Assessment Index (GAI) that could be applied to the assessment of the PES for geomorphology.

1.2 AIMS

The aims, as listed in the project proposal, are as follows:

- to establish a geomorphological database for South African rivers.
- to develop a method to determine the geomorphological reference condition (GRC) for a river reach. This was defined as the channel morphology that would be characteristic of a river reach under natural conditions and would provide habitat to support the natural fauna and
- flora. It is recognised that this morphology can change in response to the inherent variability of natural systems.
- to develop guidelines for classification of the present geomorphological state (PGS).
- to refine the geomorphological index for the biomonitoring programme.

1.3 APPROACHES TAKEN

Geomorphological data were collected using a standard format developed by Rowntree and Wadeson (2000) as part of the River Health Programme. Data collection was undertaken at as many biomonitoring sites across the country as was feasible given the time, personnel and financial constraints of the project. These data were stored in a database developed at Rhodes University. This database formed the basis for further analysis.

Development of a method to determine the reference condition was to be based on the approach similar to that used by Rosgen (1998) (Chapter 2 of this report) in which characteristic channel morphologies would be predicted from reach variables such as gradient and valley form. The initial approach of this project was to classify river reaches in terms of their zonal gradient classes (see Rowntree *et al.*, 2000) and assess whether channel morphology and dominant bed material could be accurately predicted using channel gradient (see Chapter 3). If common groupings could be found for undisturbed 'reference' sites, it would then be possible to gauge how far a 'disturbed' reach was removed from its reference condition. If the gradient did not accurately predict the morphology and/or bed material of the reach, it would be assumed that an alteration from reference had occurred. However, while using the data collected at available sites within the RHP, convincing relationships that could be used to define reference condition remained elusive (see Chapter 3). It was decided that a different approach with more of a systems focus would be taken. This new approach and its application are developed in Chapters 4 & 5.

Guidelines for assessing the present geomorphological state were developed in association with a project initiated in 2003/2004 (Project no 2003-046) as a DWAF/RQS study in collaboration with IWR S2S (Thirion & Kleynhans, 2003). The aim of this project was to develop an integrated EcoStatus model to address the need for an integrated EcoClassification system. Geomorphology was considered to be a key component of this model as one of the systems drivers, along with hydrology and water quality.

The approach to assessing the PES for geomorphology crystallised as a result of collaborative model development. One output from this project has been a series of rule-based models that are collectively know as Assessment Indices. The model for geomorphology is termed the geomorphology driver assessment Index (GAI). This model should also become the geomorphological index for use in the biomonitoring programme. The process of index development and guidelines for its use are given in Chapter 4.

The format of the final GAI is such that the data requirements had to be modified from those initially recommended for the biomonitoring programme by Rowntree and Wadeson (2000). Although it is possible to transfer data between the two systems, it is not a straight forward process and requires expert interpretation. This has meant that the compilation of the database was been delayed until the data requirements for the GAI stabilised. The framework for the database is now in place, but data input is an ongoing process.

CHAPTER 2
CONCEPTUAL BASIS FOR THE GEOMORPHOLOGICAL REFERENCE CONDITION – A REVIEW OF RELEVANT LITERATURE

2.1 GEOMORPHOLOGICAL CHANGE

The central aim of the project has been to improve our assessment of the extent to which human impacts have changed rivers from their natural condition. The measurement and understanding of geomorphological change presents many challenges to the researcher as well as the river manager. Much has been written about river channel process, form and change. River channels are dynamic *systems* and, as such, adapt in response to various stimuli at different spatial and temporal scales, even though they may retain an overall stability or dynamic equilibrium status.

A river may be seen as having various degrees of freedom that constitute the parameters which may be altered in a fluvial system. These are accepted by many as including the river's velocity, slope, flow depth, planform and width (Hey, 1974, cited in Gregory, 1977). Although these degrees of freedom may be acknowledged in theory, the establishment of cause-effect relationships with regards to alteration of these parameters is difficult. This difficulty arises from the complex interrelationships of a myriad independent and dependent variables across space and time.

As has been highlighted by White (1971), at any one time relationships between variables exist and may potentially be defined. If a true picture of a river and its functioning is to be achieved, it is necessary to compare the conditions of these variables over a period of time. Hence, the study of change implies a necessity to consider timescale in all its complexity. After all, as stated by Thornes (1977), the phenomenon of change can only be recognized over time, resulting in one's perception of change being temporally conditioned. In terms of analysis of the physical structure of river channels this poses a problem in terms of human timeframes and our associated paradigms. It must be acknowledged that although rivers are physical systems operating in the present time, they also have unique and extensive histories that cannot be disregarded if current river processes are to be understood (Knighton, 1984). In the context of river management, however, the focus tends to be on spatial and temporal scales at which human impact may significantly alter river form and process.

In theory, changes to a river system may be viewed as autogenic or allogenic, although in reality these conditions are not always easily differentiated. Autogenic changes are those inherent within river systems and involve channel migration, cut-offs, and so on. Allogenic changes are brought about by external factors such as altered discharge or sediment load (Lewin, 1977). In the literature, autogenic and allogenic changes have also been referred to as intrinsic and extrinsic changes respectively (Schumm, 1980). River management should aim to differentiate between these types of change, and focus on the role which human impact plays in the initiation of allogenic/extrinsic change.

According to Thornes (1977), there are two main problems associated with identifying cause and effect (process-form relationships) in river systems (particularly in the context of commonly used hydraulic geometry relationships). These are, firstly, the issue of indeterminacy of response, also termed system "singularity" or "uniqueness" (whereby channels have many different ways of responding to the same stimulus for change) and its converse, the equifinality problem (whereby different change stimuli can produce similar results). It has been eloquently stated by White (1971, p.71) that: "if there is any conclusion that springs from a comparative study of river systems, it is that no two are the same. Each river is distinctive in characteristics of basin and flow. And rare are the streams that, regardless of size, are homogenous within their own drainage areas". Secondly, it has to be borne in mind that channel changes are transient in nature, making it difficult to know whether what is observed at the present time is the end product of a change process (though such an "end product" is, in itself, likely to be a dynamic situation), or whether the river channel is still on a path of change which will produce different results.

2.2 THE REFERENCE CONDITION CONCEPT

In order to analyse change, it is often necessary to compare a present and/or altered condition with an initial or reference condition. In the context of natural systems this comparison is exceedingly difficult, particularly where initial or reference conditions are unrecorded and, hence, often unknown. Various practitioners in different disciplines have addressed channel change and, recently, the idea of the reference condition. Some of the concepts and ideas expressed in the literature will be briefly reviewed in the following sections with the aim of placing the concept of a geomorphological reference condition, particularly for South African river reaches, in context.

It is an increasingly common trend for river managers to develop/design management strategies according to a "design with nature" (McHarg, 1969) approach whereby development of river basins is undertaken with as much understanding as possible of how a system would function naturally (King, *et al*, 2000). An example is the goal of controlling releases from impoundments in such a way as to emulate the natural flow regime as far as possible (e.g. King, *et al*., 2000).

To facilitate management decisions, it is necessary to devise some method of separating the human impacts from natural channel changes, that is to identify a "benchmark" condition (or, more likely, range of conditions) which reflects the natural state of the river system. This reference condition can then be used as a "standard" or "control" against which modified streams and/or predicted impacts due to development may be compared, rated in terms of condition, and then effectively managed.

2.3 INTERNATIONAL APPLICATION OF THE REFERENCE CONDITION CONCEPT

In the USA, there have been at least two projects/studies undertaken in terms of the establishment of reference conditions. The Montana Department of Environmental Science formed a reference condition subgroup in 1999, the mission of which is to "coordinate reference condition activities that can be used to assess Montana water bodies, and act as a clearinghouse or repository for reference data" (Apfelbeck, 2001). This group has defined the reference condition as characterizing "the 'full potential' of a water body to function or support aquatic life" or as representing "the natural range of conditions for water bodies that have minimal human disturbances". The reference condition is based on data collected for a number of sites which fall into the same region and have similar geomorphology, and tend to be some of the least disturbed sites in a particular ecoregion. At the reference sites, the following types of data are collected (Apfelbeck, 2001):-

- physical structure and habitat (e.g. bankfull width, channel cross-section, pebble counts, percent fines, flow, woody debris)
- water temperature, and water column and sediment chemical parameters
- biological data to characterize the algae, macroinvertebrates and fish communities
- riparian vegetation community data
- contaminants in fish tissue, etc.

(It should be noted that these data are site specific and, as such, do not take account of the catchment context).

These reference data are then used to deduce a range of conditions that could be expected for a particular water body (water bodies within the same region are grouped according to the ecoregions in which they lie, as well as geomorphological similarity). Similar data for non-reference sites within that water body are then collected and it is envisaged by Apfelbeck (2001) that the comparison of these with the reference or expected data will allow the establishment of decision criteria

"to determine the condition, level of impairment, or ability to function of a particular water body, set restoration targets for impaired water bodies, assess the effects of a particular activity on water quality and assess best management practices" (Apfelbeck, 2001, p. 1).

This project is still in the initial stages and there is, to date, limited feedback available. What seems to be the strength of this approach is the integration of various disciplines in the formulation of an overall range of reference conditions based on data collected at various sites. The acknowledgement of the necessity for ranges rather than set and finite conditions is important due to the dynamic nature of stream variables.

Also in the USA, Rosgen (1998) addressed the reference reach concept in the context of geomorphology. He defines the reference reach as "a portion of a river segment that represents a stable channel within a particular valley morphology". This definition is intended to include reaches that are not "pristine" or "relic" reaches, as pristine reaches are very rarely found. An assessment of stream condition or state (i.e. stability) is determined in level III and verified in level VI of Rosgen's (1994,1996) geomorphological classification (Rosgen, 1998).

Rosgen (1998) recommends that data on morphology and discharge (where gauging stations are present) collected at reference sites are converted to dimensionless ratios which can be used to extrapolate data to ungauged, disturbed and/or unstable reaches in similar valley types. This is done in order to ascertain what conditions should be present, and to guide river managers in terms of restoration, stream enhancement, stabilization and stream naturalization projects (Rosgen, 1998). This so-called "stable reference reach approach" is thought to be effective in setting realistic management goals due to its ability to integrate independent and dependent variables of a system by the use of the above-mentioned ratios. Although this approach seems sound in theory, the very definition of a "stable" river channel poses complex challenges due to the inherently dynamic nature of river systems.

Another potential approach noted by Rosgen (1998) is to model sediment transport as accurately as possible and then back-calculate reference conditions with regards to effective discharge, depth and slope. However, it must be acknowledged that the effects of any significant error in the sediment model may lead to incorrect deductions being made, and therefore to erroneous steps being taken in terms of management. Significant errors are highly likely when one considers that no sediment model is, in fact, an accurate representation of reality.

In Canada, the National Water Research Institute (NWRI) has fostered the adoption of the "reference condition approach" to water management. Like Montana's reference condition subgroup, the NWRI aims to establish a database of unimpacted sites. The environmental and biological attributes of these sites will thus be known and these will be used to design various predictive models which aim to match certain environmental variables to corresponding biological conditions. The idea is that when a set of environmental parameters is entered into one of the predictive models, the model will output the "ideal" biological parameters for the site. These can then be compared to what is actually found, facilitating the establishment of the "health" of the test site (Environment Canada, 1999). This approach seems flawed in that it does not appear to acknowledge that the health of a river can be judged according to its abiotic as well as its biotic factors; i.e. the approach assumes the "health" of the physical environment (e.g. the geomorphology) to remain constant whilst the biota adjust independently of this. In reality, where the physical environment (which is often impacted by human activity) forms the template upon which ecosystems exist and function, this is obviously not always the case. Notwithstanding this, a biomonitoring program which focuses on benthic invertebrates has been undertaken over three years at 250 "reference sites" which fall into as many different stream orders and ecoregions as possible. Measured variables, which are mainly abiotic, include water analyses for suspended solids, total [P], [N] and major ions, riparian vegetation, canopy cover and channel slopes. Reference conditions have been established for both the Great Lakes and the Fraser River basin (Environment Canada, 1999).

The Scottish Environment Protection Agency has addressed the establishment of biological reference conditions and the setting of class boundaries as per the European Union (EU) Water Framework Directive (Owen, no date). The Water Framework Directive (WFD) states that "the establishment of reference conditions is required to provide a 'baseline' against which to measure the effects of past and present human activities upon each water body. Specifically, reference conditions must enable the effects of human activities on aquatic ecosystems to be distinguished from natural 'background' variation" (Owen, no date, p.1).

Because the WFD relates to reference conditions of all water bodies in the EU (i.e. not solely river systems), the issue of typology is important. The directive states that water bodies should be classified into types and sub-types on grounds of their hydromorphological and physico-chemical attributes. Reference conditions for these attributes should then be established for a particular surface water body type at "high ecological status", along with the associated biological reference conditions. High ecological status is defined as a condition wherein there are "no, or only very minor, anthropogenic alterations to the values of the physico-chemical and hydromorphological quality elements for the surface water body type from those normally associated with that type under undisturbed conditions" and "the values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion" (Owen, no date, p. 1).

According to Owen (no date), it is implied by the WFD that it should be possible to predict the biological reference conditions for a water body from the physical and chemical factors that define its type. The RIVPACS classification system for benthic macroinvertebrates in the UK adopts this approach in that it predicts what assemblages of invertebrates should be present at a site according to its physical and physico-chemical characteristics. However, Owen questions the validity of what he terms a "single predictive typology" on grounds of the fact that "the reference condition for any biological quality element is likely to be a range of values reflecting the natural variation that biological communities show from one location to another and over time". It would thus seem that in order to detect changes which result from human impact, and to differentiate these from natural variations, a very large number of water body types would have to be defined, which would detract from the logistical practicality of the exercise (Owen, no date).

These debates aside, the WFD defines three general procedural approaches to deriving reference conditions, depending on the availability of data, summarized by Owen (no date) as follows:-

- The establishment of reference condition can be either spatially based (an existing site/network of sites which are of high ecological status) or based on modelling, or a combination of these.
- Reference conditions based on modelling can be derived using either predictive models (e.g. RIVPACS) or hind-casting using historical, palaeolimnological and other available data.
- Where it is not possible to apply these methods, expert judgement may be used to establish reference conditions.

The process for establishing reference conditions in EU rivers as described in the WFD may be divided into five main steps (Owen, no date):-

1. Develop a typology for rivers in the member state.
2. Minimize types required where there is high biological variability by developing sub-typologies, where necessary, including site-specific methods.
3. Set pressure criteria for determining "very minor" disturbance.
4. Decide which general approach to use for identifying potential reference conditions dependent on the current state of disturbance and the availability of data.
5. Evaluate variables' classification methods against a given list of criteria

The strength of the approach of the WFD is that it takes into account the importance of the reference conditions of both biotic and abiotic variables and that it outlines a uniform approach for the EU region whilst allowing for flexibility according to circumstance and availability of necessary data. It also stresses the need for regular reviewing of reference conditions established due to the anticipated influence of climate change and other variables which cannot reasonably be address in the context of river basin management.

The Cooperative Research Centre for Catchment Hydrology, together with the Land and Water Resources Research and Developmental Corporation in Australia, has released a rehabilitation manual for Australian streams (Rutherfurd *et al.*, 1999). In this manual it is stated that there is an assumption that "by assisting stream managers to return the physical character of a stream (including water quality and quantity) to as close to its pre-European condition as possible…this will encourage, or accelerate the recovery of the native biological communities in the stream." (Rutherfurd *et al.*, 1999, p.16). This alludes to the reference condition concept.

It is advised in the "*Rehabilitation Manual for Australian Streams*" that if there is a lack of knowledge regarding the rehabilitation goals for a river reach, a similar but stable reach in the same system should be sought and copied. It is also stated that, when trying to understand the condition of a river (particularly with regards to biological communities), one should look for the limiting requirement which is defined as "that resource which is essential to the stream community, but is most lacking from the environment" (Rutherfurd *et al.*, 1999).

With regards to human impacts on river reaches, Rutherfurd *et al.* (1999) stress that the following needs to be appreciated:-

1. natural disturbance is important in streams
2. human influence has added new disturbances and has altered the frequency and impact of many natural disturbances
3. severe disturbance will reduce complexity, which will reduce ecological diversity
4. after disturbance, streams will gradually recover complexity
5. once a disturbance has ceased, streams will gradually recover "equilibrium", which may or may not be the same as the pre-disturbance equilibrium state.

It is important to note that if and once reference conditions have been established for a stream, and whilst these may give an indication as to the "state-of-the-river", they may not constitute viable goals for rehabilitation efforts. In terms of aiming for maximum ecological diversity, it may often be more beneficial to gain an understanding of the natural recovery process which is underway and to aid this process, hereby increasing the recovery rate. The rate at which stream morphology and, therefore, related biotic components will recover after a disturbance depends on the stream power, sediment supply, frequency of large floods and riparian vegetation in the system (Rutherfurd *et al.*, 1999). Biological recovery, on the other hand, depends on the presence of appropriate environmental conditions in the project area, a source of animals or plants to recolonize the area, the rate of population growth and the nature of the disturbance (Rutherfurd *et al.*, 1999). Biological recovery is often quicker than geomorphological recovery, though the initiation of biological recovery may depend on an improved geomorphological status and, conversely, biological recovery in terms of vegetation will aid geomorphological recovery. It must be borne in mind that disturbances caused by human action are often enduring ones that do not cease. This may stifle the natural recovery process.

2.4 THE REFERENCE CONDITION CONCEPT IN THE SOUTH AFRICAN CONTEXT

The increasing water requirements of the South African population have necessitated the alteration of the flow regimes of most of the country's rivers by the construction of inter-basin transfer schemes and impoundments. In addition to these direct channel impacts, there is also evidence of extensive anthropomorphic change in most of the country's catchments as a result of land-use change, flood protection strategies and urban development. These alterations to South African catchments and their channels have resulted in new water and sediment regimes in the nation's rivers, and hence a net change in their geomorphological and ecological status.

At a legislative level, the South African National Water Act No. 36 of 1998 includes the concept of the Reserve. The Reserve is divided into two parts. These are, firstly, the basic human needs reserve, i.e. the "quantity and quality of water required for basic human use" and, secondly, the ecological Reserve which refers to "the quantity and quality of water required to protect the aquatic ecosystems which are the base of the water resource" (O'Keeffe, 2000, p. 41). The latter has been translated by practitioners into the concepts of the Instream Flow Assessment (IFA), the Instream Flow Requirement (IFR) and, most recently, the Enviornmental Water Requirement (EWR). The reader should note that the terminology related to these concepts changes regularly. The IFA is a process undertaken by a group of specialists in relevant fields in order to produce an IFR or EWR which is presumably a representation of the natural flow regime that should be maintained in any particular river system or reach in order to ensure the ecological Reserve.

Although methodologies differ, the idea of controlling altered flow regimes in an attempt to mimic natural or reference conditions as closely as possible is one that exists across the globe.

The building block methodology (BBM) was the first standard methodology to be developed to support the determination of environmental water requirements for the ecological Reserve (Tharme, 2000). This methodology established the concept of the present ecological state whereby certain habitat and ecological parameters are given scores on grounds of their condition relative to their "reference condition". This largely theoretical reference condition is assumed to be what the relevant ecosystems and their habitats would be like in the absence of anthropogenic interference. According to the BBM, the present ecological state (PES) was, in turn, used to decide upon an appropriate ecological management class (EMC) for the relevant site (King, *et al.*, 2000). This concept of establishing a PES in relation to a reference condition prevails in a modified form in current methodologies (Kleynhans *et al.* 2005). Thus, methods are needed for establishing both ecological and habitat (or geomorphological) reference conditions.

As part of the National River Health Programme (NRHP), which aims, amongst other things, to report on the state of South Africa's rivers in relation to natural conditions, the ecological reference condition project was undertaken. Dallas (2000) documents the theoretical basis and processes involved. The project was initiated in response to a need for an "established benchmark with which monitoring information can be compared" (Dallas , 2000, p.1), which was expressed by various role players in the NHRP's biomonitoring process.

The ecological reference condition is defined as "the condition that is representative of a group of least impacted or minimally disturbed sites organized by selected physical, chemical and biological characteristics" (Reynoldson *et al.*, 1997, cited by Dallas, 2000 p. 2). This condition is used as a standard by which conditions of test sites may be assessed.

According to Dallas (2000), there are two types of reference condition, namely site-specific and regional. On the one hand, site-specific reference conditions are often used in a paired site scenario whereby a monitoring site is compared to one other site either upstream or downstream of it. Regional reference conditions, on the other hand, are based on measurements at various sites within homogenous zones. This homogeneity may be acknowledged at a relatively coarse level (e.g. ecoregions) or at a finer and, supposedly, more accurate level (e.g. geomorphological zones or river types). In cases where all sites in a particular region or zone are significantly impacted, reference conditions are often established according to the best attainable sites or are derived from historical data or ecological models (Dallas, 2000).

Internationally, there are two main approaches to deriving ecological reference conditions, namely the multimetric approach and the multivariate approach (Dallas, 2000). If the multimetric approach is selected, sites are classified according to geographic and physical attributes such as climate, physiography, geology, soils and vegetation, as well as additional variables, e.g. stream size, hydrologic regime, elevation and natural riparian vegetation. Sites are then designated to homogenous zones and it is assumed that test site characteristics should, ideally, match the conditions of the reference sites in that zone (Dallas, 2000). The multivariate approach, by comparison, does not make assumptions regarding the similarities of biological communities at different sites based on either physical or chemical attributes. Instead, sites are classified by multivariate analysis of fauna and then probabilities of sites belonging to each of the groups of reference sites are calculated. The biomonitoring programmes RIVPACS and AusRivAS followed in the United Kingdom and Australia, respectively, make use of the multivariate approach (Dallas, 2000).

The approach used in South Africa to date is a regional, multimetric one whereby homogenous zones are delineated and test site conditions are assessed against reference conditions established for each zone.

"Least-impacted" reference sites are selected within these spatial units with the aid of land-use maps, local knowledge and expert knowledge of previous workers at certain sites (e.g. researchers, DWAF officials), field work is undertaken and ecological reference conditions are thus established.

2.5 THE CONCEPT OF THE GEOMORPHOLOGICAL REFERENCE CONDITION IN RSA

It has been shown above that, in the South African context, significant progress has been made in the development of procedures and methods for the identification of the PES for certain biotic components. However, there is not, to date, an established method for determining the geomorphological reference condition. The geomorphological processes at work in an area have been acknowledged as important factors in determining the structure and functioning of riverine ecosystems due to their influences on channel form and substrates as a result of erosional and depositional forces (Rowntree, 2000).

Homogenous zones required for the establishment of ecological reference conditions are largely delineated according to geomorphic parameters. The problem, however, is that the use of largely independent variables such as climate, geology and soils for this delineation can give the impression that the geomorphological template on which the ecosystems being analysed exist is unchanging and inherently stable. This, however, is far from being true. Anthropogenic impact alters water and sediment regimes in drainage basins, thus altering aspects of their physical habitats such as substrate, channel dimensions and channel dimensions. This, in turn, will have far-reaching impacts on the channel biota.

It is necessary to assess the overall reference condition for a site in order to set its management objectives. To this end, it is necessary for the condition of biotic communities as well as their habitats to be ascertained. Work in this regard has been undertaken abroad (e.g. Rosgen, 1998) and is currently being undertaken in South Africa.

Progress has been made in terms of geomorphological classification and zonation (see Rowntree & Wadeson, 1999; Rowntree *et al.*, 2000). It is thus possible to group rivers and river reaches in a regional or longitudinal manner according to their morphological similarities (see table 2.1). By making use of available historical data and empirical data, it was hoped that reference sites may be identified, reference conditions (which may be in the form of ranges) established in terms of form and process, and judicious management decisions may be facilitated.

2.6 CONCLUSION

The usefulness of the reference condition concept has been acknowledged by river managers worldwide. A summary of the international approaches to deriving reference conditions, as discussed in this chapter, is presented in Table 2.2.

Identifying reference conditions represents an attempt to understand and quantify the degree to which river systems have *changed* as a result of human activity, and to design and implement effective conservation and rehabilitation strategies. Discerning reference conditions for river reaches is confounded by the complexity of river systems and the elusiveness of clear cause and effect relationships between many variables at a range of spatial and temporal scales.

In South Africa, approaches to ascertaining river health as well as studies undertaken to calculate the EWRs for river systems rely on the derivation of reference conditions for a number of river components which includes geomorphology.

Significant progress has been made in terms of geomorphological classification in South Africa (Rowntree & Wadeson, 1999), which is the first step towards derivation of reference conditions. The remainder of this document is dedicated to exploring the practicalities of deriving geomorphological reference conditions and assessing the PGSs for South African rivers.

Table 2.1 Geomorphological Zonation of River Channels (after Rowntree and Wadeson, 1999)

Longitudinal zone	*Macro-reach characteristics*			*Characteristic channel features*
	Valley form	*Gradient class*	*Zone class*	
A. Zonation associated with a 'normal' profile				
Source zone	*V10*	*not specified*	*S*	*Low gradient, upland plateau or upland basin able to store water. Spongy or peaty hydromorphic soils.*
Mountain headwater stream	*V1, V3*	*> 0.1*	*A*	*A very steep gradient stream dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades.*
Mountain stream	*V1, V3*	*0.04 - 0.99*	*B*	*Steep gradient stream dominated by bedrock and boulders, locally cobble or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool, Approximate equal distribution of 'vertical' and 'horizontal' flow components.*
Transitional	*V2, V3, V4, V6*	*0.02 - 0.039*	*C*	*Moderately steep stream dominated by bedrock or boulder. Reach types include plain-bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited flood plain development.*
Upper Foothills	*V4, V6*	*0.005 - 0.019*	*D*	*Moderately steep, cobble-bed or mixed bedrock-cobble bed channel, with plain-bed, pool-riffle or pool-rapid reach types. Length of pools and riffles/rapids similar. Narrow flood plain of sand, gravel or cobble often present.*
Lower Foothills	*V8, V10*	*0.001 - 0.005*	*E*	*Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may be bedrock controlled. Reach types typically include pool- riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent than rapids or riffles. Flood plain often present.*
Lowland river	*V4, V8, V10*	*0.0001-0.001*	*F*	*Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering pattern within a distinct flood plain develops in unconfined reaches where there is an increased silt content in bed or banks.*

Table 2.1 (continued) Geomorphological Zonation of River Channels (after Rowntree and Wadeson, 1999)				
B. Additional zones associated with a rejuvenated profile				
Rejuvenated bedrock fall / cascades	*V1, V4*	*>0.02*	*A/B/Cr*	*Moderate to steep gradient, confined channel (gorge) resulting from uplift in the middle to lower reaches of the long profile, limited lateral development of alluvial features, reach types include bedrock fall, cascades and pool-rapid.*
Rejuvenated foothills:	*V2, V3, V4, V6*	*0.001 - 0.02*	*D/Er*	*Steepened section within middle reaches of the river caused by uplift, often within or downstream of a gorge; characteristics similar to foothills (gravel/cobble bed rivers with pool-riffle/ pool-rapid morphology) but of a higher order. A compound channel is often present with an active channel contained within a macro channel activated only during infrequent flood events. A limited flood plain may be present between the active and macro-channel.*
Upland flood plain	*V8, V10*	*< 0.005*	*Fr*	*An upland low gradient channel, often associated with uplifted plateau areas as occur beneath the eastern escarpment.*

Table 2.2 Summary of International Reference Condition Concepts

Country	Author/ Department	Programme/ Approach	Definition of Reference Condition	Outline of Approach	Site Selection	Variables Monitored
USA	Montane Dept. of Environmental Science (reference condition group)		a) the condition that represents the 'full potential' of a water body to function or support aquatic life b) the natural range of conditions for water bodies that have minimal human disturbance.	1) Deduce range opf conditions that could be expected for a particular water body. 2) Collect similar data for non reference sites within that water body. 3) Comare these with the reference data. 4) Establish decision criteria to determine the health of a particular water body. 5) Set restoration targets, assess the effects of certain activities on water quality and assess management practices	Lease disturbed sites in particular ecoregion with similar geomorphology.	Bankfull width, channel cross-section, pebble counts, percent fines, flow, woody debris; water temperature; water column and sediment chemical parameters. Biological data to characterize the algae, macroinvertebrates and fish communities; riparian vegetation community data; contaminants in fish tissue.
USA	Rosgen (1998)	'Stable reference reach approach'	A reference reach is a portion of river segment that represents a stable channel within a particular valley morphology.	1) Data collected at reference sites. 2) Data converted to dimensionless ratios. 3) Data extrapolated to ungauged, disturbed and/or unstable reaches in similar valley types. 4) Data used to guide river managers in terms of restoration, stream enhancement, stabilization and stream naturalization.	Sites selected to represent a variety of valley types.	Morphology, discharge.
Canada	National Water Research Institute (NWR)		Sites un-impacted by human activity.	1) Environmental and biological attributes of reference sites used to design predictive models which match environmental variables to corresponding biological conditions. 2) Models output the 'ideal' biological parameters for a given site. 3) 'Ideal parameters' compared to what is observed. 4) 'Health' of the test site is established.	Undisturbed sites selected by ecoregion.	Biomonitoring using benthic invertebrates. Water analysis for suspended solids, total [P], [N] and major ions' riparian vegetation, canopy cover; channel slopes.
Scotland	Scottish Environment Protection Agency	European Union (EU) Water Framework Directive (WFD)	Condition that reflects no, or "very minor", anthropogenic alterations to natural physico-chemical, hydromorphological and biological quality elements for a surface water body type.	1) Develop a suitable river classification system. 2) Set pressure criteria for determining 'very minor' disturbance. 3) Decide which general approach to use for identifying reference conditions dependent on the current state of disturbance and the availability of data. 4) Evaluate variables against a given list of criteria.	Dependent on choice of classification system.	Dependent upon general approach selected to identify reference conditions.
Australia	Cooperative Centre for Catchment Hydrology with the Land and Water Resource research and Development Corporation	Rehabilitation manual for Australian streams	A similar but stable reach in the same system as a reach being rehabilitated.	If there is a lack of knowledge regarding the rehabilitation goals for the river reach, a similar but stable reach in the same system should be sought and copied. Once reference conditions have been established for a stream, these may give an indiocation as to the 'state-of-the-river' but they may not constitute viable goals for rehabilitation efforts.	Similar but stable reach in the same system as given study reach.	Project specific.
South Africa	DWAF	EcoStatus models	The condition that is representative of a group of least impacted or minimally disturbed sites organized by selected physical, chemical and biological characteristics.	1) Homogenous zones delineated. 2) Test site conditions assessed against reference conditions for each zone.	Sites selected according to ecoregions and geomorphological zones.	Water quality (biomonitoring of macroinvertebrate communities); morphology; riparian vegetation; fish assemblage data.

CHAPTER 3
AN EMPIRICAL APPROACH TO DETERMINING THE REFERENCE CONDITION FOR SOUTH AFRICAN RIVERS

3.1 INTRODUCTION

The following objectives were adopted to arrive at the geomorphological reference conditions for South African river sites:

1. Define what is meant by "reference condition" in terms of geomorphology.
2. Collect data for a wide range of field sites and compile into a geomorphological database.
3. Categorise channel characteristics according to the zone classes proposed by Rowntree *et al*. (2000).
4. Test the hypothesis that reach characteristics can be predicted from the reach drivers gradient and stream power.
5. Assess the effect of human induced disturbance on the above relationships.
6. Make recommendations for determining the reference condition of a river reach.

3.1.1 Define what is meant by "reference condition" in terms of geomorphology

The concept of reference condition has been discussed at length in Chapter 2. For the purpose of this chapter, the definition of reference condition that was adopted was "the channel morphology that would be characteristic of a river reach under natural conditions and that would provide habitat to support the natural fauna and flora." (see section 1.2) The spatial unit for which the reference condition is determined is the reach, defined as *a length of channel within which the local constraints on channel form are uniform, which has a characteristic channel pattern and degree of incision, and within which a characteristic assemblage of channel morphologies result from the combined effects of erosion and sediment deposition.* Rowntree and Wadeson (1999) used significant changes in channel gradient (a 50% increase based on 20 m contours on a 1: 50 000 map) as the primary desk-top identifier of reach boundaries.

3.1.2 Collect data for a wide range of field sites and compile into a geomorphological database.

In an effort to make the findings of this project relevant to existing river management programmes and frameworks within South Africa, a decision was taken at the project Steering Committee meeting held early in 2003 that data would be collected primarily at Sites selected for the National River Health Programme (NRHP).

This was to ensure the representation of geomorphology within the programme and to fill in gaps in river data across the country. These data were to be complied into a database that would eventually link with the Rivers Database of the NRHP.

3.1.3 Categorise channel characteristics according to the zone classes proposed by Rowntree *et al.* (2000)

According to Rowntree *et al.* (2000), reaches in the same zone should display similar morphological features (Table 2.1). Reaches were grouped into zone classes and then analysed within these groups to ascertain whether trends were evident in terms of reach type and dominant bed material.

3.1.4 Test the hypothesis that reach characteristics can be predicted from the reach drivers gradient and stream power

The zonal classification of river geomorphology proposed by Rowntree *et al.* (2000) has been used by geomorphologists to guide the determination of reference condition for study sites used in EWR determinations. This is based on the premise that the reach gradient plus position on the river long profile can be used to predict the natural channel morphology. The zonal classification system presented by Rowntree *et al.* (2000) was based on a limited data set backed up by the experience of South African river ecologists. This project gave the opportunity to test and modify the original zonal classification based on a much larger data set.

If gradient and streampower are key drivers of reach geomorphology it should be possible to predict the reach morphology from these two variable alone. Analyses were therefore carried out to explore these relationships for the available data set.

3.1.5 Assess the effect of human induced disturbance on the above relationships

If reach gradient, or its derivative – zone class – is to be useful as a predictor of reference condition, it follows that the channel morphology of an impacted river should deviate from the morphology characteristic of the zone class.

In cases where gradient was not an adequate predictor of reach type and bed material, the impact class was checked to ascertain whether human impact may have led to morphological change.

3.1.6 Make recommendations for determining the reference condition of a river reach

Following the data analyses, recommendations were made for determining the reference condition for a river reach. For a number of reasons, it was concluded that the approach adopted in this project was not sufficient to resolve the issue of reference condition. The underlying philosophy of the reference condition concept with respect to geomorphology was re-evaluated. This re-evaluation is in part reflected in the assessment of the present ecological state for geomorphology (Chapter 4) and is explored in depth in Chapter 5.

3.2. DATA COLLECTION

The researchers involved in this project have, over a number of years, assessed over 200 sites either as part of the NRHP or in conjunction with EWR determinations. The majority of these sites were visited during the first two years of this particular project. Various data have been captured with the aid of standardized field forms (see section 3.2.1). In addition, a desktop study of these sites was undertaken. This chapter presents methods employed in the collection and analysis of both field and desktop data. It should be noted that although the term "site" is used, and specific co-ordinates are given for each site, wherever possible data was recoded only after the reach (as opposed to one particular point) had been walked and assessed.

3.2.1. Field Data

Field forms

The design of a standardized field form intended to guide workers in the collection of geomorphological data at river sites had begun before this particular project commenced (Rowntree and Wadeson, 2000). This form has since undergone a series of modifications in response to criticisms from NRHP field workers who had found the requirements for data collection impractical in terms of data both time and the level of skills or training needed. If the geomorphological database is to be expanded on an ongoing basis as part of the River Health Programme, it is important that the relevant field form be "user friendly".

[It should be noted that data collection forms have since been modified further due to a change in data format required for the assessment of the PES within the newly developed Ecostatus framework (Chapter 4)].

Table 3.1 Definitions of Impact Classes "A" to "F"

CLASS	Geomorphological change	Anthropogenic Indicators
A: unmodified natural	no changes, erosion and deposition within reach are in balance	No human impacts identified in the catchment
B: largely natural	short term changes that can be reset within the frequency of the 'bankfull' flood.	Human impacts identified, but no clear evidence of channel response
C: moderately modified	slow trajectory of change, can be reset within five to ten 'bank full' events by restoring natural flow/ sediment regime and bank stability	Significant human impacts, changes to bed structure evident, localised bank erosion and channel widening, or deposition and narrowing. Changes reversible in the short term.
D: largely modified	well into the trajectory of change, may be difficult to restore natural conditions; river adjusting its form to the current sediment load and flow regime.	Major human impacts resulting in significant long term changes to channel geometry, pattern or reach type that may be irreversible.
E: seriously modified	engineering intervention required for rehabilitation	Channel structure largely engineered, but bed perimeter includes some natural materials that can be worked by fluvial processes (includes gabions, engineered bank stabilisation, channel straightening or re-alignment, bulldozing.
F: critically modified	major engineering intervention required for rehabilitation	Totally engineered channel, no natural material in the channel perimeter

The final version of the field form as used in this project for collecting data at River Health Sites is presented in Appendix 1. The form aids the collection of field, which is augmented by data that are collected as part of a desktop study. The data collected in the field reflect river channel characteristics as well as human impacts on the channel and riparian zone geomorphology.

Data collected in terms of dominant bed materials, reach type and human impacts were of particular importance to the approaches outlined for this project (see section 3.1). The impact matrix (section 6 of the data form) is used to estimate the impact class (A to F) of a particular site (Table 3.1).

Site Selection

The majority of sites used in this study were part of the RHP monitoring network. In addition, sites selected for EWR studies were included. Thus, practitioners in disciplines other than geomorphology had selected many of the sites prior to the commencement of this project (see Section 3.2.3). Some additional sites were selected by the project researchers in an effort to ensure that sites were distributed across as large an area of the country as possible. Data collection is ongoing. However, for the purposes of this report, a set of data pertaining to 150 sites located across South Africa has been considered (see Figure 3.1).

The majority of these sites were in the eastern half of the country because this is where the River Health Programme was most active.

Data Reliability

Because four different workers collected the field data over an extended period of time, and because the data are largely qualitative in nature, it is acknowledged that the chance for discrepancies in interpretation of features exists. In addition to this problem, flow conditions encountered at sites are not always conducive to accurate geomorphological assessment (e.g. flood conditions) and accessibility is often limited due to safety issues (e.g. sites located within the Kruger National Park) or relief.

In an effort to ensure that discrepancies in interpretation were avoided as far as possible, the three chief field workers (Rowntree, Wadeson and du Preez) undertook two of the main field trips together and assessed as many sites as possible simultaneously. Interpretations were compared and discussed in order to align approaches and mindsets as far as possible.

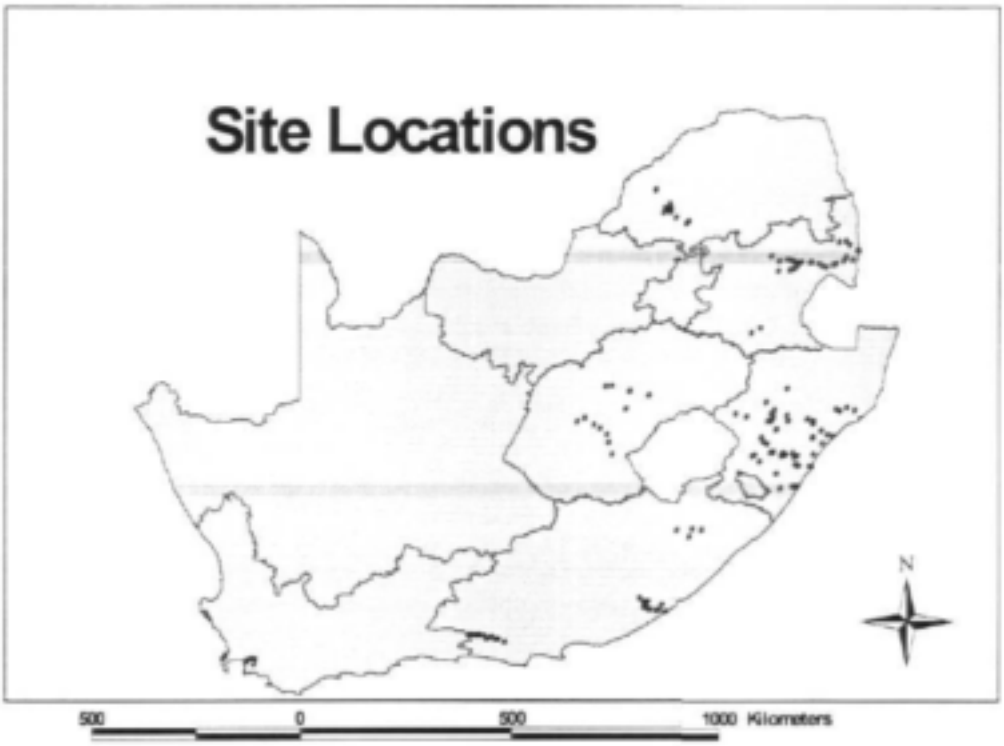

Figure 3.1 Site Location Map

To ensure that data collected were interpreted and analysed in context, a section pertaining to data reliability was included as sections 4 and 5 of the field form (see Appendix 1). These sections indicate how accurately bed conditions and morphological units could be assessed as well as how long a segment of the channel was assessed (i.e. to what degree the site assessed has been viewed "in context" by the field worker concerned). These precautionary measures allow an assessment of the level of confidence in the data.

Data Representivity

It is difficult in advance of a survey such as this to determine what would constitute a representative sample of river sites in terms of geomorphology. The field survey contributed to our knowledge of what kind of river channels are encountered in South Africa, as well as what human impacts are most common in South African river systems. For this reason, it was important that sites were visited across as large an area of the country as possible within the time span of this project. As the database has expanded, gaps in the data set have been identified and provide the incentive for future data collection.

The main way in which sites were grouped was by channel gradient. It is acknowledged that the lower gradient river channels have been far more extensively assessed than have the steeper headwater type streams. There are also large areas of the country that have not yet been assessed. This affects the validity of conclusions from the findings. The augmentation of the database is intended to be ongoing as related projects and programmes are undertaken across the country.

3.2.2 Desktop Data

Data Required

The two key variables used to represent reach drivers were channel gradient and stream power. Channel gradient was estimated for both the site and the reach within which the site was situated. The site gradient was calculated as the gradient between the immediate upstream and downstream contours, where gradient is change in height divided by channel length. To calculate the reach gradient it was necessary to first identify the reach boundaries. A section of the channel extending upstream and downstream of the site was digitised from the 1: 50 000 topographic sheets using the ArcView GIS package. The position of contours was noted so that the gradient between contour intersections could be calculated. Reach boundaries were identified where the gradient increased in either the upstream or downstream direction by 50 % or more. The reach gradient was calculated as the difference in height over the length of the reach (from the contours) divided by the length of the reach. Channel gradient was used to assign the reach to a zone class according to Table 2.1.

Stream power is a measure of the total amount of energy available for geomorphological work. Stream power is calculated as follows:

$$\Omega = \rho\, g\, Q\, S_o$$

where ρ = water density, g = gravitational constant, S_o= energy slope (water, bed), Q = discharge.

Stream power is thus seen to be a function of discharge and channel gradient. An important question is "what discharge?". Dollar and Rowntree (2002) in their review of dominant discharge concepts explained how geomorphologists have commonly used a single discharge to represent the suite of floods that are together responsible for achieving gemorphological work and the resulting channel morphology. One index of dominant discharge that has been adopted by geomorphologists is the mean annual flood (MAF). This is a convenient measure due to the fact that hydrologists have derived statistical models for estimating the MAF as input to regional flood analyses. Mkhandi and Kachroo (2001), in their regional flood frequency analysis for southern African, subdivided South Africa into regions for which the MAF could be estimated from the catchment area using an empirically derived equation. This set of equations was used to estimate the MAF for each of the sites in the geomorphological study.

Quaternary catchment area was derived from the WR90 database. Total upstream catchment areas were calculated in the software programme SPATSIM by Prof. Denis Hughes of the Institute for Water Research (IWR).

3.3. DATA ANALYSIS

The data analysis was designed to test the following three objectives:

1. Categorise channel characteristics according to the zone classes proposed by Rowntree *et al.* (2000).
2. Test the hypothesis that reach characteristics can be predicted from the reach drivers, gradient and stream power.
3. Assess the effect of human induced disturbance on the above relationships.

3.3.1 Categorise channel characteristics according to the zone classes proposed by Rowntree *et al.* (2000)

Sites were grouped according to the zone classes given in Table 2.1. Most sites fell within the lower foothills and upper foothills classes. Less than ten sites were classified as lowland rivers and less than ten as transitional and headwater stream combined. Further analysis was therefore confined to the two classes of foothill sites.

For each group of sites, a profile was developed to show the frequency distribution of sites by a) reach type and b) dominant bed material.

3.3.2 Test the hypothesis that reach characteristics can be predicted from the reach drivers gradient and stream power

Scatter graphs were drawn to test the hypothesis that a) reach type and b) dominant bed material can be predicted from gradient and/or the mean annual flood. Sites were first grouped by reach type, then for each group a scattergram was drawn to show the location of sites in relation to gradient and MAF. If the reach type could be predicted between by gradient alone, all sites within one reach type should have grouped within a narrow gradient band, irrespective of the MAF. If streampower was a better predictor, sites should have grouped along a line of equal stream power that connects sites with a low gradient, but high MAF, with sites with a high gradient, but low MAF. Lines of equal stream power should discriminate between different reach types if plotted on the same diagram.

3.3.3 Assess the effect of human induced disturbance on the above relationships

Outliers from the above relationships were examined in terms of the level of human impact. Data were viewed in spreadsheet format. Where site characteristics were not correctly predicted by zone class, that site's impact class was checked to ascertain whether human impact could have significantly altered channel morphology.

3. 4. RESULTS

3.4.1 Categorise channel characteristics according to the zone classes proposed by Rowntree *et al.* (2000)

Mountain Headwater Streams

Only 9 sites within this zone class were assessed. Of these, 5 were bedrock or boulder dominated, two were cobble dominated, one was gravel dominated and one was sand dominated. All 5 of the sites that were dominated by bedrock or boulders displayed the predicted cascade or step-pool reach type. The sand dominated site can be considered as an outlier due to the fact that it was a steep section located within a reach of much lower gradient. It was also awarded a "D" impact rating, which may indicate that impacts have changed its morphology somewhat.

Mountain Streams

Of the 6 sites assessed in this gradient class, 5 were dominated by bedrock or boulders, as was predicted by Rowntree *et al*. (2000). The sixth site was sand dominated, but had an impact rating of "D" which may explain this. The number of sites is too small to allow meaningful generalizations to be made.

Transitional Streams

Four sites were classified as transitional. Two of them were mixed channels and two were alluvial. Their reach types were classified as plane bed, pool-riffle and pool-rapid and they had mixed bed material. This is to be expected in transitional streams, but the small number of sites does not allow generalizations to be made.

Upper Foothill Streams

Sixty upper foothill sites were assessed. The majority of sites displayed pool-riffle morphology as can be seen in Figure 3.2.

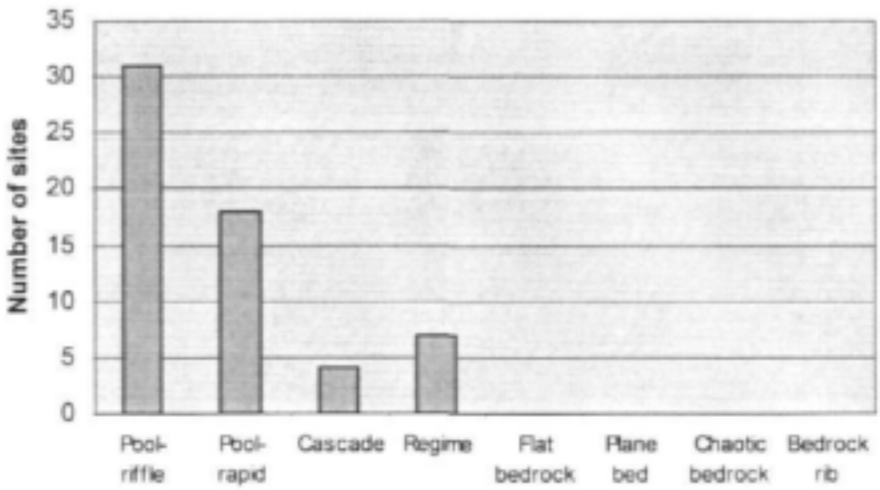

Figure 3.2 Reach Morphology of Upper Foothill Sites

Twenty four sites were dominated by bedrock, 9 by boulders, 18 by cobble, and 9 by gravel and/or sand. The percentages of dominant bed materials are illustrated in Figure 3.3.

Lower Foothill Streams

Sixty-five upper foothill sites were assessed. The majority of sites displayed pool-rapid morphology as can be seen in Figure 3.4. Forty-two sites were dominated by bedrock, 4 by boulders, 7 by cobble, and 9 by gravel and/or sand. The dominant bed materials are illustrated in Figure 3.5.

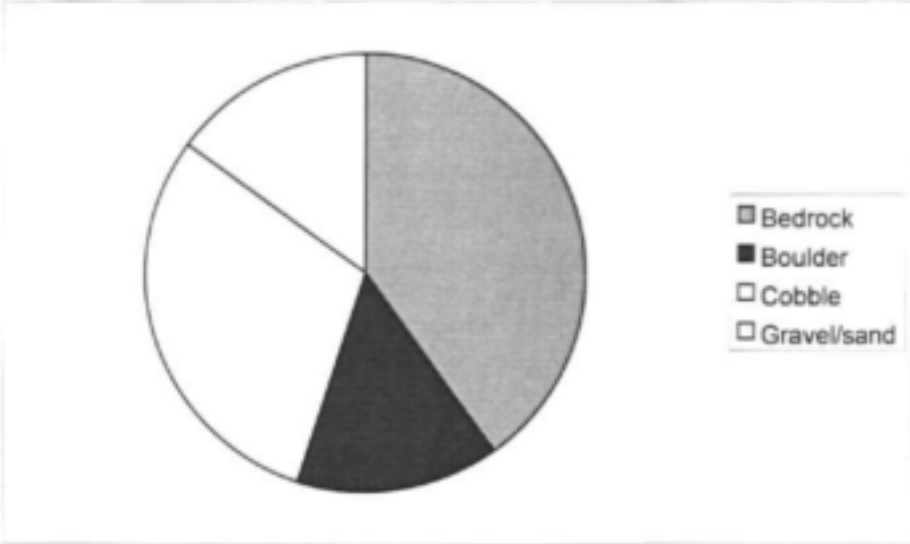

Figure 3.3 Dominant Bed Materials of Upper Foothill Sites

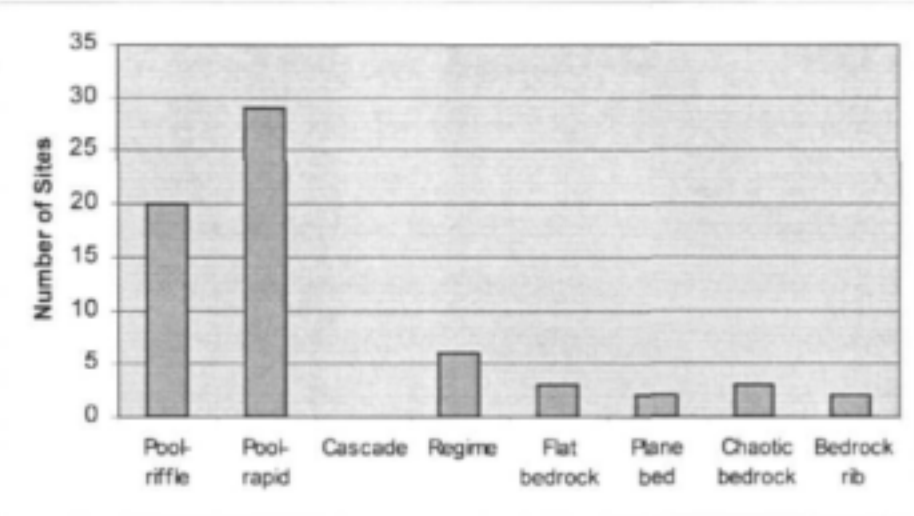

Figure 3.4 Reach Morphology of Lower Foothill Sites

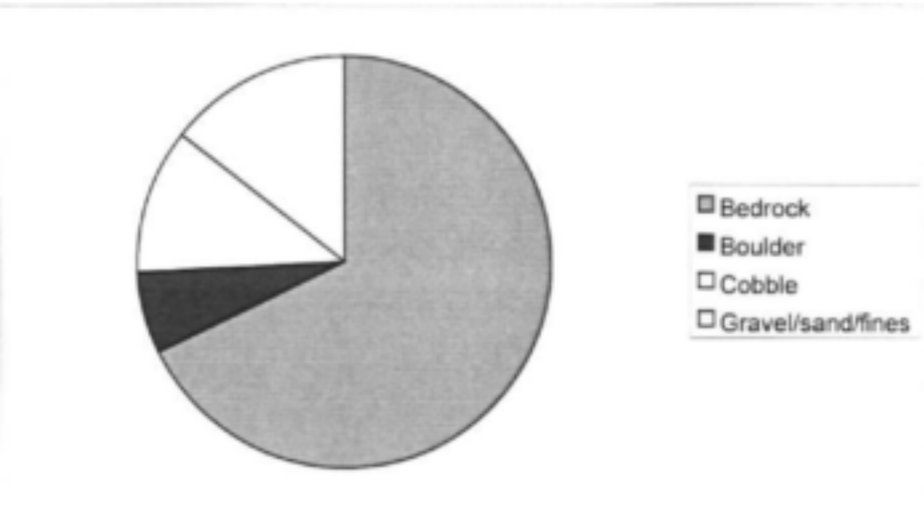

Figure 3.5 Dominant Bed Materials of Lower Foothill Sites

Lowland Rivers

Nine lowland river sites were assessed. Six of these were dominated by bedrock, one by cobble and two by sand. Four sites displayed pool-riffle morphology, two pool-rapid morphology, one bedrock fall morphology and two regime morphol

3.4.2. Testing the Validity of Gradient and Stream Power as Predictors of Channel Characteristics

Comparison of Site and Reach gradients

For each of the sites, reach gradient as well as site gradient were calculated. A comparison between site gradients and reach gradients is presented in Figure 3.6. It is interesting, but perhaps expected, that there is less discrepancy between site and reach gradients as gradient decreases. Overall, reach gradients and site gradients were not significantly different (i.e. for most sites, bot site and reach gradients fell into the same gradient/zone class). Site gradient was used in further data analyses as field data was site specific and not necessarily representative of the reaches within which sites fell.

A stream-power approach to predicting channel characteristics

For each of the reach types that were represented by at least 3 sites in the sample, a scatter plot was drawn in order to gauge the combined effect of discharge and gradient (i.e. the effect of stream power) on the occurrence of these different channel types.

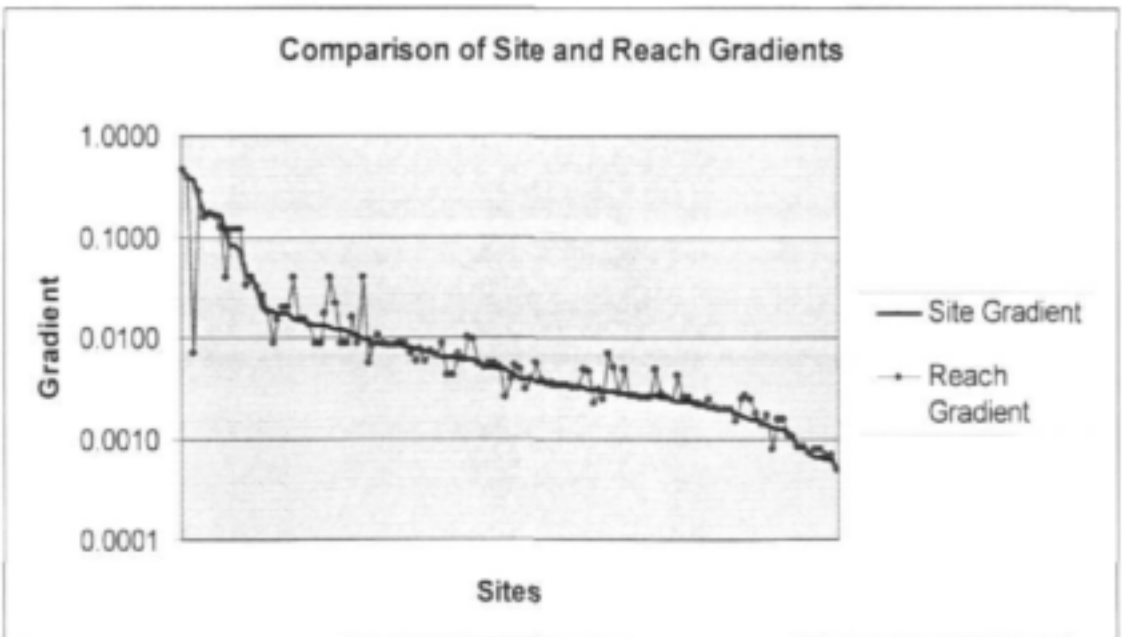

Figure 3.6 Comparison of Site and Reach Gradients

If gradient alone is important, each reach type should cluster within a narrow gradient range that is distinct from the range for other reach types. If stream power is important then the same reach type should be found at lower gradients for higher discharges and vice versa. The results are presented in Figure 3.7. A similar analysis was completed to determine whether discharge, gradient and stream power can be used to explain the occurrence of dominant bed materials. The results of this second analysis are presented in Figure 3.8. These graphs do not indicate that either gradient or streampower can be used to discriminate between the different reach types or dominant bed materials. Some patterns can be identified, however.

Cascade reaches are only found at gradients characteristic of the upper foothills zones and above while plain bed reaches were limited to gradients characteristic of both upper and lower foothill reaches. Pool-riffle reaches were found across all gradients, but were concentrated in the higher gradients of the upper foothill zones, whereas pool-rapid reaches were more likely to occur at lower gradients, in lower foothill zones. Suprisingly, regime reaches were found at all gradients including those of the mountain stream zone. This may reflect a classification error as regime reaches by definition are found exclusively in sand-bed and fine gravel-bed rivers; sand bed rivers were restricted to gradients below 0.008 (see below). Chaotic bedrock reaches were confined to the bedrock 'anastomosing' reaches of the lowveld rivers.

The overwhelming majority of sites contained a dominant bedrock component or were cobble bed streams. This in part reflects the predominance of bedrock in South Africa rivers, but also is a result of a sampling bias towards site with large mobile substrate that is preferred for SASS sampling. Bedrock in various combinations with other substrate classes was found across the gradient range. The only substrate class that showed a more restricted range was sand, which was found only at gradients below 0.008.

3.4.2. Qualitative Assessment of Human Impact

For each of the sites, human impact was qualitatively assessed with the aid of an impact matrix (section 6 of the field form that is presented in Appendix 1) and the site was placed within an "impact class" between A (unimpacted sites) and F (most severely impacted sites) (Table 3.1).

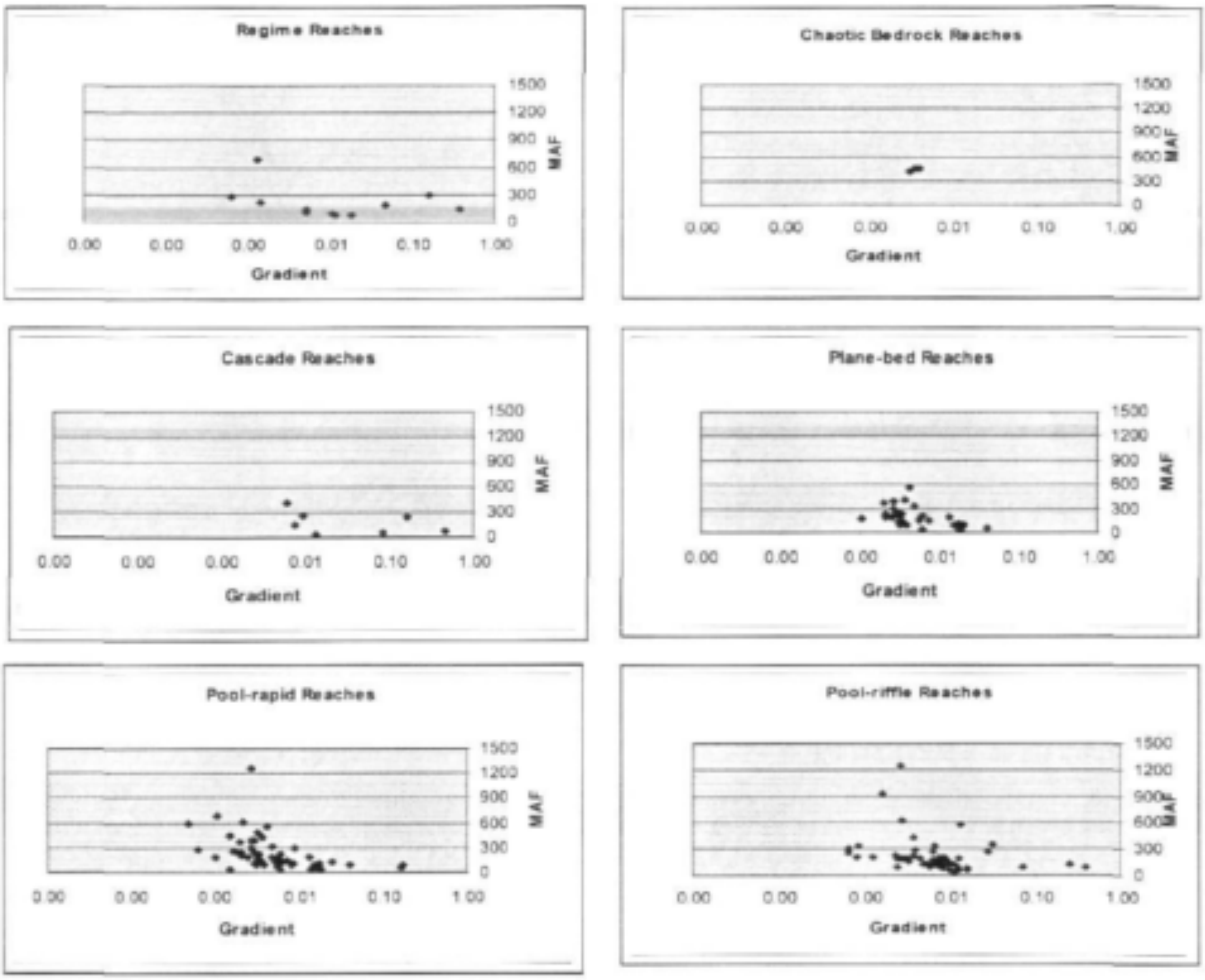

Figure 3.7. Distribution of sites in different reach types in relation to Mean Annual Flood and gradient

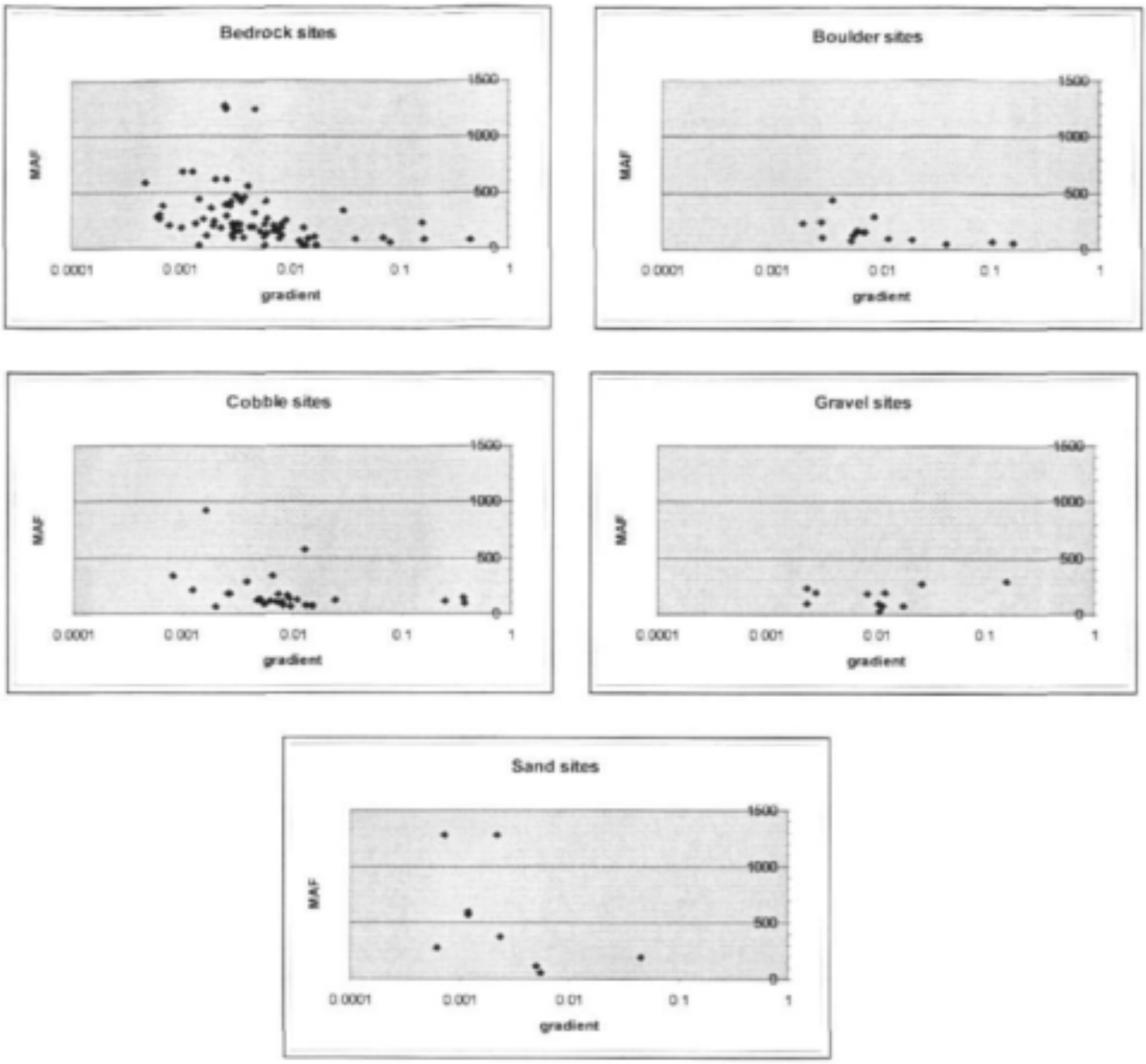

Figure 3.8. Distribution of dominant bed material in relation to Mean Annual Flood and gradient

The number of sites that fell into each impact class is presented in Figure 3.9. It can be seen that the majority of the sites fall into classses "C" and "D" and a smaller but significant number in impact class “B”. It can be seen from Table 3.1 that only impact class D is likely to have been affected to the extent that either the reach type of the dominant bed material would have changed. These are the sites that are therefore not expected to be representative of reference condition.

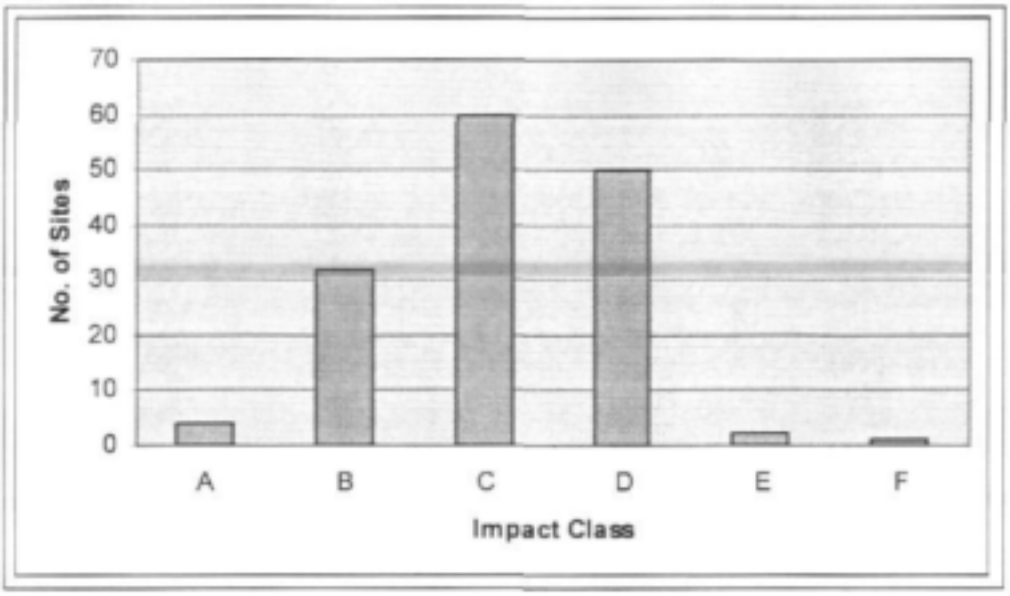

Figure 3.9 Number of Sites in each Impact Class

3.5. DISCUSSION

3.5.1. Introduction

The results of the analysis of site morphology do not reveal significant trends that can be used to derive a method by which to identify geomorphological reference conditions for South African river systems. An alternative approach to determining the reference condition is therefore suggested in Chapters 4 and 5.

3.5.2. Discussion of Findings

Categorise channel characteristics according to the zone classes proposed by Rowntree et al. (2000)

The only two zone classes in which there were enough sites to perform data analysis were the upper foothill and lower foothill classes. It is interesting to note that the upper foothill sites were dominated by pool-riffle morphology, whilst the lower foothill sites were dominated by pool-rapid morphology. Both groups displayed a strong bedrock influence, but this was, surprisingly, more prevalent in the lower foothills class.

Although the number of sites representing other geomorphological zones were limited, the results did confirm that mountain headwater streams and mountain streams were characterised by bedrock and boulder channels with cascade and step-pool morphology. Lowland rivers had a surprisingly high bedrock component (six out of nine reaches).

The above results indicate that many of South Africa's rivers tend towards a supply limited condition in their lower reaches. This suggests that geomorphological processes are dominated by floods with a high stream power and transport capacity exceeding the sediment supply.

Test the hypothesis that reach characteristics can be predicted from the reach drivers gradient and stream power

There are no clear indications from the analysis of the 150 sites that either gradient or streampower can be used to indicate reach type or the dominant bed material. Although river zones identified according to gradient classes may tend towards a particular channel morphology, there is considerable variability within any one zone that masks any predictive relationship. There is no indication of a streampower threshold that can be used to identify reaches that might be vulnerable to change should there be a shift in streampower in a manner analogous to that identified by Leopold and Wolman for meandering and braided channels (Leopold & Wolman, 1957).

Assess the effect of human induced disturbance on the above relationships

According to the qualitative impact matrix used to gauge the level of human impact at each of the sites assessed, the majority of the sites are classified as being in impact classes C and D (moderately and largely impacted, respectively). They cannot therefore be considered to be in their reference condition. However, this assessment has gauged the severity of human impact simply by noting what types of impact are present at each site. It has not taken into consideration the inherent resistance or resilience of a site to impact or change. Of the sites surveyed, 52% were found to be bedrock influenced. This is not necessarily an indication of the amount of bedrock influence in South African river channels. Once again, site selection is likely to have influenced this outcome as sites are often selected on grounds of accessibility. This often results in the inclusion of causeways, bridges, dams or weirs in assessment reaches. Many of these features are constructed where there is localized bedrock as it offers stability to the structures. Thus, the selection of bedrock-influenced reaches is indirectly favoured. It should be borne in mind that the same type of impact is likely to have very different effects on an alluvial channels and bedrock channels. Other factors such as valley form, lithology, catchment size and climate are likely to influence the way in which a given channel will respond to impacts or natural changes.

3.6 CONCLUSION

The findings obtained by taking the approach outlined in section 3.1 were not conclusive with respect to reference conditions. When grouped by gradient classes believed *apriori* to indicate the different river zones as given in Table 2.1, reaches falling in mountain headwater, mountain, upper foothill and lower foothill zones did conform to the expected channel morphology, but there was significant variability and overlap between zone classes. Given the available data, distinct channel morphologies cannot be ascribed to the reference condition for each zone class, but at the same time the evidence does not show the zone classes to be invalid. It is proposed that Table 2.1 can be used to give a first indication of the range of channel morphologies that can be expected in the different river zones. It also remains a valid framework for ecological studies. The search for ecological reference sites should be guided by the zonation framework, and comparison between ecological reference sites should take cognisance of their geomorphological classification. Guidelines for classifying site geomorphology are given in Chapter 4 (section 4.2.3).

Although the data analysis remained inconclusive with respect to the geomorphological reference condition, it did suggest areas that may be worthy of further investigation. It was proposed that a different approach be taken in the endeavour to define and describe geomorphological reference conditions for South African river sites. An alternative approach to arriving at the PGS was suggested. This new approach is presented in chapter 4. Chapter 5 presents alternative ideas pertaining to the concept of a reference condition and its relevance to geomorphological systems and their management.

CHAPTER 4
DEVELOPMENT AND APPLICATION OF THE GEOMORPHOLOGY DRIVER ASSESSMENT INDEX

4.1 INTRODUCTION

4.1.1 EcoClassification and the Development of Terminology

Legal requirements for the protection of water resources were introduced through the National Water Act of 1998. Methods for determining the ecological water requirement (EWR) for the ecological Reserve have been developed through the Resource Directed Measures (RDM) office of the Department of Water Affairs and Forestry. One requirement of the RDM is that the resource must be classified; one component of this classification is EcoClassification. At the start of the present reference condition project there was no standard set of methods in place to derive the EcoClassification for a river reach. To meet this need a study was initiated in 2003/2004 (Project no 2003-046) as a DWAF/RQS study in collaboration with IWR S2S (Thirion and Kleynhans, 2003). The aim of this project was "to devise a set of rule-based models to determine the present ecological state (PES) for various components and an integrated ecological river state (referred to as the EcoStatus)." (Kleynhans *et al*., 2005). The rule-based models focussed on developing a reliable and consistent method to determine the ecological categories for the present and future conditions of the river reach.

Terminology for EcoClassification has been developing in parallel with the present WRC project. An attempt is made here to clarify current terminology, as of July 2005.

EcoStatus describes the "totality of the features and characteristics of the river and its riparian areas that bear upon its ability to support an appropriate natural flora and fauna and its capacity to provide a variety of goods and services" (Iversen *et al.*, 2000). Kleynhans *et al.* (2005) modified this definition to take account of the proposition by Beechie *et al*. (2002) that assessment of the EcoStatus based directly on the biological response, using biological indicators, can be used to identify where ecosystem functions have been impaired, and may suggest causes of impairment.

The EcoStatus is assessed in terms of two groups of components: ecosystem drivers and biotic responses (Figure 4.1). The drivers include hydrology, water quality and geomorphology. The biotic responses include fish, invertebrates and riparian vegetation.

It is these responses that are used to derive the EcoStatus for the river reach. The status of each of the separate drivers is used to explain the EcoStatus value and suggest future trends.

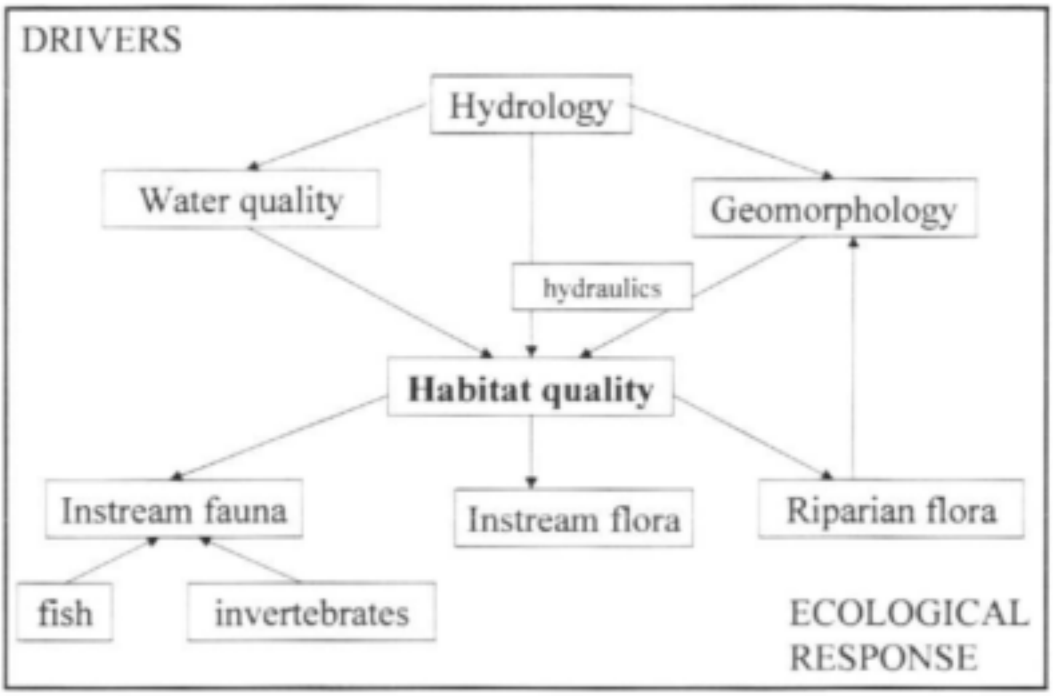

Figure 4.1 Driver-response model for an integrated river EcoStatus

Reference condition describes the condition of the site, river reach or other delineation and its biophysical components prior to anthropogenic change and is formulated for each component considered in EcoStatus determination (Kleynhans *et al.* 2005 p. 1-4). It provides the reference against which the present and future states can be compared.

The Ecological Category (EC) describes a state of the river. This may be the Present State or a Recommended State, or some other state. The generic description of these categories is given in Table 4.1.

The Present Ecological State (PES) of a river is an assessment of the degree to which the present river ecosystem has been modified from the natural condition, and the extent to which the health of the ecosystem may be compromised by the capacity of the river to provide the range of habitats, in an appropriate quantity and quality, necessary to support it. The PES is assessed for each component of the river in terms of the ecological categories given in Table 4.1.

Table 4.1 Generic descriptions of Ecological Categories (Kleynhans et al., 2005).

ECOLOGICAL CATEGORY	DESCRIPTION
A	Unmodified, natural.
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem functions are still predominantly unchanged.
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions have occurred.
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions are extensive.
F	Criticall/Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

The **Recommended Ecological Category (REC)** is the recommended condition of the river ecosystem towards which river management should aim. It is applied separately to each component as well as to the EcoStatus .

An **Assessment Index** is used to derive the EC for each component using a rule-based model; the model output is an assessment index that can be related directly to the ecological category as indicated in Table 4.1. The assessment index may either be a driver assessment index or a response assessment index. The Geomorphology EC is assessed using the **Geomorphology Driver Assessment Index (GAI)**.

This chapter describes the underlying principles and application of the GAI rule based model. This is an expanded version of the chapter to be published in the Manual for EcoStatus Determination (Kleynhans *et al*. 2005).

The process of developing the GAI has been ongoing for some years, with various versions being forthcoming. The prototype geomorphological index was published in 1999 (Rowntree and Ziervogel 1999) followed by a field guide in 2000 (Rowntree and Wadeson 2000). One problem with the early attempts to develop a geomorphological index was that it was done in isolation from the biotic indices. The EcoStatus project opened up the opportunity to work alongside the biologists and derive a model structure that was consistent between the groups of specialists. This meant reworking basic concepts so that the end product is quite different from the geomorphological index published in 1999.

Being a rule-based system, development has largely been a mental process, adapting the rules to best capture the geomorphological system in a structure that is logical and sensible to ecological practitioners. It is difficult to test such an index in an absolute sense as there is no reference against which to make judgements. The only real test seems to be "does it make sense?" The GAI as presented in this report is the end product of a series of indices that have been applied within the Komati EWR, the Kromme EWR, the Kat EWR and to assessing the impact of a proposed dam on the Kabouga. The GAI is the index that appears to "make the most sense" in terms of geomorphological processes and ecological response.

4.1.2 Geomorphology and River Ecosystems

The availability of suitable habitat is an important criterion for ecosystem health. Water quality, flow hydraulics and substrate are three important habitat components of aquatic ecosystems. These three components form the basis of the hydraulic biotope classification of Rowntree and Wadeson (1999). Channel morphology is an important habitat driver because it determines the distribution of water and its hydraulic characteristics (e.g. depth and velocity) at any given discharge. Sediment (in the form of clay, silt, sand, gravel, cobbles or boulders) or bedrock make up the morphological units and at the same time provide the substrate for vegetation and for aquatic fauna. Geomorphological processes drive channel morphology. Figure 4.1 (above) depicts these relationships in terms of system drivers (hydrology, water quality and geomorphology) and system response (aquatic/riparian fauna and flora). Riparian vegetation is shown as both a response and a driver. Vegetation, while a biotic component in its own right, also provides habitat for other species and acts as a control for many geomorphological processes. Geomorphology is thus one of the key drivers of river ecosystem processes and forms one of the three driver components of the EcoStatus model. For an introduction to the science of geomorphology and its place in the management of river ecosystems the reader is referred to the text by Freeman and Rowntree (2005).

The rule-based model developed to derive the geomorphological driver assessment index is used to derive the PES of the river reach within which a study site is situated.

Assessment of the PES ecological category requires that we compare the present condition of the river to its reference condition. We therefore need to begin by considering how best to assess the reference condition.

4.1.3 Determining the Reference Condition for the River Reach

The geomorphological reference condition (GRC) was defined in Chapter 1 as the channel morphology that would be characteristic of a river reach under natural conditions and would provide habitat to support the natural fauna and flora. The problems inherent in identifying the reference condition for channel geomorphology have been discussed at length in Chapter 2. The data analysis presented in Chapter 3 shed little light on suitable methods for achieving this difficult task. There are thus a number of problems associated with determining a geomorphological reference condition, where the definition of the GRC is phrased in terms of channel morphology and available habitat. An alternative is to take a systems approach to defining reference condition, which recognises geomorphological processes as drivers of the ecological system. We have therefore have adopted the following definition.

> *The geomorphological reference condition is the geomorphological system that supports the natural ecosystem, where a system is a set of components connected through flows of energy and matter to accomplish a set function.*

Given this definition, the PES for geomorphology is assessed in terms of system changes that impact on flows of energy and matter, as well as changes to factors that may affect the system's resistance or resilience to change. Channel morphology is seen as the dynamic and indeterminate product of the geomorphological system.

4.1.4 The Nature of Geomorphological Systems

In the geomorphological system, energy takes the form of gravitational energy (hillslopes) and kinetic energy (streamflow), while matter is comprised of sediment that is derived from the hillslopes and is transported through the river channel. Storage of sediment within the system is largely responsible for creating channel morphology. Flows of energy and matter within the geomorphic system are shown in Figure 4.2.

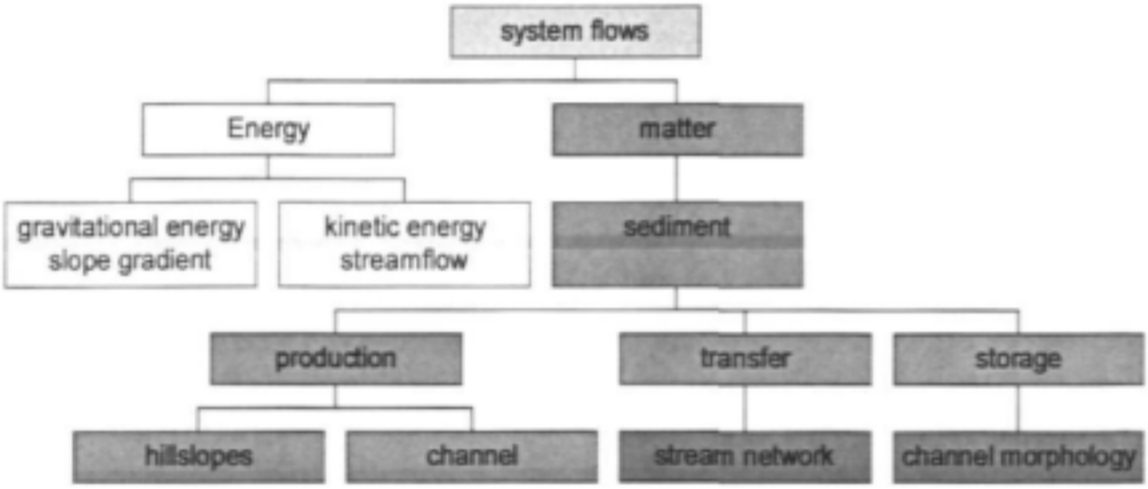

Figure 4.2 Flows of energy and matter within the geomorphological system

Connectivity is a key indicator of geomorphological system health. Connectivity allows the free flow of energy and materials through the system and, as a result, mutual adjustment between system components. Connectivity is counterbalanced by storage sites, which allow material to be retained in the system. The PES of a river can therefore be evaluated with respect to both increases and decreases in connectivity. Connectivity within the geomorphic system is shown in Figure 4.3.

There are three main scales of **connectivity** recognized within river systems. The first scale relates to the interface between hillslopes and the drainage network (hillslope-channel), the second to longitudinal connectivity within the drainage network itself, and the third is connectivity at the reach scale. At this last scale there may be changes to (a) longitudinal connectivity that cause energy changes within the reach (e.g. due to the presence of a weir), (b) between the channel and the flood plain or riparian zone and (c) between the surface of the channel bed and the underlying sediments. This latter component is termed vertical connectivity.

The second important indicator of geomorphic system change relates to the **sediment budget** for the specified reach. Changes to the reach sediment budget result from an adjustment to the balance between **sediment delivery** to the channel and the capacity of the stream flow to transport that sediment. Both increased or decreased catchment erosion and a change in hillslope-channel coupling will affect sediment delivery.

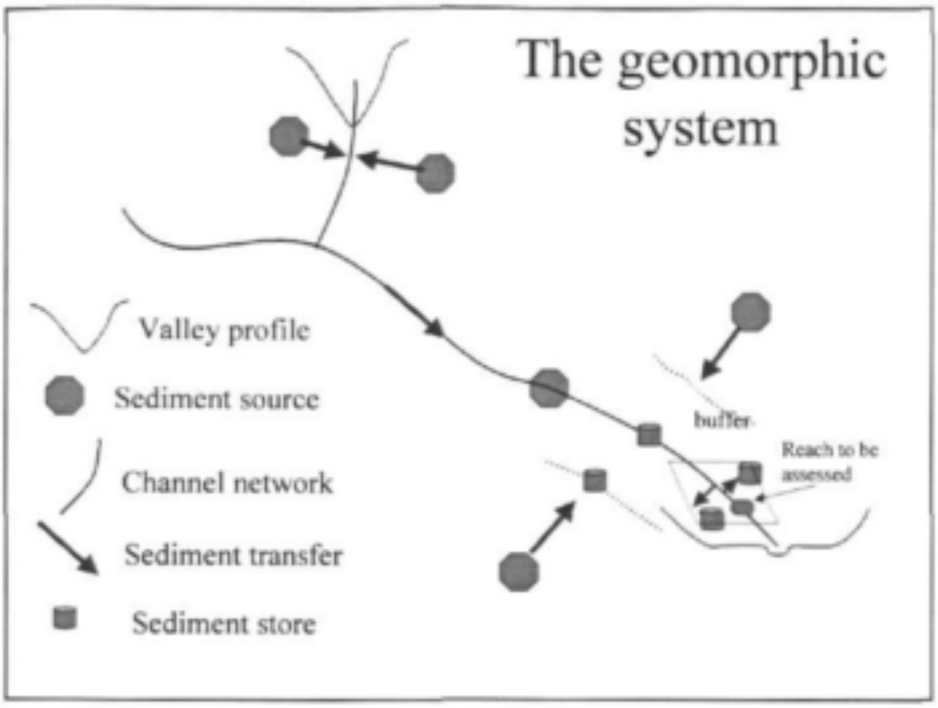

Figure 4.3 Connectivity within the geomorphic system

Changes to the magnitude and frequency of flood events will change the capacity for sediment transport. The reach sediment budget is to some extent a reflection of changes to the extent and severity of hillslope or channel bank erosion; it is also a reflection of the change in connectivity and the effective catchment area for sediment supply (Fryers *et al.*, in prep).

Channels can be classified as **transport-limited** or **supply-limited**. The channel is said to be transport-limited if the supply (including sediment in storage in the reach) is greater than the long-term transport capacity of the flows. The result is a true **alluvial channel** with a morphology adjusted to the magnitude and frequency of flows (the effective discharge) conveyed through it. If, however, the supply of material within the competence of the effective discharge is less than the transport capacity, the channel is said to be supply-limited. The result will be a **bedrock-controlled channel** or a channel in which the size of the bed material exceeds the competence of 'normal' floods (i.e. those with a return period of between one to five years). **Mixed channels** also exist where alluvial and bedrock sections alternate. Whether a channel is supply- or transport-limited will affect its **resistance** and **resilience** to change. Bedrock channels are resistant to change but alluvial channels are more resilient.

The third indicator of system change is change to the **resistance of the perimeter** to erosional forces. Resistance to erosion is related to the size, cohesiveness of the **sedimentary material** or extent of bedrock and the effectiveness of the **vegetation cover**. Resistance factors can be applied separately to the **channel bed, channel banks, in-channel bars** and the **out-of channel flood zone**.

The last system component is the **channel morphology** itself. Channel morphology provides the direct link to river habitat. Unfortunately changes to channel morphology over geomorphological time are often difficult to assess. Channels are dynamic features and morphological change is the result of the cumulative effect of a sequence of flood events. It is difficult to know over which temporal scale to assess morphological change. Change also occurs at a number of different spatial scales ranging from the **bed material** and **bed structure** to the **channel cross section** (defined in terms of width and depth) to the **channel planform** (e.g. sinuosity, secondary channels), including the longitudinal pattern (e.g pool-riffle sequences). Each of these spatial scales is linked to temporal scales of change and impacts can be considered to be more severe and more permanent as the spatial scale increases.

4.2 GUIDELINES FOR ASSESSING THE PRESENT ECOLOGICAL STATE FOR GEOMORPHOLOGY

4.2.1 Introduction

Following from the definition of Reference Condition given in section 4.1.3, the PES for geomorphology is assessed in terms of changes to the geomorphological system, rather than changes to morphology and habitat *per se*. The PES is assessed firstly in terms of system changes that impact on flows of energy and matter, that is changes to system connectivity and the sediment budget, secondly in terms of changes to factors that may affect the system's resistance or resilience to change, and thirdly in terms of observed changes to morphology and associated habitat components.

The assessment of the PES (geomorphology) is based on a set of four metric groups, that relate to change within the geomorphic system:

To what extent has the capacity of the geomorphological system to support the natural ecosystem been degraded due to the following?:

- System connectivity
- Sediment balance
- Resistance of the channel to change
- The channel morphology

The steps required to run the GAI model for assessing the PES are set out as follows:

- Data collection format (4.2.2)
- Classification (4.2.3)
- Weighting metric groups (4.2.4)
- Rating degree of change by metric group (4.2.5)
- Assigning confidence levels (4.2.6)
- Assessing the proportion of change that is flow related (4.2.7)

4.2.2 Data collection format

Data for assessing the PES are collected in accordance to the guidelines given below in sections 4.2.3 to 4.2.5. Examples of the standard data collection format are given below (Figures 4.4, 4.5, 4.6, 4.7, 4.8, 4.10). These show data that was collected at a site on the Kat River in the Eastern Cape.

Two types of data are collected:

- **classification data**, which allow channel typing, and can be used to guide the assessment of reference channel type.
- **condition assessment data**, which are used directly to assess the PES.

All data from the field forms are transcribed directly into a spreadsheet that automatically calculates the scores for the individual components, the final PES score, the overall confidence rating and the proportion of the change that is considered to have been affected by changes in flow. Data are transcribed into two worksheets: Classification and PES Data. The remaining worksheets contain the separate components of the rule-based model. These worksheets should not be altered by the data recorder.

4.2.3 Classification

The classification of channel geomorphology is carried out according to the guidelines presented by Rowntree and Wadeson (1999). An example of a data sheet is given in Figure 4.4.

Site details

The first data block is largely self evident. Data are required to identify the site, its location and the recorder.

The channel gradient is normally estimated from the contours on a 1: 50 000 map. The distance along the channel between the two contours upstream and downstream of the site is measured. The gradient is calculated as

$$\frac{\text{vertical height (i.e 20m)}}{\text{distance (m)}}$$

Channel classification

Channel classification is carried out according to three components: channel pattern, channel type and reach type.

Channel pattern relates to the number of channels (single-thread or multiple-thread) and the sinuosity. Sinuous channels show clear meanders within the valley floor sediments, straight channels follow the line of the valley floor. Note that the valley floor itself may be sinuous, but the channel may be considered straight.

Channel type is classified according to channel perimeter materials. Channels formed predominantly in bedrock are separated from those formed in alluvial sediments. Mixed channels include alternating sections of bedrock and alluvium. This channel type is common in South Africa. Channel type is then classified according to the dominant bed material (normally the largest 'common' size class)

Reach type depends firstly on channel type. The different reach types commonly found in South African rivers are described in Table 4.2 and Table 4.3.

Morphological Units

Morphological units are the channel components that are most closely associated with habitat. The composition and arrangement of morphological units determine the flow hydraulics at any given discharge, that is, the distribution of depth and velocity across the stream bed. Morphological units also provide the substratum for organisms. These habitat units, characterised by particular combinations of depths, velocities and substratum, are known as hydraulic biotopes. Morphological units are identified separately for bedrock and alluvial sections. Descriptions of different morphological units are given in Tables 4.4 and 4.5.

Channel confinement

The last component that must be completed in the classification data sheet refers to channel confinement. This is a measure of the ability of the channel to shift its position laterally. It is also a measure of the degree of coupling between the hillslope and channel. Confinement is related to the configuration of the valley floor with respect to the adjacent hillslopes.

A rating of 5 is ascribed to the least confined system which is a wide flood plain. The lowest rating is given to a narrow V-shaped ravine in which the channel fills the full width of the valley floor. A channel that is incised into alluvial terraces is given a relatively high rating (2) as the active channel is confined within the macro-channel banks.

GEOMORPHOLOGICAL DATA SHEET: CLASSIFICATION

RIVER SYSTEM	Kat	RECORDER	Leanne/Kate
RIVER	Kat	DATE	7 02 05
SITE	K1	LAT	32 57002778
QUATERNARY CATCHMENT	Q94B	LONG	26 72191667
MAP REFERENCE	3226DA	ALTITUDE	640
		GRADIENT	0 00628

CHANNEL CLASSIFICATION

Channel pattern	single thread, straight	single thread		multiple thread			
		sinuous	straight	sinuous	straight		
Reach type	mixed pool-rapid	bedrock			mixed or alluvial		
		bedrock fall	bedrock cascade	flat bedrock	pool-rapid	pool-riffle	plain bed
		pool-rapid			step-pool	flat bed	regime
Channel type (select ONE from each row	mixed boulder		bedrock	mixed	alluvial	fixed boulder	
		bedrock	boulder	cobble	gravel	sand	silt & clay

CHANNEL CONFINEMENT	Score (/5)
broad flood plain	5
confined valley flood plain	4
flood plain confined on one side	3
incised channel (often with flood benches)	2
gorge with narrow valley floor	1.5
V-shaped valley	1
ravine	0.5
Score	2
confidence	4

MORPHOLOGICAL UNITS		tick
bedrock	waterfall	
	rock steps	
	rapid	x
	bedrock pool	
	bedrock pavement	
	bedrock island/ core bar	
	backwater	
	bedrock run	
alluvial	step	
	rapid	x
	plane bed	
	riffle	x
	run	x
	shallow pool	x
	deep pool	x
	flat sand bed	x
	backwater	x
alluvial bars	point bar	
	lateral bar	
	mid-channel bar	x
	tributary bar	
	lee bar	
secondary channels		x
vegetated islands		x

Figure 4.4 Data sheet for channel classification. This example shows the data sheet for a site on the Kat River. Data are entered into the shaded (yellow) boxes with double borders.

Table 4.2 Summary of the reach types found in alluvial systems (modified from Rowntree and Wadeson 1999)

Reach Type	Description
Step-Pool	Characterised by large clasts which are organised into discrete channel spanning accumulations that form a series of steps separating pools containing finer material.
Plane-Bed	Characteristic of cobble or small boulder channels that lack well defined bedforms or discrete morphological units. At low flows consist of shallow water with scattered cobble or boulder.
Pool-Riffle	Characterised by an undulating bed morphology that defines a sequence of bars (riffles) and pools.
Pool-rapid	Channels are characterised by long pools backed up behind channel spanning steep boulder deposits forming rapids.
Regime	Occur in either sand or mobile gravel. Bedforms adjust during flood events as flow velocity increases and decreases Plane-bed morphology, sand waves, mid channel bars or braid bars may all be characteristic.

Table 4.3 Summary of the reach types found in bedrock controlled systems. (modified from Rowntree and Wadeson 1999)

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

Table 4.4 Morphological units in bedrock controlled systems (modified from Rowntree and Wadeson 1999)

Morphological unit	Description
Waterfall	Abrupt continuity in channel slope; water falls vertically; never drowned out at high flows. Height of fall significantly greater than the channel depth.
Rock steps	Step like succession of small waterfalls drowned out at bankfull flows, height of fall less than channel depth.
Rapid	Local steepening of the channel long profile over bedrock, local roughness elements drowned out at intermediate to high flows.
Bedrock pool	Area of deeper flow forming behind resistant strata lying across the channel (includes plunge pools below waterfalls).
Bedrock pavement	Horizontal or near horizontal area of exposed bedrock.
Bedrock island/ core bar	Accumulation of finer sediment on top of bedrock to form a bar or island.
Backwater	Morphologically detached side channel which is connected at lower end to the main flow.
Bedrock run	A channel formed in bedrock with a moderate gradient, a uniform trapezoidal cross section and low roughness relative to depth.

Table 4.5 Classification of alluvial morphological units (modified from Rowntree and Wadeson 1999)

Morphological unit	Description
step	Formed by large clasts (cobble and boulder) organized into discrete channel spanning accumulations
rapid	Local steepening of the channel long profile over boulders, local roughness elements drowned out at intermediate to high flows.
plane bed	Topographically uniform bed, lacking well defined scour or depositional features.
riffle	A transverse bar formed of gravel or cobble, commonly separating pools upstream and downstream.
run	A section of channel of moderate gradient with a uniform trapezoidal cross section and low roughness relative to depth.
Pool (shallow, deep)	Topographical low point in an alluvial channel cased by scour; characterised by relatively finer bed material.
flat sand bed	Sands or fine gravels fill bed without forming distinct morphological features. Dunes or ripples may be present.
backwater	Morphologically detached side channel which is connected at lower end to the main flow
point bar	A bar formed on the inside of meander bends in association with pools. Lateral growth into the channel is associated with erosion on the opposite bank and migration of meander loops across the flood plain.
lateral bar or channel side bar	Accumulation of sediment attached to the channel margins, often alternating from one side to the other so as to induce a sinuous thalweg channel
mid-channel bar	Single bars formed within the middle of the channel, with strong flow on either side.
tributary bar	Forms immediately downstream of a tributary junction due to the input of coarse material into a lower angled channel.
lee bar	Accumulation of sediment in the lee of a flow obstruction
secondary channel	High flow distributary channel on the inside of point bars or lateral bars; may form a backwater at low flows.
islands	Mid-channel bars which have become stabilised due to vegetation growth and which are submerged only at high flows which would cause overbank flooding.

4.2.4 Assessment of weightings for metric groups

The weighting relates to the relative importance of each metric group or components of metric groups in terms of the likely ecological response, or the final PES score. Weighting of the GAI metric groups should carried out before data on change ratings are collected. This is to prevent the observer biasing the weightings towards the most impacted metric group. Each group should be ranked and weighted according to the relative importance that changes to each component will have on the ability of the geomorphological system to support aquatic and riparian ecosystems. The rank and associated weighting will vary with the channel classification (Section 4.2.3).

As a general rule system connectivity will be ranked 1, with a weighting of 100. The sediment balance will have a high ranking/weighting in a lowland alluvial system, where the bed is dominated by sands and gravels, but will have a lower weighting in higher gradient and bedrock systems that are likely to be supply limited. Perimeter resistance will have a relatively high weighting for channels with uncohesive banks as bank stability will be susceptible to changes in vegetation cover and bank steepening. Channel morphological changes, although directly related to habitat, is not normally given a high weighting because changes to channel morphology are difficult to discern and confidence levels are generally low.

An example of the portion of the PES data sheet giving weightings for the different GAI metrics is given in Figure 4.5. Within each metric group, the separate components must also be weighted in a manner similar to that described above.

Table 4.6 Habitat rating categories (modified from Table 4.1)

Rating modification from reference	General habitat modification	Geomorphological change
0-0.5 = none	No discernible impact, or the modification is located in such a way that it has no impact on habitat quality, diversity, size and variability.	Changes to the geomorphological system have no discernible impact on habitat quality, diversity, size and variability.
0.5 - 1 = small	The modification is limited to very few localities and the impact on habitat quality, diversity, size and variability is also very small.	Small changes to the geomoprhological system may have resulted in a largely undiscernable impact on habitat quality, diversity, size and variability.
1-2 = moderate	The modifications are present at a small number of localities and the impact on habitat quality, diversity, size and variability is also limited.	Moderate changes to the geomorphic system system have resulted in a discernable but largely reversible change to channel processes and morphology. Habitat quality, diversity, size and variability is largely unchanged.
2-3 = large	Clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	Changes to the geomorphological system have resulted in a definite change to habitat quality, diversity, size and/or variability. Changes largely irreversible.
3-4 = serious	The modification is frequently present and the habitat quality, diversity, size and variability in almost the whole of the defined area is affected. Only small areas are not influenced.	Changes to the geomorphological system have resulted in a change in channel state (supply or transport limited channel). Widespread changes to habitat quality, diversity, size and variability
4-5 = extreme	The modification is present overall with a high intensity. The habitat quality, diversity, size and variability in almost the whole of the defined section are influenced detrimentally.	Irreversible changes resulting in a widespread transformation of channel morphology and associated habitats.

PES DRIVER WEIGHTING	rank	weighting
SYSTEM CONNECTIVITY	1	100
SEDIMENT BALANCE	4	50
PERIMETER RESISTANCE	2	80
CHANNEL MORPHOLOGY	3	60

Figure 4.5 PES driver weighting for Site 1 on the Kat River. This is in a relatively steep mixed boulder pool-rapid reach so the sediment balance has been given a low ranking.

4.2.5 Assessment of changes to drivers by metric groups

The assessment of the PES (geomorphology) is described in terms of the four metric groups:

- System connectivity
- Sediment balance
- Resistance of the channel to change
- The channel morphology

Guidelines for assessing the PES are generalized and there can be no strict rules as to how to relate the degree of change, or rating, to the type of impact. This remains a matter of expert judgment based on experience. It is important that changes are rated with respect to presumed associated changes in habitat following the guidelines given in Table 4.6.

System connectivity

The format for recording data on system connectivity is shown in Figure 4.6a. Each component of connectivity must first be ranked and given a weighting before the rating scores are filled in. The GAI component for system connectivity is shown in Figure 4.6b. Note that the data recorded in Figure 4.6a are carried automatically into the spreadsheet shown in Figure 4.6b.

SYSTEM CONNECTIVITY	rank	weighting	rating	confidence	flow related	Comment on reason for rating	Guidelines
hillslope-channel connectivity	2	85	1	4	0	local gully erosion, bank erosion	This could be due to a change in drainage density or catchment hardening
upstream-downstream connectivity	1	100	3	4.5	75	upstream dam, infrequent causeways	A reduction could be due to dams, weirs, causeways, bridges, landslides. The removal, any of the above or channel straightening increases connectivity
within-reach connectivity	3	80	0.5	4	0	bridge with in-channel supports in reach	Changes to in-reach connectivity might be due to local weirs, causeways or other obstruction that cahnges the distribution of energy within the reach itself
channel-flood zone connectivity	4	60	2	4.5	100	smaller floods	Connectivity refers to the frequency that water spills out of the channel on to the flood plain, or activates secondary channels. The degree of channel-flood plain connectivity can be affected directly through channel incision, channel aggradation or construction/destrution of levees or flood walls. Indirectly connectivity is affected by changes to flood magnitude and frequency
vertical connectivity	5	20.00	1	3	75	armouring	Vertical connectivity is the connectivity between the channel surface and the channel bed or hyporheic zone. It relates both to the passage of water and the turn over of sediments. Channel armouring and hardening both decrease vertical connectivity
Other	0						

Ratings: This site lies a few kilometres below the Kat Dam which is considered to have a large to serious impact (3) on the upstream-downstream connectivity. Reduced magnitude and frequency of floods resulting from the presence of the dam has a secondary impact on channel-floodplain connectivity which is rated as moderate to large (2) while localized development of gullies and tracks has had a small to moderate (1) impact on hillslope-channel connectivity. A small to moderate reduction in vertical connectivity is ascribed to armouring of the bed (removal of fines). The resultant weighed score is 1.64. Sixty four percent of this score is flow related and the confidence score is 4.34. Information about the system is good, but the confidence is reduced due to poorer understanding of system processes.

Relative weightings: this reach is classified as an incised upper foothills site; upstream-downstream connectivity is normally considered to have the highest rank, followed by channel hillslope connectivity. With a limited flood zone channel-flood plain connectivity is of limited importance. Bedrock outcrops are frequent in the channel so vertical connectivity is naturally constrained and therefore has a low weighting.

Figure 4.6a Data form for system connectivity with an example of rating for Site 1 on the Kat River.

SCORING GUIDELINES							
GEOMORPHOLOGY DRIVERS							
COMPONENTS	RANK	RELATIVE WEIGHTING (%)	RATING	WEIGHT	WEIGHED SCORE	% FLOW RELATED (EVENT HYDROLOGY; HIGH FLOWS, FLOODS)	CONFIDENCE
System Connectivity							
CHANGE TO INTER-SYSTEM CONNECTIVITY							
hillslope-channel connectivity	2	85.00	**1.00**	0.25	0.25	0	4.00
upstream-downstream connectivity	1	100.00	**3.00**	0.29	0.87	75	4.50
within reach connectivity	3	80.00	**0.50**	0.23	0.12	0	4.00
channel-flood plain connectivity	4	60.00	**2.00**	0.17	0.35	100	4.50
vertical connectivity	5	20.00	**1.00**	0.06	0.06	75	3.00
Other		0.00	**0.00**	0.00	0.00	0	0.00
Score		345.00		1.00	1.64	64	4.34

Figure 4.6b System connectivity component of the GAI for Site 1 on the Kat River, Eastern Cape. Values are automatically carried forward from the data form (Figure 4.6a

Weightings depend partly on the channel classification. Upstream-downstream connectivity will normally be ranked high, except in headwater streams. Confined channels will have a high rank for hillslope-channel connectivity. The weighting for within-reach connectivity will be highest in moderate gradient channels. Channel-floodplain connectivity will be given a relatively high weight in unconfined channels with a wide flood plain, but will be given a low weight in confined or incised channels. Vertical connectivity is most important in alluvial channels, least important in bedrock channels.

The **ratings** for changes to system connectivity are assessed according to the following guidelines. Ratings are largely based on expert judgement and experience.

- **hillslope-channel connectivity** - changes to hillslope-channel connectivity could be due to a change in drainage density or to catchment hardening that promotes increased runoff due to decreased infiltration.
- **upstream-downstream connectivity** - a reduction in upstream-downstream connectivity could be due to dams, weirs, causeways, bridges, landslides upstream of the study reach. The removal of any of the above or channel straightening increases connectivity
- **within-reach connectivity** - changes to in-reach connectivity might be due to local weirs, causeways or other obstruction that changes the distribution of energy within the reach itself
- **channel-floodplain connetcivity** - connectivity refers to the frequency that water spills out of the channel on to the flood plain or flood bench or activates secondary channels. The degree of channel-flood plain connectivity can be affected directly through channel incision, channel aggradation or construction/ destruction of levees or flood walls. Indirectly connectivity is affected by changes to flood magnitude and frequency
- **vertical connectivity** - vertical connectivity is the connectivity between the channel surface and the channel bed or hyporheic zone. It relates both to the passage of water and the turn over of sediments. Channel armouring and hardening both decrease vertical connectivity.

Sediment balance

To answer the question 'To what extent has the capacity of the geomorphological system to support the natural ecosystem been degraded due to changes in the sediment balance?'

we need to consider the extent to which changes in both flood hydrology and/or sediment supply have changed the balance between the transport capacity of the flow and the availability of sediment in the reach.

Sediment supply

The availability of sediment is assessed in terms of changes to the sediment supply from the hillslopes and the sediment supply from the upstream channel. Changes to the sediment supply are rated on the scale of 0-3 (no change, small to moderate change, large change and serious change). Guidelines for rating changes to sediment supply are given in Table 4.7.

Table 4.7 Guidelines for rating changes to sediment supply

	Impact	**SEDIMENT INPUT (from catchment) (increase)**
0	None	
1	Small to moderate	localized gully erosion (< 10% of catchment) plus limited sheet erosion, moderately coupled to stream channel
2	Large	active gully or sheet erosion over catchment, strongly coupled channel
3	Serious	extensive gully and sheet erosion over significant areas of catchment (> 50%), strongly coupled to channel
It is unlikely that the sediment input would have decreased from natural, but soil conservation practices or a change in land use may have reduced sediment input from a formerly degraded landscape.		
	Impact	**SEDIMENT INPUT (from upstream channel reach) (increase)**
0	None	
1	Small to moderate	localised bank erosion on < 20 % of channel
2	Large	bank erosion on 20 to 50 % of channel
3	Serious	Bank erosion on over 50% of channel and/or widespread channel incision
	Impact	**SEDIMENT INPUT (from upstream reach (decrease)**
0	None	
1	Small to moderate	sediment trapped by causeways or small weirs, small dam upstream of major tributaries or larger dam controlling small area of catchment
2	Large	small upstream dam or series of larger weirs, significant mining of sediment, or large dam upstream of tributaries
3	Serious	upstream dam trapping all coarse sediment, no significant downstream tributaries or sediment sources.

The rating for changes to the sediment supply should take into account the extent, severity, location and history of erosion. Sheet erosion that is widespread over the catchment surface may be a greater sediment source than the more obvious gullies. Erosion sources close to the reach should be rated higher than sources that are at a greater distance. Erosion will normally decrease over time, so erosion sites that have been active for over twenty years may be stabilising.

The sediment supply rating should also take into account sediment delivery. The delivery ratio depends on hillslope and channel gradients, on the presence of buffer zones between hillslopes and the channel (e.g flood plains) and the density of the drainage network. A well-connected gully network will increase sediment delivery as will dirt roads and drainage ditches aligned up and down slope.

An appropriate timeframe for sediment delivery would be in the order of decades.

<u>Transport capacity</u>

Changes to the sediment transport capacity are related to changes in event hydrology. We need to assess the extent to which the magnitude and frequency signature of flood events has changed due to anthropogenic activities. These changes can be considered in the context of three groups of discharges:

- flows which are contained within the active channel, but are of sufficient magnitude to transport at least the finer sediments;
- flows which fill or overtop the active channel, inundate flood benches or the flood plain;
- extreme events that extent beyond the normal limits of flooding as evidenced from the sequence of flood deposits and the limits of riparian vegetation.

Guidelines for rating changes to the transport capacity of flows are given in Table 4.8. Note that these are rated on a scale of 0 (no impact) to 3 (serious impact).

In many environments it appears that the second group of floods (floods of moderate magnitude occurring once every one to two years) are the most effective in transporting sediment and controlling the channel morphology (Dollar, 2000, Dollar and Rowntree, 2003), but the first group will also contribute to the process of morphological adjustment.

It is these two groups that are most impacted by flow regulation and other human activities that affect catchment hydrology. Extreme events are almost without exception due to extreme weather phenomena, are part of the natural cycle of disturbance, but are moderated only to a small extent by human interference. It unrealistic to assess changes to the frequency of extreme events, but recent such events should be noted.

The following activities can alter the magnitude-frequency signature of floods:

- Large upstream dams that trap many of the smaller to intermediate floods have been shown to have major impacts on downstream channels. The impact of the dam can be assessed in terms of a) the % area of the catchment of the study reach that is controlled by the dam b) the % of the MAR of the study reach that is controlled by the dam and c) the capacity of the dam relative to the MAR at the dam site. Dams that have a capacity in excess of its own
- catchment's MAR and that control over 70 % of the catchment upstream of the study reach will have a large impact.
- Land use change that impacts on floods will also contribute to morphological change. Urban areas are a good example of a land use change that increases both the magnitude and frequency of floods, with corresponding effects on downstream channel morphology.
- Interbasin transfer schemes may increase 'normal' flows to the extent that the critical threshold for sediment movement is exceeded. Large to severe increases to the sediment transport capacity may be the result.

Where possible the hydrologist should be consulted for his/her assessment of changes to event hydrology. The Hydrology Driver Assessment Index contains two metrics that rate changes to event hydrology. The first refers to moderate events (group 1 above) and the second to high flow or flood events (group 2 above). This second group will include the most effective discharge for sediment transport and maintenance of the channel morphology.

Table 4.8 Guidelines for rating changes to transport capacity

	Impact	DECREASES IN TRANSPORT CAPACITY (reduction in floods)
0	None	
1	Small to Moderate	floods attenuated but volumes conserved
2	Large	Size of annual to biennial floods significantly reduced, extremes little impacted (dams controlling over 70 % of catchment; storage capacity of dam > MAR of upstream catchment
3	Serious	annual to biennial floods eliminated, flood regime dominated by extreme events
	Impact	**INCREASES IN TRANSPORT CAPACITY (increase in floods)**
0	None	
1	Small to moderate	frequency of small floods and/ or magnitude of annual flood increased
2	Large	base flow increased to above threshold for sediment movement
3	Serious	base flow increased to previous bankfull level

Combining event hydrology and sediment supply

A matrix is supplied on the data form to guide the assessment of changes to the sediment budget. This can be seen in Figure 4.7. The ratings for change to sediment supply and change to sediment transport capacity assessed according to the guidelines given above are applied to this matrix. This rating is carried forward directly to the Final Driver Status given in Figure 4.11.

We need to be aware that the long-term impact of changes to either the sediment supply or the magnitude and frequency of geomorphologically effective flows depends on the magnitude and direction of the change. If both changes are in the same direction the impact on channel processes is likely to be less than if they are in the opposite direction. For example, if both sediment supply and transport capacity increase together, the response is likely to be a bigger channel, but with no change to its general characteristics. If, however, the sediment supply increases but the transport capacity decreases, the response will be channel aggradation with the channel becoming more strongly transport limited. The converse will lead to a propensity for a supply limited channel.

SEDIMENT BALANCE				
Use the following table as a guide to assessing changes to the sediment supplied to the reach and to the sediment transport capacity. Sediment supply depends on both erosion of material from the hillslopes and the channel banks and the rate at which this eroded material moves off the slope and down the channel. Transport capacity depends on the magnitude and frequency of flood events				
	rating	confidence	flow related	comment
CHANGE TO SEDIMENT SUPPLY	-2.00	2.5		sediment trapped by upstream dam, but partly compensated by local hillslope erosion and reworking of sediment form alluvial fan at end of gorge
CHANGE TO SEDIMENT TRANSPORT CAPACITY	1.00	4		large reduction in flood magnitude due to upstream dam, but increased frequency of intermedeate events due to releases. No significant downstream tributaries
CHANGE TO REACH SEDIMENT BALANCE	3.00			
Score for discharge/sediment change (from matrix)	3.00	3.25	30	

change in discharge

change in sediment supply	-3	-2	-1	0	1	2	3	
3	5	4.5	4	3.5	3.4	3.2	3	3
2	4.5	4	3	2.5	2.25	2	3.2	2
1	4	3	2	1.5	1	2.25	3.4	1
0	3.5	2.6	1.6	0	1.6	2.5	3.5	0
-1	3.4	2.25	1	1.5	2	3	4	-1
-2	3.2	2	2.5	2.5	3	4	4.5	-2
-3	3	3.2	3.4	3.5	4	4.5	5	-3
	-3	-2	-1	0	1	2	3	

change in discharge

The change to sediment supply was rated as -2 on account of the high sediment trapping capacity of the upstream dam which is compensated to some extent by sediment supplied from in-channel and catchment erosion downstream of the dam, but upstream of the site. The change to the sediment transport capacity has been rated as 1. Despite the reduction in annual floods that will have resulted from the upstream dam, it was considered that the frequent release of pulses for irrigation would have had a greater effect on the long term sediment transport capacity.

The two scores for sediment supply and sediment transport capacity are carried over to the matrix below. A rating of -2 for sediment supply and 1 for transport capacity gives an overall change rating of 3. This suggests that the channel will be trending towards a supply limited channel, but is likely to become smaller due to the reduced magnitude of annual floods.

The final confidence level is the average of the confidence levels for the sediment supply and transport capacity ratings. The percent flow related is estimated from the relative values of the two scores. In this case the score for change to transport capacity (flow related) is one third of that for change to sediment supply so the flow related percentage has been given as 30 %.

Figure 4.7 Data form for sediment balance with an example of rating for Site 1 on the Kat River. The score for the change to the reach sediment balance is transposed directly to the Final Driver Status worksheet (Figure 4.11)

Using the matrix in Figure 4.7, it can be seen that a large positive change in sediment supply (3) and a large negative change in transport capacity (-2) are assumed to have a serious (4) geomorphological response, whereas a large reduction in both transport capacity (2) and sediment supply (2) will only have a moderate to large geomorphological response (2). It should be noted that this table has been constructed from first principles as outlined above. The accuracy of the ratings needs to be tested through continued field application.

Channel perimeter resistance

The propensity for channel change depends on the resistance (or lack of) of the channel perimeter, including the bed, banks, bars and out of channel flood zone. In all cases the present-day rating is assessed from observed characteristics. An assessment is then made of the expected reference conditions (that which would have occurred under 'natural' conditions). This allows an assessment of change to be made.

Perimeter resistance is considered to be a function of the sediment composition of the relevant feature and, in the case of banks, flood zones and bars, of the vegetation cover. It should be

noted that vegetative ground cover and root density are more important than overhead cover. Roots that extend to below the normal water level are more effective at stabilising the bank than are shallow root systems. Alien invasive woody vegetation is commonly considered to contribute to bank instability. It often inhibits ground cover and, in the case for example of *Acacia mearnsii,* may have a root system that does not extend into the saturated zone. Bank undercutting is common in these circumstances.

The geomorphologist should consult the riparian vegetation specialist to assist in rating vegetation condition and vegetation change.

Bed mobility: the rating for bed mobility is assessed according to the size of the bed material as indicated in Figure 4.8a. For example a cobble bed river would be rated 1.5 and a sand or fine gravel bed river would be rated 5. Mixed beds can be given an intermediate rating (e.g. 2.5 for a cobble bed with significant patches of gravels. Note that the highest rating is given to the most mobile material, that is the least resistant to change.

Bank stability: this is assessed in the first instance through considering both the perimeter material and the effectiveness of the vegetation cover according to Figure 4.8a. Note that the least stable banks are afforded the highest rating. Thus a channel with banks composed of sand with a dense vegetation cover affording good protection would be rated 3. The rating is then modified in accordance with the bank slope as indicated in Figure 4.8a. If this same bank was gently sloping ($<20^0$) the rating would be reduced from 3 to 2, indicating greater stability.

Bar stability: this is assessed using Figure 4.8a. Note that it is possible to have bedrock bars in supply-limited channels. Vegetation on bars imparts an important stabilising influence.

Out-of-channel flood zone: the stability of this component is rated using Figure 4.8a.

The data on the different perimeter resistance components are entered into the PES data sheet. These data are automatically carried through to the perimeter resistance change GAI worksheet for which an example is given in Figure 4.8b.

Morphological change

Habitat changes due to morphological change are assessed separately for the substrate and channel geometry. Substrate changes refer to changes of sediment composition and sediment structure on the bed, bars, banks and flood zone. Channel geometry changes are assessed in terms of the reach type, cross-section change, loss or gain of secondary channels and channel roughness. A change to reach type would represent a major change to the configuration and characteristics of the channel, but may be due to a short-term extreme event, with gradual change back towards an earlier condition. Cross-section change will be reflected by changes to the channel width or mean depth, and to the width-depth ratio. Secondary channels contribute to habitat diversity and provide refuge during flood events. Loss or gain of secondary channels is an important indicator of habitat change. Lastly, channel roughness determines the hydraulic response, the mean velocity and depth of flows at any given discharge and the pattern of flow types. Roughness is contributed by sediment size and bed structure, channel form irregularities and vegetation.

PERIMETER RESISTANCE WEIGHTING	rank	weighting	flow related
BED MOBILITY	2	80	50
BANK STABILITY	1	100	40
BAR STABILITY	2	80	40
FLOOD PLAIN STABILITY	4	30	30

PERIMETER RESISTANCE

BED MOBILITY	rating	confidence
Present day bed material	1	4
Reference bed material	2	3
		3.5

bedrock/ paved	boulder	cobble	Co & Md gravel	Sand and fine gravel
0	0.5	1.5	3.5	5

BANK (IN)STABILITY		
Present day stability	3	4
Reference stability	2.5	3
		3.5

Bank stability matrix

		VEGETATION COVER poor	moderate	dense
low cohesion	sand/gravel	5	4	3
moderate cohesion	mixed	4	3	2
cohesive	silt-clay	3	2	1
weathered bedrock / gabion wall		0.5	0.5	0.5
intact bedrock/ concrete wall		0	0	0

BANK SLOPE

Stability rating

		1	2	3	4	5
	> 45%	2	3	4	5	6
bank slope	20 - 45%	1	2	3	4	5
	<20%	0.5	1	2	3	4

BAR (IN)STABILITY		
present stability	1	4
reference stability	1.5	2
		3

Bar (in)stability matrix

		VEGETATION COVER poor	moderate	dense
low cohesion	sand/gravel	5	4	3
moderate cohesion	mixed	4	3	2
	cobble	3	2	1
	boulder	1.5	1	0.5
weathered bedrock		0.5	0.5	0.5
intact bedrock		0	0	0

FLOOD ZONE (IN)STABILITY		
present stability	3	4
reference stability	1	2
		3

Flood zone (in)stability matrix

		VEGETATION COVER poor	moderate	dense
low cohesion	sand/gravel	5	4	3
moderate cohesion	mixed	4	3	2
cohesive	silt-clay	3	2	1
weathered bedrock		0.5	0.5	0.5
intact bedrock		0	0	0

Figure 4.8a Portion of data form for assessing perimeter resistance

GEOMORPHOLOGY DRIVERS							
COMPONENTS		RELATIVE WEIGHTING (%)	RATING	WEIGHT	Weighed score	flow related (event hydrology;high flows, floods)	CONFIDENCE
BED MOBILITY		80.00	1	0.31	0.31	50.00	3.5
BANK (IN)STABILITY		100.00	-0.5	0.38	0.19	40.00	3.5
BAR (IN)STABILITY		80.00	0.5	0.31	0.15	40.00	3
FLOOD ZONE (IN)STABILITY		30.00	-2	0.12	0.23	30.00	3
TOTALS		260.00		1.00	0.65		
Perimeter resistance rating					**0.65**		
FLOW RELATED (%)					**55.29**		**3.38**

	BED MOBILITY	BANK (IN)STAB-ILITY	BAR (IN)STAB-ILITY	FLOOD PLAIN STABILITY
reference condition	2	2.5	1.5	1
present condition	1	3	1	3
change in perimeter resistance	1	-0.5	0.5	-2

The present day bed is composed of cobble and boulder with small pockets of gravel. Mobility was rated as 1. The reference condition was believed to include a higher proportion of gravels, rated at 2. The present day bank stability was rated at 3, due to a moderate vegetation cover and a mixed bank material of sand, gavel and boulder. The reference condition was assumed to be slightly more stable due to a better vegetation cover. Bars are assumed to have become more stable (from 1.5 to 1) due to a small reduction in gravel and increased vegetation growth.

Figure 4.8b Assessment of perimeter resistance component of the GAI for Site 1 on the Kat River

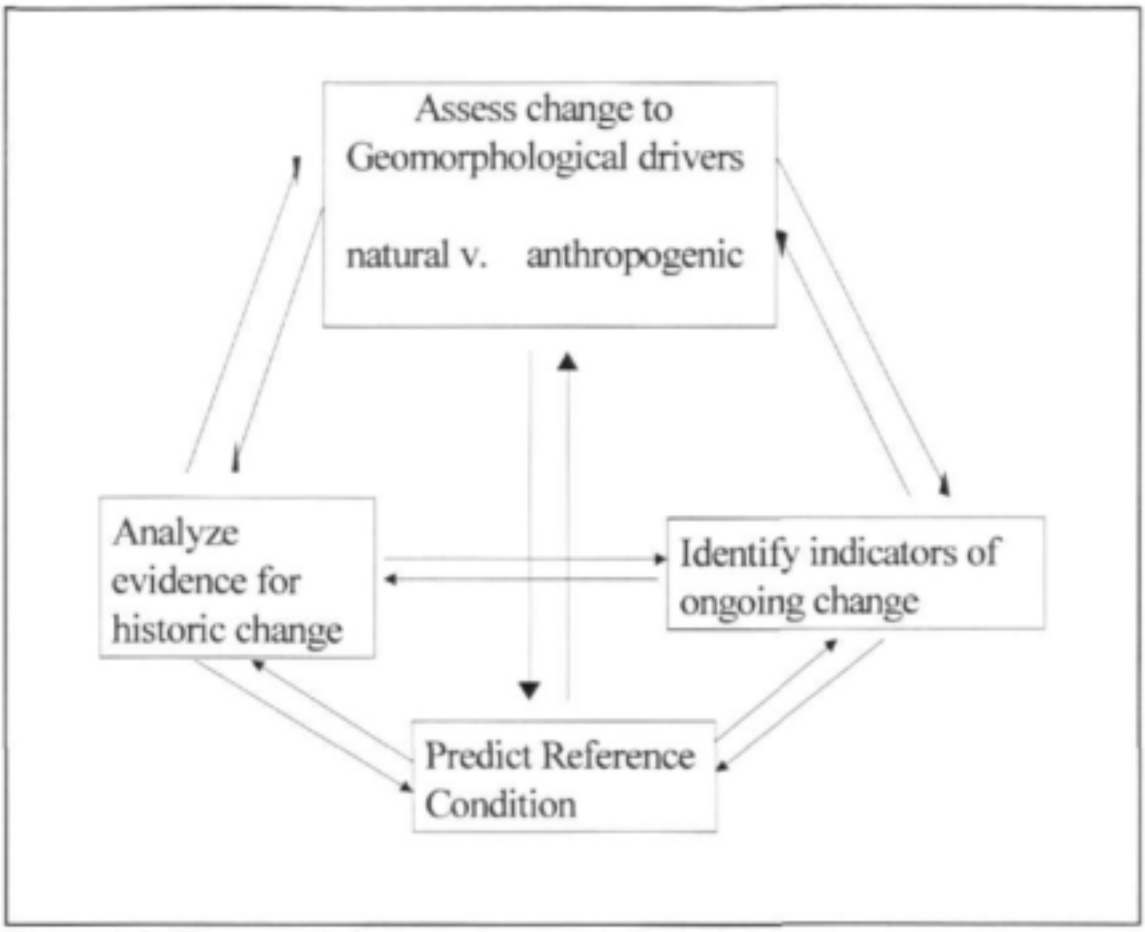

Figure 4. 9 Framework for assessing morphological change

It may be difficult to assess habitat changes due to morphological change because of a lack of historical information. Ideally change should be assessed in terms of actual morphological change relative to a morph-ological reference condition, but this is often difficult to carry out due to a lack of competence to assess the geomorphological reference condition for a river reach. Figure 4.9 provides a framework within which a driver-driven assessment of change can be placed. Aerial photographs or anecdotal evidence can be used to assess historical changes to channel morphology. A field assessment of the present channel will provide evidence of ongoing change in terms for example of bank erosion, bar development, loss or gain of secondary channels.

MORPHOLOGICAL CHANGE					
ASSESS HABITAT CHANGES DUE TO:	rank	weighting	rating	confidence	flow related
SUBSTRATE CHANGES					
CHANNEL BED	1	100	2	2	55
BARS	2	90	1.5	2.5	70
CHANNEL BANK	3	80	0.5	2	40
FLOOD ZONE SEDIMENTS	4	75	0.5	2	40
HYDRAULIC GEOMETRY					
REACH TYPE	1	100	0	4	50
CROSS-SECTION SHAPE	2	80	2	2	50
SECONDARY CHANNELS	2	80	1	2	50
CHANNEL ROUGHNESS	4	50	1.5	2	50

The main substrate change is a coarsening if the channel bed due to armouring. Frequent irrigation releases have resulted in the removal of fines from between cobbles. The main change to the hydraulic geometry (channel shape) is a narrowing of the main channel due to the stabilisation of lateral bars and islands by vegetation. This in turn has increased channel roughness and created secondary channels.

Figure 4.10a Portion of the data form for morphological change with an example for Site 1 on the Kat River

GEOMORPHOLOGY DRIVERS							
COMPONENTS		RELATIVE WEIGHTING (%)	RATING	WEIGHT	WEIGHED SCORE	flow related (event hydrology;high flows, floods)	CONFIDENCE
SUBSTRATE CHANGES							
CHANNEL BED		100.00	2.00	0.476	0.95	55.00	2.00
BARS		90.00	1.50	0.429	0.64	70.00	2.50
CHANNEL BANK		80.00	0.50	0.381	0.19	40.00	2.00
FLOOD ZONE SEDIMENTS		75.00	0.50	0.357	0.18	40.00	2.00
SUB-TOTAL					1.96		
HYDRAULIC GEOMETRY							
REACH TYPE		100.00	0.00	0.476	0.00	50.00	4.00
CROSS-SECTION SHAPE		80.00	2.00	0.381	0.76	50.00	2.00
SECONDARY CHANNELS		80.00	1.00	0.381	0.38	50.00	2.00
CHANNEL ROUGHNESS		50.00	1.50	0.238	0.36	50.00	2.00
SUB-TOTAL					1.50		
TOTALS		210.00	4.5	1.00	1.73		
Morphology Driver status:					**1.73**		
FLOW RELATED						**53.55**	**2.08**

Figure 4.10b Assessment of the channel morphology component of the GAI for Site 1 on the Kat River

Finally the river zone, classified in terms of reach gradient and stream power, can be used to get a first approximation of expected channel morphology. These four aspects can then be compared to derive an assessment of the change rating.

Examples of the data sheet and driver metric worksheet for assessing morphological change are given in Figures 4.10a and 4.10b respectively.

4.2.6 Assigning the level of confidence

The level of **confidence** depends firstly on the availability and accuracy of information and secondly on the level of the assessor's understanding of geomorphological response to a system change as indicated below in Table 4.9. For example we may know that there is a dam upstream of the reach (confidence level 5) and we are certain from previous studies that the dam will have some impact on geomorphology, but the exact nature of the response is uncertain (confidence level 3). From the matrix in Table 4.9 we would rate our overall confidence as moderately high (4). In other cases we may be uncertain of the extent of erosion in the catchment due to poor information (2), and uncertain of the geomorphological response to increased sediment inputs (3). Our overall confidence in the rating will therefore be low (2.5).

Table 4.9 Guidelines for confidence ratings

			Information				
			Poor		Moderate	Good	
			1	2	3	4	5
Understanding	Poor understanding of both direction and amount of change	1	**1**	**1.5**	**2**	**2.5**	**3**
		2	**1.5**	**2**	**2.5**	**3**	**3.5**
	Understands direction of change but cannot quantify	3	**2**	**2.5**	**3**	**3.5**	**4**
	Good understanding of direction and amount of change.	4	**2.5**	**3**	**3.5**	**4**	**4.5**
		5	**3**	**3.5**	**4**	**4.5**	**5**

4.2.7 Assessing the proportion of change that is flow related

Changes to the metric groups and their sub-components may be due to flow related causes such as changes to flood magnitude and frequency or to non-flow related causes such as catchment landuse, clearing of riparian vegetation or structural changes to the channel such as would result from building a causeway. The assessor must make a decision as to what percentage of the change can be ascribed to flow related causes.

The most important flow related causes will be those that can be related to a change in the magnitude and frequency of flood events. This can directly affect the connectivity between channel and flood zone and the capacity of the flow to transport sediment and maintain an open channel. There may be indirect effects on perimeter resistance if vegetation cover has been affected by water availability and scouring affects of floods. Changes to channel morphology are often a direct result of changes to flow magnitude, but are also due to changes in sediment supply and vegetation cover. Whether of not these changes are themselves flow related must be evaluated.

4.3 THE FINAL DRIVER STATUS

The separate weightings, scores, confidence levels and flow related percentages for each metric group (system connectivity, reach sediment balance, channel perimeter resistance and morphological change) are carried forward to the worksheet for the Final Driver Status. This is where the value for the GAI is calculated. An example is given in Figure 4.11.

FINAL DRIVER STATUS

GEOMORPHOLOGY DRIVERS							
COMPONENTS	RANK	RELATIVE WEIGHTING (%)	RATING	WEIGHT	Weighed score	flow related (event hydrology;high flows, floods)	CONFIDENCE
System Connectivity	1.00	100.00	1.64	0.34	0.56	63.72	4.34
Reach sediment balance	4.00	50.00	3.00	0.17	0.52	30.00	3.25
Channel perimeter resistance	2.00	80.00	0.65	0.28	0.18	55.29	3.38
Morphological change	3.00	60.00	1.73	0.21	0.36	53.55	2.08
TOTALS		290.00		1.00	1.62		
System Driver status:					1.62		
Driver status:(%): >89=A; 80-89=B; 60-79=C; 40-59=D; 20-39=E; <20=F					67.59		
HABITAT DRIVER CATEGORY					C		
FLOW RELATED (%)						49.77	3.42

The final driver status is derived by combining the separate ratings estimate for the four different driver metrics: system connectivity, reach sediment balance, channel perimeter resistance and morphological change as given in Figures 4.5, 4.6, 4.7 and 4.8 respectively. These values are automatically brought forward to the final driver worksheet. The % flow related and confidence values are also calculated from the values derived for the separate driver metrics.

Figure 4.11 Worksheet for calculating the final driver status for the site on the Kat River

4.4 APPLICATION OF THE GEOMORPHOLOGY DRIVER ASSESSMENT INDEX

4.4.1 Application to assessing the recommended Ecological Category for an EWR determination

According to Kleynhans *et al*. (2005), eight steps must be followed in order to determine the Recommended Ecological Category for a river reach. These are given as:

1. Determine the Present Ecological State (PES); assess the extent to which the river has changed away from natural conditions.
2. Determine the trend of change to the PES if the level of present day impacts is maintained.
3. Determine the critical cause for the PES and the observed trends.
4. Determine the source of the cause noted in 3.
5. Determine the ecological importance and sensitivity categories as well the social importance.
6. Determine the Ecological objectives for the river reach; given the importance and sensitivity of the river, determine whether management should seek to maintain or improve the PES.
7. Determine what measures would need to be put in place to address the main causes and sources of the PES (3 & 4) and assess whether the PES recommended under 6 is realistic.
8. Determine the recommended Ecological Category for the river reach based on a consideration of the ecological objectives (6) and the difficulties faced in attaining these.

The role of geomorphology in achieving these eight steps is outlined below.

1. The GAI is used in step one to assess the Ecological Category for the PES of the geomorphology driver.

2. The second step considers on going change to the PES. It is difficult to provided prescriptive guidelines for this assessment. The assessor must consider the following alternatives:
    - the channel morphology has not yet responded to a change in system drivers but is likely to do so in the future;

- the channel morphology has undergone preliminary change as a result of changes to the system drivers; future change is likely to result in a change in the Ecological Category.
- the channel morphology has undergone change in response to a change in system drivers, but has now achieved a new level of 'stable' self organisation.

The geomorphologist needs to consider the time since system changes occurred, the resistance of the channel to change and the resilience of the channel. Resilience refers to the ability of the channel to reorganise itself following change. Alluvial channels are normally less resistant but more resilient than bedrock channels. An index of resistance to change is assessed as part of the GAI rule-based model.

3. The critical causes for the PES and observed trends can be derived from the GAI rule-based model. Both the rating and weighting of the different geomorphological system components should be taken into account when making this assessment.

4. The source of the causes should be noted. Example might include:
   Cause – system connectivity has decreased
   Source – upstream dam

   Cause – sediment balance has changed towards a more transport limited system
   Source – tributary catchment erosion has increased sediment input below an upstream dam that has reduced sediment transport capacity

5. The ecological importance and sensitivity are normally rated with reference to the biological components and habitat. The geomorphologist may consider the reach to be of geomorphological importance if the reach provides unique or rare physical habitat. An example would be the Pongola floodplain. Geomorphological sensitivity could be expressed in terms of the resistance and resilience of the reach to system change.

6. The ecological objectives will normally be driven by ecological considerations and the implications for habitat. The geomorphologist must therefore set objectives to meet the recommended habitat requirements.

7. The geomorphologist must give advice on how the causes of a low PES score can be addressed. The source of a low PES for geomorphology is often in the catchment or the riparian zone rather than being flow related. Addressing this may require active rehabilitation such as erosion control structures or fencing the riparian zone to allow re-growth. This is outside the scope of the normal EcoStatus process. Where the cause of the low score is flow related but the source is a large engineering structure such as an upstream dam, addressing the cause may be problematic. In many cases it is unrealistic to expect to be able to improve the Ecological Category for geomorphology.

8. The recommended EC is a joint decision by all specialists based on the available information derived from applying steps 1-7 above to all the components.

4.4.2 Application of the Geomorphological Driver Assessment Index to the National River Health Programme

There is scope for applying the GAI as the geomorphological index used in the National River Health Programme. Rating the ecological drivers from a geomorphological perspective would contribute to our understanding of the observed ecological responses at biomonitoring sites.

The index has not been developed specifically as a monitoring tool, but it could be used to identify the impact of major system changes over the time scale of the monitoring programme.

For more detailed monitoring of change at a site it will be necessary to make quantitative measurements of specific features such as the particle size distribution of sediment on the channel bed and bars, bed packing and embeddedness, and bank erosion. Assessment forms are provided in Appendix 2. These measurements will enable short term changes to be identified; it must be remembered that these may be reversible and short-term and do not indicate a long term system change.

4.5 CONCLUSIONS

This chapter presents the development of a revised Geomorphological Index, the Geomorphological Driver Assessment Index (GAI). This index takes the form of a rule-based model that integrates the extent to which changes in the components of the geomorphological system are believed to compromise the natural river ecology. The GAI can be used to assess the Ecological Category of a reach, which in turn can be applied to assessing the Present Ecological State and the Recommended Ecological Category. It can also be used to examine the effect of different management scenarios on the geomorphological system. Although the development of the GAI has been within the context of determining Environmental Water Requirements, the index can also be used as a component of river health and is recommended as the standard method for carrying out geomorphological assessments within the National River Health Programme.

The majority of data collected to date have been based on an earlier version of data forms. These will need to be converted to the new format and the data entered into the GAI rule based model so as to derive ecological categories for all monitoring sites. This should not present too great a problem for sites familiar to the project researchers; where data were collected by other field workers it may be more difficult to make the conversion. The data that has been collected and converted to the new format thus far is presented in Appendix 3.

A fundamental difference between the GAI as presented here and earlier assessment methods is a change to the conceptualisation of the Reference Condition. Rather than seeing the Reference Condition as being a deterministic channel morphology that can be predicted from reach and catchment controls, the Reference Condition is conceptualised as a geomorphological system composed of flows, storages and responses that are dynamic and indeterminate. This thinking is in line with the systems paradigm that is being applied increasingly to fluvial geomorphology.

CHAPTER 5
ADOPTING A SYSTEMS PARADIGM IN FLUVIAL GEOMORPHOLOGY

It should be noted that this is a largely theoretical chapter that presents new ideas that are considered relevant to this project. The chapter points a way forward for river research, but does not claim to address immediate technical and management-related matters. This chapter introduces concepts and terminology that may be unfamiliar to many readers. A glossary of relevant terms is included at the end of the chapter.

5.1 INTRODUCTION

Despite the long history of the discipline of fluvial geomorphology, cause-effect relationships within river systems are relatively poorly understood, and difficult to unravel. As stated by Dollar (2000, p.3), "There is by no means consensus of opinion as to how fluvial systems function". He further describes the understanding of modern fluvial systems as "fragmentary" (Dollar, 2000, p.29). It is believed that a systems based approach could provide a stepping stone towards a measure of coherence.

If management of river systems is to be effective, it is important that steps are taken to probe the intricate links that exist within and between systems and to gain a better understanding of such links, particularly those which are confounded by human impact. This is especially important within the South African context, this is especially important due to the fact that southern African rivers are quite different from the temperate alluvial systems that have been extensively studied in northern temperate regions of Europe and North America (Dollar, 2000). South African rivers pose a unique suite of management problems.

Ways of thinking (dubbed "paradigms" by Kuhn in 1970) in Western science can be broadly broken down into two main classes, namely reductionism and holism (or the "systems approach"). The reductionist approach[1] holds that a complex entity can be

[1] The reductionist approach (i.e. reductionism) is defined as "The dominant approach to the scientific method, which reduces the complexity of causative factors in the real world to one or at most a few factors which are then hoisted up as the explanatory substance of that reality. Reduces organisms, and life itself, to their mechanistic parts and disregards the interconnections and dynamism between genes, physiological systems, organisms and their environments. Opposite is systems approach." (Center for Alternative Development Initiatives, 2004).

understood as a sum of its constituent parts (i.e. if one can fully comprehend each of the parts and its relationship to other parts, one can understand the whole), whilst the holistic

approach holds that it is not only impossible to fully understand each part of a system and its relationships with other parts, but that a system can exhibit its own properties independent of the characteristics of its parts, i.e. a system can behave as an entity in its own right (Laszlo, 1972; CALRESCO, 2004).

It seems that these two ways of thinking have alternated over time (Laszlo, 1972). The reductionist approach has found favour due to its seeming rigour, but has been criticized due to its inability to capture the essence of reality in natural systems. The holistic approach, on the other hand, has been criticized due to its supposed reliance on insight over objective and factual inquiry (Laszlo, 1972) but favoured due to its endeavour to understand reality in all its complexity, rather than idealizing or over-simplifying it. However, recently, efforts have focused on developing more rigorous methods of holistic enquiry. An example of this is nonlinear dynamical systems theory (NDS). Aspects of this body of theory will be outlined later in this chapter.

An holistic outlook is warranted in river science. Rivers are widely recognised as being natural *systems*. A system may be simply defined as "A collection of interacting parts that forms an integrated and consistent whole, isolatable from its surroundings." (CALRESCO, 2005). This definition will be expanded upon later in this chapter.

It has been widely stated by those involved in river research and management that rivers, or perhaps more specifically "catchments", are complex systems (e.g. Dollar, 2000; Rhoads, 1994). Systems terminology abounds in the area of river research (eg. equilibria, thresholds, scale etc.), though systems theory (see explanation below) is often not explicitly applied. Although the term "river system" is now commonplace in the literature, there have been different interpretations as to what this means.

For some, systems frameworks are merely a context for chiefly reductionist studies, i.e. the belief is held that a complex system is merely the sum of its parts and may thus be understood and predicted as knowledge of components increases. The current method of ascertaining the environmental water requirements (EWRs) for river systems in South

Africa has been designed with this premise as its philosophical basis (see King *et al.*, 2000). On the other hand, as has been described above, systems scientists believe that systems may be more than the sums of their parts, and may hence be inherently unpredictable and exhibit certain emergent properties which cannot necessarily be explained by examination and summation of discrete system components (see Section 5.3 below). Phillips (1999) gives a balanced view in which he recognizes that the reductionist and systems approaches are "complementary not competitive" (p.11). Reductionist studies are necessary for the provision of data, but a systems approach is essential if reductionist findings are to be placed in a meaningful context.

Much of the valuable empirical work which has been done to date has been undertaken within a largely reductionist paradigm. This has resulted in a degree of understanding regarding relationships between certain fluvial system variables. Classic examples of these include the work done by Wolman and Miller (1960) which identified a relationship between magnitude and frequency of flood events and the amount of geomorphological work which they accomplish. Leopold and Wolman (1957) also completed research which, they reported, established a positive relationship between slope, discharge and channel pattern. However, subsequent to both of these studies, researchers completed empirical work, the findings of which seemed to limit the universality of the relationships that had been identified (Baker, 1977; Simpson & Smith, 2001). There are countless examples which could be cited of studies that have identified links (in particular contexts) between flow magnitudes, geomorphic effectiveness and channel characteristics, eg. Pickup & Warner (1976), Andrews (1980), Alabyan & Chalov (1997).

Other examples are studies which have identified relationships between channel characteristics and vegetation. These include the following (amongst many others):

- Bendix (1999) who tested the relationship between stream power and riparian vegetation cover.
- Abernethy & Rutherfurd (2000) who examined the relationship between the weight of riparian trees and bank stability.
- Thorne (1990) who studied the effects of vegetation on riverbank erosion and stability.

One of the main areas of reductionist study that has been utilized by many fluvial geomorphologists is palaeoflood hydrology, where the relationships between discharge and channel dimensions are used to infer previous flow regimes for river systems. However, it is stated by Thornes (no date) that palaeohydrology has since entered more into the arena of non-linear science.

In the South African context, fluvial geomorphological studies have been predominantly of an applied nature in recent years and have thus tended increasingly towards a systems-type approach (even though this has been more implied than explicitly stated) in an effort to solve real problems in complex catchment systems. However, various reductionist studies have provided data and established links between variables in South African systems which are often not analogous to systems encountered in America or Europe (Dollar, 2000). Examples of such studies are:

- Rowntree & Dollar (1999) who investigated the relationship between vegetation and channel stability.
- Hattingh (1994) who used conventional wisdom in the area of sedimentology (ie. the relationships between environmental characteristics and sediment deposition) to draw conclusions regarding previous climatic regimes.
- Smith & Zawada (1990) and Zawada & Hattingh (1994) who used relationships established in the area of palaeoflood hydrology to construct flow records for various South African Rivers.

In the realm of river management, various reductionist studies have provided data for larger system-type approaches. Examples of these are work done by Broadhurst *et al.* (1997), who identified relationships between discharge and flow resistance in various channel types in the Sabie River. It should be noted that non-linear modelling may be used in reductionist research (eg. stochastic models which include an element of randomness and hence imply nonlinearity).

Clearly, much valuable work has been undertaken within a reductionist paradigm. However, it is safe to say that there is an increasing tendency for fluvial geomorphologists to make use of the tools and concepts which systems theory (particularly nonlinear dynamical systems theory) has to offer in studying fluvial landscape systems (Phillips, 1996). In this chapter, certain relevant systems concepts will be presented and defined, and the history of systems thinking in fluvial geomorphology will be outlined. In addition, the applicability of systems theory concepts to fluvial geomorphology in general will be discussed, particularly within the context of this project.

5.2 WHERE GEOMORPHOLOGICAL SYSTEMS FIT IN

The term "system" is defined in various ways. Amongst these are the following:

1. "A collection of interacting parts that forms an integrated and consistent whole, isolatable from its surroundings. The concept of dynamics or change over time is central to our treatment within complex systems." (CALRESCO, 2004)

2. "A collection of components organized to accomplish a specific function or set of functions." (Interoperability Clearinghouse, 2004)

3. "Any organized assembly of resources and procedures united and regulated by interaction or interdependence to accomplish a set of specific functions." (United States Joint Forces Command, 2004)

4. "A set of actors or entities bound together by a set of rules and relationships into a unified whole. A system's health is dependent on the health of the whole pattern, which can sometimes be reflected (and thus measured) in the status of a key part of the system." (State of New Jersey, 2004)

5. "1. A group of interacting, interrelated, or interdependent parts made up of matter and energy that form a complex whole.
 2. Anything that uses matter and energy to organize, maintain, or change itself, e.g., the sun, a glass of water, a frog, a city." (Wisconsin K-12 Energy Education Programme, 2004).

6. "A collection of subsystems, components, or elements that work together, e.g., to provide some major aspect of infrastructure's services (e.g., water distribution system, building electrical system); the value of the assemblage is greater than the sum of its parts. Also, a set of building components specifically designed to work together to facilitate construction (e.g., modular building system)." (Matrix Group, 2004)

For the purposes of this particular project, in which Fluvial Geomorphology will be considered as a system, definition 3 will be adopted in combination with definition 4, ie. the fluvial geomorphological system is seen as an organized assemblage of resources (components/variables) and procedures (processes) regulated by interaction or interdependence to accomplish a set of specific functions. It is also assumed that the health of these systems can sometimes be reflected in the status of certain key parts of them.

Many different types of system have been identified and discussed in the literature. It is beyond the scope of this report to discuss every system type in detail. For the purposes of justifying the systems approach within the context of this project, and in order to contextualize fluvial geomorphological systems within the vast realm of systems literature and theory, only the basic system types will be presented and discussed. A more detailed explanation of "complex systems" will be given, as this is the system class into which fluvial geomorphological systems fall.

The most basic way in which systems are classified is as "open", "closed" or "isolated". Open systems are systems in which there is a transfer of matter and energy across system boundaries; closed systems can only exchange energy (ie. they cannot exchange matter) across their boundaries and isolated systems cannot transfer either matter or energy with their surroundings. Fluvial geomorphological systems, like most environmental systems, are open.

Within the open systems category, there are many different types of systems. Relationships between the various components of a system can be either linear or non-linear. Linear systems are those whose relationships are proportional, and for which the best fitting regression line is a straight one. Non-linear systems, on the other hand, are those whose "outputs are not proportional to the inputs across the entire range of the inputs." (Phillips, 2003, p.4).

In addition to its degree of linearity, a system can be defined as dynamical if it exhibits complex variability over time. Dynamical systems, at any point in time are on a trajectory of change, which is defined as "The path through *state space* taken by a system. It is the sequence of states plotted against time." (CALRESCO, 2004).

State space, in turn, is defined as "The total theoretical possibilities available to the system, by combinations of the parts." (CALRESCO, 2004); state space is often referred to as phase space in the literature.

A system is referred to as dissipative if there are certain end-points (named attractors) in its state/phase space that its trajectory tends towards. In contrast to being termed "dissipative", a system would be termed "conservative" if there were no attractors in its phase space, and "ergodic" if its trajectory eventually "covers" the entire phase space (Center for Naval Analysis, 2004).

All of this said, it seems opportune to define fluvial geomorphological systems using the above terminology. Fluvial systems are open, non-linear, dissipative systems.

Furthermore, earth surface systems (ESS) -which include fluvial geomorphological systems- are complex, occuring where the hydro-, bio-, litho- and atmospheres meet, making them extremely difficult to model and manage (Phillips, 1999). Complex systems are defined as : "Systems not describable by a single rule. Structure exists on many scales whose characteristics are not reducible to only one level of description. Systems that exhibit unexpected features not contained within their specification. Systems with multiple objectives." (CALRESCO, 2004).

5.3 SYSTEMS THEORY

Various bodies of systems theory have developed as people have begun to take what Laszlo (1972) referred to as a "systems view of the world". Examples include General Systems Theory, Nonlinear Dynamical Systems Theory and Complexity Theory. All three of these bodies of theory are applicable within the context of river system research. Systems thoeory as a whole has also found application in many other disciplines, e.g. management (eg. Emery, 1969), computer science and information technology (eg. Gelenbe & Mitrani, 1980; Astrom & Wittenmark, 1997), ecology (eg. von Bertalanffy, 1968; Capra, 1996), political studies (eg. Jervis, 1997) and others.

5.3.1 General Systems Theory

The term "General Systems Theory" was first coined by Ludwig von Bertalanffy in 1947 (von Bertalanffy, 1968). It is concisely defined and summarized by Heylighen & Joslyn (1992) as follows:

> "the transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence. It investigates both the principles common to all complex entities, and the (usually mathematical) models which can be used to describe them. Systems theory was

proposed in the 1940s by the biologist Ludwig von Bertalanffy. Von Bertalanffy was both reacting against reductionism and attempting to revive the unity of science. He emphasized that real systems are open to, and interact with, their environments, and that they can acquire qualitatively new properties through emergence, resulting in continual evolution. Rather than reducing an entity (e.g. the human body) to the properties of its parts or elements (e.g. organs or cells), systems theory focuses on the arrangement of and relations between the parts which connect them into a whole (cf. holism). This particular organization determines a system, which is independent of the concrete substance of the elements (e.g. particles, cells, transistors, people, etc). Thus, the same concepts and principles of organization underlie the different disciplines (physics, biology, technology, sociology, etc.), providing a basis for their unification."

Or, in the words of von Bertalanffy (cited by Lucas, 2005),

> "Compared to the analytical procedure of classical science with resolution into component elements and one-way or linear causality as basic category, the investigation of organized wholes of many variables requires new categories of interaction, transaction, organization, teleology..."

The idea of a body of theory that cuts across the boundaries of individual scientific disciplines is an intuitively attractive and potentially highly useful concept for river science, where one of the main challenges is to achieve a common language which can be spoken by practitioners of various disciplines.

General systems theory also suggests that system principles discovered within one discipline are likely to be applicable within other disciplines. It argues that "however complex or diverse the world that we experience, we will always find different types of organization in it, and such organization can be described by principles which are independent from the specific domain at which we are looking. Hence, if we would uncover those general laws, we would be able to analyze and solve problems in any domain, pertaining to any type of system." (Whole Systems Glossary, 2004).

Thus, theory can often be drawn from a diverse range of disciplines to complement the theory of any one particular discipline. As such, General Systems Theory has been instrumental in bringing about the unity of science (von Bertalanffy, 1968).

5.3.2 Nonlinear Dynamical Systems Theory

Dynamical systems theory has been defined as "The mathematical study of the behaviour through time of systems. This studies the attractor structure, bifurcation behaviour and phase portraits of the system." (CALRESCO, 2005).

Some of the most prevalent concepts which fall under the banner of nonlinear dynamical systems theory are chaos, dissipative structures, bifurcation, catastrophe theory, and fractal geometry.

Chaos

A system that exhibits chaos is unpredictable in the long term and is highly sensitive to initial conditions (CALRESCO, 2005). However, it is also bounded, thus restricting the number of potential endpoints and allowing some form of coarse scale prediction.

Dissipative structures

A dissipative structure is a system that takes on and dissipates energy as it interacts with its environment. The term itself expresses a paradox, because dissipative suggests falling apart or chaos, while structure suggests organization and order. Dissipative systems are those able to maintain identity only because they are open to flows of energy, matter, or information from their environments (Prigogine & Stengers, 1984, cited by Scheuler & Scheuler, 2001).

Fractals

Fractals are forms or shapes that are self-similar, ie. they repeat themselves at a variety of scales such that a view of each scale looks similar to the scales above and below it. Fractal geometry was introduced by Benoit Mandelbrot (who saw the need for a geometry that could describe natural features that traditional Euclidean geometry could not) in 1975. Rodriguez-Iturbe and Rinaldo (1997) along with many others have applied fractal geometry to river systems. It is generally accepted that a self-organized system will exhibit some sort of fractal form, eg. drainage networks.

Bifurcation

A bifurcation is defined as "A point at which a system splits into two alternative behaviours, either being possible, the one actually followed often being indeterminate (unpredictable)." (CALRESCO, 2005).

Catastrophe theory

Catastrophe theory is a body of mathematical theory that was introduced by Thom in the 1960s. It explores how small, continuous changes lead to discontinuities in a system. The "catastrophes", ie. the discontinuities may be points of bifurcation (CALRESCO, 2005).

Complexity Theory

Complexity theory is defined as "The study of how critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties." (CALRESCO, 2005).

The question of the "chaoticity" of a system is key to the understanding of complex systems (Phillips, 1999). A system is chaotic if "its long term behaviour is unpredictable and tiny changes in the accuracy of the starting value rapidly diverge to anywhere in its possible state space. There can however be a finite number of available states, so statistical prediction can still be useful" (CALRESCO, 2004).

Where chaos (termed "deterministic complexity" by Phillips (1999)) is present, a system is highly sensitive to small perturbations. This is termed "sensitivity to initial conditions". Systems on the "edge of chaos" have the tendency to self-organize to a state between order and chaos.

Self-organization

Self-organization is an emergent property of complex systems. Emergent properties are characteristic of complex systems, and are defined as "System properties that are not evident from those of the parts. A higher level phenomenon, that cannot be reduced to a sum of the simpler constituents and needs new concepts to be introduced."; "Modelling emergent dynamical hierarchies is central to future complexity research." (CALRESCO, 2004).

Self-organization in a system refers to the spontaneous emergence of order, without external pressures being applied, in a system that is far from equilibrium (CALRESCO, 2005).

Self-organized criticality

The theory of self-organized criticality states that "a system becomes critical when it reaches a steady state at which every part of it becomes unstable. Then a small fluctuation can trigger changes that produce events, which obey power law distributions, at all space and time scales. Self-organized criticality should not be confused with self-organization resulting in coherent structures, such as hurricanes. The latter is triggered by the system being far from equilibrium and in the thermodynamic regime where the minimum entropy production theorem does not apply." (Tsonis, 1998, p.1)

5.3.3 Origins of Systems Thinking in Geomorphology

Recently, Shin (2000) has traced the development of geomorphological thinking from the time of original researchers like Playfair through to current approaches. It is clear that thinking has moved away from purely reductionist approaches to include more systems approaches.

The first papers in which a systems view of geomorphology was explicitly promoted were those by Strahler (1952) and Chorley (1962). Strahler stated his belief that it had become necessary to move on from the largely historical Davisian view of fluvial geomorphology (e.g. Davis, 1901; Davis, 1980) and to begin appreciating the dynamic nature of geomorphic systems. Chorley went a step further to incorporate the general systems theory established by von Bertalanffy (Shin, 2000). Chorley (1962) felt that the approach of Davis had adopted philosophies relating to closed systems and that it was necessary to view fluvial systems as open systems instead (Shin, 2000). Another seminal paper which indicated the rise of systems thinking must surely have been the acknowledgement of the importance of scale in understanding rivers by Schumm and Lichty (1965).

Since the early 1990s certain researchers have seen fit to view fluvial geomorphology within an explicitly stated systems paradigm. In 1992, a special edition of the journal "Geomorphology" was dedicated to the discussion of geomorphological systems. The selection of papers published in that volume support a systems view of geomorphology whilst acknowledging the potential limitations of the systems approach. Various researchers have gradually built up a sound case for the validity of systems theory as a tool by which to gain an understanding of fluvial systems. More recently, work has been done by workers such as Phillips (e.g. 1999, 2003), Rhoads (1988) and Brunsden (1996) which has moved away from attempts to quantify individual processes and has, instead, moved towards an analysis of systems in terms of their non-linear interactions and complexities related to these.

Research has also been done in the area of landscape system sensitivity to change (Thomas & Allison (eds.), 1993). An understanding of the sensitivity (which includes the concepts of resistance and resilience) of a system to extrinsic change is also important if one hopes to gauge the trajectory of that system. If a system is at some sort of equilibrium and is highly sensitive to change, it may also paradoxically be highly resilient to change (if negative feedback allows rapid self-adjustment). However, if a system is sensitive to change due to the fact that it is chaotic or at the edge of chaos, then it might be highly susceptible to imposed change. If a system structure is highly resistant to change, then it is likely to withstand a high degree of imposed change to drivers/inputs. However, if a large enough change to drivers is imposed (eg. a dam is built across a channel), then recovery from the change may be

unlikely if the system is also resistant to intrinsic (self-regulatory) changes. Such a system would have low resilience. The sensitivity of a system will pose interesting challenges to managers who will need to weigh up the issues of resilience and resistance when deciding to what degree the river system can be changed and/or managed.

Of particular importance in the context of this research project is the work presented by Phillips (1992) and Thomas & Allison (1993) as these works cite examples where developed theoretical constructs have been applied and tested. Furthermore, there has been work done which aims to improve the understanding of geomorphological systems by presenting a clearer understanding of climatic systems which are intricately linked with them (Viles & Goudie, 2002).

The importance of self-organization theories

Within the context of this particular project, perhaps the most intriguing systems concept is that of self-organization. As has been pointed out in Chapter 2 of this report, the original notion of a "reference condition" has been replaced as a systems perspective has been taken. It now seems more important to understand the system that is being dealt with, and to gain some idea of the trajectory that it is on. If systems tend to self-organize after a perturbation, then a measure of a system's type and degree of self-organization would go a long way towards allowing one to gain an understanding of its trajectory, and hence its potential endpoints. Thus, if systems tend to self-organize, it is necessary to understand the different types of self-organization that can occur, eg. self-organized criticality, stabilizing self-organization, etc.

5.3.4 Applicability and Application of Self-organization Theory in Geomorphology

A comprehensive review of the different definitions of self-organization and studies which illustrate these is presented by Phillips (1999), who states his belief that "the determination of the self-organization properties of a landscape should be a starting point rather than a goal of geographic explanation" (p.466). Research undertaken at a variety of scales suggests that self-organization does take place in geomorphological systems. Although the examples given below relate particularly to fluvial geomorphology, the idea of self-organization has been investigated by other geomorphologists as well, for example Coco *et al.* (2003) who studied self-organization in beach cusp formation systems and Phillips (2000) who studied self-organization in soil forming proceses.

In the context of fluvial geomorphology, at the landscape scale, Rigon *et al*. (1994) have proposed what they term a "quantitative characterization of landscape forming processes" within a framework of self-organized criticality. They argue that understanding the mechanisms of landscape evolution depends on an understanding of geomorphological thresholds, principles of minimum energy expenditure and self-organized criticality. A link between landscape forming processes and fractal dimensions of landscapes is suggested (Rigon *et al*., 1994), whereby self-organizing processes manifest as fractal landscape patterns. Rodriguez-Iturbe and Rinaldo (1997) also link the fractal nature of river networks to self-organized criticality (Tsonis, 1998). Along the same lines of reasoning, de Boer (1999) uses modelled fluvial systems to argue that landscape-scale order and pattern is a result of processes which are happening at a small scale over long periods of time as landscape systems organize themselves. Bolliger *et. al* (2003) found that modelled systems that exhibited self-organized criticality, and hence fractal dimensions, were robust to imposed variations in initial conditions and to perturbations.

At the planform scale, Stolum (1996) hails river meandering as a self-organization process. He found, by looking at empirical data as well as simulated data, that "the meandering process self-organizes the river morphology, or planform, into a critical state characterized by fractal geometry" (Stolum, 1996, p.1). Work presented by Hooke (2004) supports the notion that rivers meander in such a way as to reach a critical state of sinuosity at which point clustering of meander cutoffs takes place. Stolum (1996) further states that the state of a river's planform fluctuates at a critical state between being ordered and chaotic.

At the reach scale, Fonstad and Marcus (2003) have concluded that bank failure could indicate that a system is reaching a state of self-organized criticality. When the lengths of bank failures were measured over long distances, power law relationships between the magnitude and number of bank failures were revealed. Fonstad and Marcus (2003) suggest that these power-law structures "can be interpreted as the spatial signal of a self-organized critical system, in which local instabilities function to generate broader scale order." (Fonstad & Marcus, 2003, p.281). In this paper, they argued that if a system is at a critical state, then stability is likely to be an impossible goal on the part of river managers. In fact, local stabilization, and hence a reduction in small, frequent points of instability, could lead to an increase in the number of large scale failures or areas of instability (Fonstad & Marcus, 2003).

At the scale of the morphological unit, Church *et al.* (1998) present field and experimental observation data of what they term "stabilizing self-organized structures" in gravel-bed stream channels. This is a different concept to the self-organized criticality identified previously in this section. These self-organizing structures significantly reduce sediment transport and are considered to promote stability in gravel channels.

5.3.5 Limitations of Systems Theory in Understanding Geomorphological Systems

Phillips (1996) states that although nonlinear dynamical systems (NDS) theory has offered a suite of very useful concepts and tools to fluvial geomorphologists, the application of this theory should be undertaken with caution. Geomorphological systems have been shown to exhibit some of the more intricate traits of nonlinear dynamical systems, such as self-organization and deterministic chaos. However, Phillips (1996) has identified for troubling aspects to identifying whether geomorphological systems exhibit deterministic uncertainty. These are:

a) expectations of what NDS theory can or should reveal are unrealistic

b) many NDS concepts and analytical techniques are imported from mathematics and physics, where the simple, abstract systems bear little resemblance to complicated real-world landscapes

c) NDS analyses are often based on mathematical models which lack rigorous field tests

d) merely showing that a geomorphic system exhibits deterministic complexity, while providing a plausible explanation for unexplained real-world complexity, provides no mechanistic explanations of geomorphic process or evolution.

Phillips (1996) concludes that some of the concepts and definitions of traditional, mainstream nonlinear dynamical systems theory may indeed be inappropriate to earth surface systems. However, he also argues that it is worth developing appropriate alternative concepts and definitions for earth science as many testable hypotheses developed within NDS theory have shown themselves to be relevant to the earth sciences.

5.4 RELEVANCE OF THE SYSTEMS PARADIGM TO THIS PROJECT

The primary aim of this project was to derive a method by which to gauge the geomorphological reference conditions for South African rivers. If these systems are indeed nonlinear dynamical systems, however, deriving a "reference condition" may be redundant. These systems exhibit chaos and associated unpredictability and although sensitive to initial conditions, these initial conditions become irrelevant to the present condition.

Self-organization, and particularly self-organized criticality, is a systems concept which needs to be further investigated in the context of managing South African river systems. Self-organisation is a measure of the systems intrinsic adaptation to the current set of external drivers. Self-organised criticality implies a hierarchy of pattern and structure that could be considered to be the optimal ecosystem condition given the current externalities. The 'reference condition' may be better thought of as the *attractor* to which the system is tending, rather than a *past* condition from which it has moved. It is proposed that the degree of self-organisation is a better measure of ecosystem health than a measure that compares the present condition to a historic reference condition. The challenge is to find ways of measuring self-organisation in geomorphic systems. Research reviewed in this chapter has shown how this challenge is being addressed by a number of geomorphologists working abroad; we now need to apply and adapt these methods to South African rivers.

Self-organised criticality also has implications for how we conceptualise instability. The concepts of stability and instability need to be clarified. Instability is often viewed as an indication of an "unhealthy" system. However, within a systems paradigm, it would seem that instability, if viewed in context, may give some indication of a system's trajectory towards a critical state. Work done abroad suggests that instability at one level of the hierarchy may in fact indicate the establishment of order at a higher level (eg. Fonstad and Marcus, 2003). Mathematical relationships (power law functions) that indicate that a system is tending towards self-organized criticality have been identified between the magnitude and number of instability features such as bank failures (Fonstad & Marcus, 2003). We therefore need to review our perceptions of channel instability in the context of managing South African river systems.

Ideas introduced in this chapter will be expanded upon in a PhD thesis that is currently being completed in the Rhodes University geography department. The aim of this thesis is twofold. Firstly, the thesis will examine the philosophical underpinnings of fluvial geomorphology in South Africa. Secondly, it aims to explore the relevance, applicability and implications of the systems approach to fluvial geomorphological problems.

5.5 GLOSSARY OF SYSTEMS TERMINOLOGY INTRODUCED IN THE CHAPTER

For the reader's convenience, the important terms introduced in this chapter are as follows:

GLOSSARY OF SYSTEMS TERMINOLOGY

a) attractor: "A point to which a system tends to move, a goal, either deliberate or constrained by system parameters (laws). The three standard attractor types are fixed point, cyclic and strange (or chaotic)" (CALRESCO, 2004).

b) chaotic system: A system is chaotic if "its long term behaviour is unpredictable and tiny changes in the accuracy of the starting value rapidly diverge to anywhere in its possible state space. There can however be a finite number of available states, so statistical prediction can still be useful" (CALRESCO, 2004).

c) complex systems: (i) "Systems not describable by a single rule. Structure exists on many scales whose characteristics are not reducible to only one level of description. Systems that exhibit unexpected features not contained within their specification. Systems with multiple objectives." (CALRESCO, 2004).

(ii) "Systems that are on the edge of order and chaos. Although a complex system is not predictable over a very long time interval, it does retain information about its past. A complex system also displays the following qualities: Control of the system is dispersed rather than centralized. Components of the system spontaneously organize themselves into patterns. The system is adaptive to its environment. The system contains multiple equilibria or niches. The system has many levels of organization. The system demonstrates emergent behavior." (Susquehanna University, 2004).

d) dissipative system: "A system is referred to as dissipative if there are certain end-points (named attractors) in its state/phase space that its trajectory tends towards. In contrast to being termed "dissipative", a system would be termed "conservative" if there were no attractors in its phase space, and "ergodic" if its trajectory eventually "covers" the entire phase space (Center for Naval Analysis, 2004).

e) emergence: "System properties that are not evident from those of the parts. A higher level phenomenon, that cannot be reduced to a sum of the simpler constituents and needs new concepts to be introduced."; "Modelling emergent dynamical hierarchies is central to future complexity research." (CALRESCO, 2004).

f) linear systems: those who's relationships are proportional, and for which the best fitting regression line is a straight one.

g) nonlinear systems: those whose " outputs are not proportional to the inputs across the entire range of the inputs." (Phillips, 2003, p.4).

h) state space: "The total theoretical possibilities available to the system, by combinations of the parts."; state space is often referred to as phase space (CALRESCO, 2004).

i) system:
(i) "Any organized assembly of resources and procedures united and regulated by interaction or interdependence to accomplish a set of specific functions." (United States Joint Forces Command, 2004).
(ii) "A set of actors or entities bound together by a set of rules and relationships into a unified whole. A system's health is dependent on the health of the whole pattern, which can sometimes be reflected (and thus measured) in the status of a key part of the system." (State of New Jersey, 2004).

j) systems theory: "The interdisciplinary idea that systems of any type and in any specialism can all be described by a common set of ideas related to the holistic interaction of the components. This nonlinear theory rejects the idea that system descriptions can be reduced to linear properties of disjoint parts."; " The systems approach relates to considering wholes rather than parts, taking all the interactions into account. It considers processes rather than things to be primary." (CALRESCO, 2004).

k) trajectory: "The path through *state space* taken by a system. It is the sequence of states plotted against time." (CALRESCO, 2004).

CHAPTER 6
CONCLUSION

6.1 SUMMARY OF AIMS

This project set out to achieve the following aims:

- to establish a geomorphological database for South African rivers.
- to develop a method to determine the geomorphological reference condition (GRC) for a river reach.
- to develop guidelines for classification of the present geomorphological state (PGS).
- to refine the geomorphological index for the biomonitoring programme.

6.1.1 Establishing a geomorphological database for South African rivers

Data has been collected for some 200+ sites from across South Africa. The distribution of these sites reflected the activities of the NRHP; there is a concentration of sites in Mpumalanga, Limpopo and KwaZuluNatal. The NRHP became active in Free State and the Western Cape during the course of this project so new sites were added in to reflect this. Progress in the Eastern Cape and Northern Province has been slow.

These data have been collated in the first instance into an Excel database. An early version of an interactive database using visual basic was developed but continued problems of programme development delayed its full development. Meanwhile new approaches to developing geomorphological indices linked to a National Ecostatus project lead to this database being superseded by a rule-based model using Excel. It is proposed that this new model forms the basis of the geomorphological database. (see section 6.1.3 below). Eventually the data should be incorporated into the national rivers' database.

The majority of data collected to date has been based on an earlier version of data forms. These are being converted to the new format and the data entered into the GAI rule based model so as to derive ecological categories for all monitoring sites. This has not presented too great a problem for sites familiar to the project researchers; where data were collected by other field workers it has been more difficult to make the conversion. This will reduce the confidence level for these sites.

Through this data collection programme, field scientists from the RHP have been introduced to geomorphological data and a number of data collectors have been given training in data collection. These include practitioners from Limpopo Province, the Western Cape and the Eastern Cape (Unitra). Geomorphological data is now collected on a regular basis in Limpopo and the Western Cape Provinces. Geomorphology has been included explicitly in state of the rivers reports from both these provinces. The state of rivers' report for the Buffalo River, Eastern Cape (DWAF, 2004) also includes a key contribution from a geomorphologist on this project team.

6.1.2 Developing a method to determine the geomorphological reference condition (GRC) for a river reach

The hypothesis on which this project was based initially was that channel gradient for a river reach could be used to classify river reaches into zone class, and that each zone class will have a characteristic morphology classified in terms of reach type and dominant bed material. This was based on the zonation concepts developed by Rowntree and Wadeson in an earlier WRC project (Rowntree and Wadeson, 1999; Rowntree *et al.* 2000).

Rowntree and Wadeson first presented their geomorphological zonation concepts at a workshop in Cape Town in 1996 (Uys *et al.*, 1996). It was at this workshop that the initial gradient classes related to the different zones were established in discussion with river ecologists from across South Africa. These classes were later modified according to the experience of the researchers. The final classification was presented by Rowntree *et al.* (2000).

Since the Cape Town workshop the geomorphological zonation concept has been widely accepted by river ecologists and the framework has been integrated into a number of management related protocols including Reserve determinations. The CSIR's River signature project is based on zonation concepts that are closely related to those proposed in this project.

Although geomorphological zonation has been accepted by many river ecologists, the links between zone class and channel morphology has often been based on 'intuition'. Zonation appears to work and has provided apparently sensible guides to field workers.

More rigorous testing based on 150 sites has not, however, been able to confirm a clear link between channel gradient and channel morphology, or stream power (which incorporates a discharge component) and channel morphology. There are a number of reasons why this might have been the case:

a. Reach type is not the most suitable descriptor of channel morphology
b. The level of analysis was too superficial
c. Sites were not correctly classified
d. Sites were not representative of the reaches in which they are situated
e. Dominance of zones D and E makes the data too homogenous for any differentiation to be meaningful.
f. The majority of sites have been modified away from their reference condition

It must be concluded therefore that, given the available data, the project has not been successful in deriving a method for determining reference condition based on geomorphological zones. It has confirmed how difficult it is to understand rivers from snapshots in time and space. Unfortunately given the wide spread of sites and the number of river systems represented, it was not feasible in the time available to undertake an in-depth analysis of spatial linkages and trajectories of change for this number of sites. The more focussed research undertaken by the CWE at Wits University into rivers of the Kruger Park has significantly increased our understanding of these systems, particularly the Sabie River (e.g. van Niekerk *et al*., 1995; Heritage *et al*., 1997; Jewitt *et al*., 1998; Rountree *et al*., 2000), but the geographical scope of this work is limited. Moreover the effort involved was beyond the time scale determined by the constraints of many management scenarios. We need to develop a more rapid method that can be applied to a range of rivers.

6.1.3 Developing guidelines for classification of the present geomorphological state (PGS) & refining the geomorphological index for the biomonitoring programme

Guidelines for the classification of the present ecological state (geomorphology) were developed in association with the DWAF sponsored Ecostatus project driven by Kleynhans and Louw (Kleynhans *et al*. 2005). One product of the Ecostatus project was a rule-based model that integrates the extent to which changes in the components of the geomorphological system are believed to compromise the natural rive. This model was termed the geomorphological driver assessment index (GAI).

The GAI can be used to assess the ecological category of a reach, which in turn can be applied to assessing the present ecological state and the recommended ecological category. It can also be used to examine the effect of different management scenarios on the geomorphological system. Although the development of the GAI has been within the context of determining Environmental Water Requirements, the index can also be used as a component of river health and is recommended by the project researchers as the standard method for carrying out geomorphological assessments within the National River Health Programme.

A fundamental difference between the GAI as presented here and earlier assessment methods is a change to the conceptualisation of the reference condition. Rather than seeing the reference condition as being a deterministic channel morphology that can be predicted from reach and catchment controls, the reference condition is conceptualised as a geomorphological system composed of flows, storages and responses that are dynamic and indeterminate. This thinking is in line with the systems paradigm that is being applied increasingly to fluvial geomorphology. This paradigm is explored further in Chapter 5.

6.2 A NEW RESEARCH DIRECTION

The primary aim of this project was to derive a method by which to gauge the geomorphological reference conditions for South African rivers. If these systems are indeed nonlinear dynamical systems, as is proposed in Chapter 5, deriving a "reference condition" may be redundant. These systems exhibit chaos and associated unpredictability and although sensitive to initial conditions, these initial conditions become irrelevant to the present condition.

It is suggested that the 'reference condition' may be better thought of as the *attractor* to which the system is tending, rather than a *past* condition from which it has moved. Furthermore, it is proposed that the degree of self-organization is a better measure of ecosystem health than a measure that compares the present morphology to a historic reference condition. A systems theory framework could usefully be applied to understanding and managing trajectories of change in river systems.

These ideas have influenced the thinking behind the GAI. The GAI is assessed in terms of changes to system drivers rather than changes to morphology *per se*. The GAI can potentially incorporate the idea of geomorphological self organisation as a measure of ecosystem health, but this in itself requires a reorientation of mind set that has not yet been put in place. Further development of conceptual frameworks will be needed to achieve this.

Work done abroad has identified self-organization at a variety of scales in geomorphological systems (see Chapter 5). In order to explore this idea further within the South African context, certain research needs can be identified.

Further research into relevant theory needs to be undertaken in order to establish sound conceptual links between stability, instability and pattern at different scales. Methods by which to measure instability and pattern, as well as system sensitivity and self-organization at different scales need to be standardised. Once a sound theoretical base and methodology have been established, these concepts need to be investigated in the laboratory (by means of flume experiments) as well as in the field.

In terms of field work, it would be useful to identify appropriate catchments as case studies. It would be interesting to study a relatively unimpacted system (e.g. the Baviaanskloof River), a moderately impacted system (e.g. the Keiskamma River) and a system that has been linked to another system via an inter-basin transfer (e.g. the Skoenmakers River).

In order to gain an understanding of each catchment, the first step would be to conduct as thorough an historical study of each catchment as possible in terms of tectonic activity, flood history, landuse change, development within the catchment and alteration of flow regime by impoundments.

With this contextual backdrop in place, the next step would be to describe each catchment (system) completely in terms of its geology, climate, size, shape, drainage pattern, landuse, soils, and vegetation. This would be an ideal opportunity to involve a team of students who would be required to undertake extensive detailed surveys of system instability, pattern and sensitivity. It has been proven that pattern can often only be discerned when a large enough area is surveyed (e.g. Fonstad and Marcus, 2003).

Once this data has been collected in the field, it will need to be analysed in order to identify patterns which may point to self-organization, or self-organized criticality.
Data analysis will require mathematical and computer expertise due to the advanced nature of the mathematical concepts involved.

Finally, based on the results of these studies, a critical appraisal of currently accepted management paradigms needs to be undertaken. This will require an integration of management objectives and scientific theory which, it is hoped, would be strengthened by research of the type that has been suggested here.

REFERENCES

Abernethy, B. & Rutherfurd, I.D., 2000: Does the weight of riparian trees destabilize riverbanks?, *Regulated Rivers Research and Management*, 16, p.565-576.

Alabyan, A.M. & Chalov, R.S., 1997: Types of river channel patterns and their natural controls, *Earth Surface Processes & Landforms*, 23, p.467-474.

Andrews, E.D., 1980: Effective and bankfull discharges of streams in the Yampa River Basin, Colorado and Wyoming, *Journal of Hydrology*, 46, p. 311-330.

Apfelbeck, R., 2001: *Montana Reference Condition Questionnaire Summary, Reference Condition Subgroup, Montana Department of Environmental Science* [Online]. Available: http://www.water.montana.edu/watersheds/mwcc/workgroups/RCresponse Summary.rtf [2002, October 29].

Astrom, K.J. & Wittenmark, B., 1997: *Computer-controlled systems : theory and design*, Prentice-Hall, New Jersey.

Baker, V.R., 1977: Stream-channel response to floods, with examples from central Texas. *Geological Society of America Bulletin*, 88, p.1057-1071.

Bendix, J., 1999: Stream power influence on southern Californian riparian vegetation, *Journal of Vegetation Science*, 10, p.243-252.

Bolliger, J., Sprott, J.C., Mladenoff, D.J., 2003: Self-Organization and Complexity in Historical Landscape Patterns, *Oikos*, 100(3), p.541.

Broadhurst, L.J., Heritage, G.L., van Niekerk, A.W., James, C.S. & Rogers, K.H., 1997: *Translating Discharge into Local Hydraulic Conditions on the Sabie River: An Assessment of Channel Flow Resistance*, WRC Report No. 474/2/97, WRC, Pretoria.

Brunsden, D., 1996: Geomorphological Events and Landform Change, *Zeitschrift fur Geomorphology*, 40(3), p.273-288.

CALRESCO (Complex and Artificial Life Research Concept), 2004: Complex systems glossary [Online]. Available: www.calresco.org/glossary.htm [2004, July].

Capra, F., 1996: *The web of life : a new synthesis of mind and matter*, Harper Collins, London.

Center for Alternative Development Initiatives, 2004: *Glossary of terms* [Online]. Available: www.cadi.ph/glossary_of_terms.htm [2004, September].

Center for Naval Analysis, 2004: *Nonlinear dynamics and complex systems theory (glossary).* [Online]. Available: http://www.cna.org/isaac/Glossb.htm [2004, September].

Chorley, R.J., 1962: Geomorphology and General Systems Theory, *US Geol. Survey Professional Paper*, 500B, p.1-10.

Church, M., Hassan, M.A. & Wolcott, J.F., 1998: Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations, *Water Resources Research*, 34(11), p.3169-3179.

Coco, G., Burnet, T.K., Werner, B.T. & Elgar, S., 2003: Test of Self-Organization in Beach Cusp Formation, *Journal of Geophysical Research*, 108(C3), p.3101.

Dallas, H.F., 2000: *The derivation of ecological reference conditions for riverine macroinvertebrates*, NAEBP Report Series No.12, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria.

Dallas, H and Fowler, J., 2000: *Delineation of river types of Mpumalanga, South Africa: establishing a spatial framework for selection of reference sites.* NAEBP Report Series No. 9, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

Davis, W.M., 1901: *Physical Geography*, Ginn, Boston, Mass.

Davis, W.M., 1980: *The Physical Geography (Geomorphology) of William Morris Davis/ compiled, illustrated, edited and annotated by Philip B. King and Stanley A. Schumm*, Geo. Abstracts, Norwich.

de Boer, D.H., 1999: Self-Organization in Fluvial Landscapes: Sediment Dynamics as an Emergent Property, *GeoComputation* [Online] Available: www.geovista.psu.edu/sites/geocomp99/Gc99/074/gc_074.htm [2005, March 17].

Department of Water Affairs and Forestry, 2004: River Health Programme (2004), *State of Rivers Report: Buffalo River System*, DWAF, Pretoria.

Dollar, E.S.J., 2000: *The determination of geomorphologically effective flows for selected eastern sea-board rivers in South Africa*, Unpublished PhD thesis, Geography Department, Rhodes University.

Dollar, E.S.J. & Rowntree, K.M., 2003: *Geomorphological Research for the Conservation and Management of Southern African Rivers, Vol. 2, Managing Flow variability: the geomorphological response*, Water Research Commission Report 849/1/03.

Emery, F.E., 1969: *Systems thinking: selected readings*, Penguin, Middlesex.

Environment Canada, 1999: *The Reference Condition Approach* [Online] Available: http://www.nwri.ca/issues/cabin/referenceconditionapproach.html [2002, October 28].

Fonstad, M. & Marcus, W.A., 2003: Self-Organized Criticality in Riverbank Systems, *Annals of the Association of American Geographers*, 93(2), p.281-296.

Freeman, N.M. & Rowntree, K.M., 2005: *Our Changing Rivers: an introduction to the science and practice of fluvial geomorphology,* Water Research Commission No. TT 238/05.

Fryirs, K.A., Brierly, G.J., Preston, N.J. & Kasai, M., in press, Buffers, Barriers and Blankets: The (dis)connectivity of catchment-scale sediment cascades, *Catena*, research paper in press.

Gelenbe, E. & Mitrani, I., 1980: *Analysis and synthesis of computer systems*, London Academic Press.

Gregory, K.J., 1977: The Context of River Channel Changes. In Gregory, K.J.(ed), *River Channel Changes*, John Wiley & Sons, Ltd., Chichester.

Hattingh, J., 1994: Depositional Environment of Some Gravel Terraces in the Sundays River Valley, Eastern Cape, *South African Journal of Geology*, 97(2), p.156-166.

Heritage, G.L., van Niekerk, A.W., Moon, B.P., Broadhurst, L.J., Rogers, K.H. & James, C.S., 1997: *The Geomorphological Response to Changing Flow Regimes of the Sabie and Letaba River Systems*, WRC Report No. 376/1/97, WRC, Pretoria.

Hey, R.D., 1974: Prediction and effect of flooding in alluvial systems, *Geol. Soc. Misc. Paper*, 3, p.42-56.

Heylighen, F. & Joslyn, C., 1992: What Are Cybernetics And Systems Science?, adapted from *Principia Cybernetica Web*, [Online]. Available: http://pespmc1.vub.ac.be/SYSTHEOR.html [2003, October 18].

Hooke, J.M., 2004: Cutoffs galore!: occurrence and causes of multiple cutoffs on a meandering river, *Geomorphology*, 61, p.225-238.

Hupp, C.R., 1990: Vegetation patterns in relation to basin hydrogeomorphology. In Thornes, J.B. (ed.), *Vegetation and erosion*, John Wiley & Sons, Chichester.

Interoperability Clearinghouse, 2004: *Glossary of terms*, [Online]. Available: www.ichnet.org/glossary.htm [2004, September].

Iversen, TM, Madsen, BL, and Bøgestrand, J (2000) River conservation in the European Community, including Scandinavia, in *Global Perspectives on River Conservation: Science Policy and Practice*, Edited by P.J. Boon, B.R. Davies and G.E. Petts, John Wiley & Sons Ltd.

Jervis, R., 1997: *System effects : complexity in political and social life*, Princeton University Press, New Jersey.

Jewitt, G.P.W., Heritage, G.L., Weeks, D.C., Mackenzie, J.A., van Niekerk, A., Gorgens, A.H.M., O'Keeffe, J., Rogers, K. & Horn, M., 1998: *Modelling Abiotic-Biotic Links in the Sabie River*, WRC Report No. 777/1/98, WRC, Pretoria.

King, J.M., Tharme, R.E. & De Villiers, M.S. (eds), 2000: *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*, WRC Report No. TT 131/00, WRC, Pretoria.

Kleynhans, C.J , Louw, M.D., Thirion, C., Rossouw, N., Rowntree, K., 2005: *River EcoClassification: Manual For Ecostatus Determination*, DWAF/WRC, Pretoria.

Knighton, D., 1984: *Fluvial Forms and Processes*, Edward Arnold, London.

Kuhn, T.S., 1970: *The structure of scientific revolutions*, University of Chicago Press, Chicago.

Laszlo, E., 1972: *The systems view of the world : the natural philosophy of the new developments in the sciences*, Blackwell, Oxford.

Leopold, L.B. and Wolman, M.G. (1957). River channel patterns: braided, meandering and straight. *United States Geological Survey Professional Paper*, 282B, p.39-85.

Lewin, J., 1977: Channel pattern changes. In Gregory, K.J.(ed), *River Channel Changes*, John Wiley & Sons, Ltd., Chichester.

Lucas, C., 2005: Cybernetics and Stochastic Systems, [Online] Available: www.calresco.org/lucas/systems.htm [2005, April 26].

Matrix Group, 2004: *Glossary of Terms*. [Online]. Available: www.ecostructure.com/res_glossary.htm [2004, September].

McHarg, I.L., 1969: *Design With Nature*, Natural History Press, New York.

Mkhandi, S and Kachroo, R. 2001: Regional flood frequency analysis for southern Africa. *Southern Africa FRIEND: IHP Technical Documents in Hydrology*, No. 15, p.130-149.

O'Keeffe, J., 2000: *Environmental Flow Assessments Within the South African Integrated Planning Process for Water Resources*, Chapter 4 in King, J.M., Tharme, R.E. & De Villiers, M.S. (eds), Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology, WRC Report No. TT 131/00, WRC, Pretoria.

Owen, R., no date: *Establishment of Biological Reference Conditions and Setting Class Boundaries in the EU Water Framework Directive*, Scottish Environment Protection Agency.

Phillips, J.D., 1996: Nonlinear dynamics and predictability in geomorphology. In *The Scientific Nature of Geomorphology* (B. Rhoads, C. Thorn, eds.). Proceedings of the 27th Binghamton Geomorphology Symposium. New York: John Wiley, p.315-336.

Phillips, J.D., 1999: *Earth Surface Systems – complexity, order and scale*, Blackwell, Massachusetts.

Phillips, J.D., 2000: Signatures of Divergence and Self-Organization in Soils and Weathering Profiles, *Journal of Geology*, 108, p.91-102.

Phillips, J.D., 2003: Sources of nonlinearity and complexity in geomorphic systems, *Progress in Physical Geography*, 27(1), p.1-23.

Pickup, G. & Warner, R.F., 1976: Effects of hydrologic regime on magnitude and frequency of dominant discharge, *Journal of Hydrology*, 29, p.51-75.

Prigogine, I. & Stengers, I., 1984: *Order out of Chaos: Man's New Dialogue With Nature*, Bantam, Toronto.

Reynoldson, T.B., Norris, R.H., Resh, V.H., Day, K.E. & Rosenberg, D.M., 1997: The reference condition: a comparison of multimetric and multivariate approaches to assess water-quality impairment using benthic macroinvertebrates, *Journal of the North American Benthological Society*, 16(4), p.833-852.

Rhoads, B.L., 1988: Mutual adjustments between process and form in a desert mountain fluvial system, *Annals of the Association of American Geographers*, 78(2), p.271-287.

Rhoads, B.L., 1994: Fluvial Geomorphology, *Progress in Physical Geography*, 18(1), p.103-123.

Rigon, R., Rinaldo, A. & Rodriguez-Iturbe, I., 1994: On Landscape Self-Organization, *Journal of Geophysical Research*, 99(B6), p.971-994.

Rodriguez-Iturbe, I. & Rinaldo, A., 1997: *Fractal River Basins – Chance and self-organization*, Cambridge University Press, Cambridge.

Rosgen, D.L., 1994: A classification of natural rivers, *Catena*, 22(1), p.69-199, Elsevier Science, B.V. Amsterdam.

Rosgen, D.L., 1996: *Applied River Morphology*, Wildland Hydrology Books, Pagosa Springs, Colorado.

Rosgen, D.L., 1998: *The Reference Reach – a Blueprint for Natural Channel Design* [Online] Available: http://www.wildlandhydrology.com/assets/The_Reference_Reach.11.pdf [2002, August].

Rountree, M.W., Rogers, K.H. & Heritage, G.L., 2000: Landscape State Change in the Semi-Arid Sabie River, Kruger National Park, in Response to Flood and Drought, *South African Geographical Journal*, 82(3), p.173-181.

Rowntree, K.M., 2000: Geomorphology. In King, J.M., Tharme, R.E. & De Villiers, M.S. (eds), *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*, WRC Report No. TT 131/00, WRC, Pretoria.

Rowntree, K.M. & Dollar, E.S.J., 1999: Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. *Earth Surface Processes & Landforms*, 24, p.127-134.

Rowntree, K.M. & Wadeson, R.A., 1999: *A Hierarchical Geomorphological Model for the Classification of Selected South African Rivers*, WRC Report No. 497/1/99, WRC, Pretoria.

Rowntree, K. M. and Wadeson, R.A., 2000. *Field manual for channel classification and condition assessment*. NAEBP Report Series No 13 Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

Rowntree, K.M., Wadeson, R.A. & O'Keeffe, J., 2000: The Development of a Geomorphological Classification System for the Longitudinal Zonation of South African Rivers, *South African Geographical Journal*, 82(3), p.163-172.

Rowntree, K M and Ziervogel, G (1999). Development of an index of stream geomorphology for the assessment of river health. National Aquatic Ecosystem Biomonitoring Programme, NAEBP Report Series No 7. Department of Water Affairs and Forestry.

Rutherfurd, I.D., Jerie, K. & Marsh, N., 1999: *A Rehabilitation Manual for Australian Streams*, Vol. 1, LWRRDC & CRCCH, Australia.

Scheuler, G. & Scheuler, B., 2001: *The Chaos of Jung's Psyche*, [Online] Available: www.scheulers.com/ChaosPsyche/glossary.htm [2005, April 26]

Schumm, S.A. & Lichty, R.W., 1965: Time, space and causality in geomorphology, *American Journal of Science*, 263, p.110-119.

Schumm, S.A., 1980: Some applications of the concept of geomorphic thresholds in Coates, D.R. and Vitek, J.D. (editors), *Thresholds in Geomorphology*, George Allen and Unwin, London, p.473-485.

Shin, D., 2000: *Principle Papers in Fluvial Geomorphology: from J. Playfair to I. Rodriguez-Iturbe* [Online]
Available: www.unc.edu/~sdhyok/fall99/geomorph/pdf
[2005, February 25].

Simpson, C.J. & Smith, D.G., 2001: The braided Milk River, northern Montana, fails the Leopold-Wolman discharge-gradient test. *Geomorphology*, 41(4), p.337-353.

Smith, A.M. & Zawada, P.K., 1990: Palaeoflood Hydrology: A tool for South Africa? – An example from the Crocodile River near Brits, Transvaal, South Africa, *Water SA*, 16(3), p.195-200.

State of New Jersey, 2004: Glossary – living with the future in mind. [Online]. Available: www.state.nj.us/dep/dsr/sustainable-state/glossary.htm [2004, September].

Stolum, H., 1996: River Meandering as a Self-Organization Process, *Science*, 271(5256), p.1710.

Strahler, A.N., 1952: The Dynamic Basis of Geomorphology, *GSA Bulletin*, 63(9), p.923-938.

Susquehanna University, 2004: [Online]. Available: www.susqu.edu/facstaff/b/brakke/complexity/glossary.htm [2004, September].

Tharme, R., 2000: An Overview of Environmental Flow Methodologies, with Particular Reference to South Africa. In King, J.M., Tharme, R.E. & De Villiers, M.S. (eds), *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*, WRC Report No. TT 131/00, WRC, Pretoria.

Thirion, T. & C.J. Kleynhans (2003) Terms of Reference: Development of an integrated system to derive an overall present ecological status for rivers. Resource Quality Services, DWAF.

Thomas, D.S.G. & Allison, R.J., 1993: Landscape Sensitivity, Wiley, Chichester.

Thorne, C.R., 1990: Effects of vegetation on riverbank erosion and stability. In Thornes, J.B. (ed.), *Vegetation and erosion*, John Wiley & Sons, Chichester.

Thornes, J.B., 1977: Hydraulic Geometry and Channel Change. In Gregory, K.J.(ed), *River Channel Changes*, John Wiley & Sons, Ltd., Chichester.

Thornes, J.B., no date: Palaeohydrological modelling: from Palaeohydraulics to Palaeohydrology, in Gregory, K.J. (ed.), *Palaeohydrology and Global Climate Change*, Wiley, Chichester.

Tsonis, A., 1998: Fractal River Basins: Chance and Self-Organization (review), *Science*, 280(5367), p.1210.

United States Joint Forces Command, 2004: *Joint forces command glossary*. [Online]. Available: www.jfcom.mil/about/glossary.htm. [2004, September].

Uys M.C. (ed.) Classification of rivers, and environmental health indicators. Proceedings of a joint South African/Australian workshop. Cape Town, South Africa. Water Research Commission Report No. TT 63/94.

van Niekerk, A.W., Heritage, G.L. & Moon, B.P., 1995: River Classification for Management: the Geomorphology of the Sabie River in the Eastern Transvaal, *South African Geographical Journal*, 77(2), p.68-76.

Viles. H.A., 1990: The Agency of Organic Beings: a Selective Review of Recent Work in Biogeomorphology, in *Vegetation and Erosion*, J. Thornes (ed.), Wiley, New York, p.5-24.

Viles, H.A. & Goudie, A.S., 2002: Interannual, Decadal and Multidecadal Scale Climatic Variability and Geomorphology, *Earth Science Reviews*, 61(1-2), p.105-131.

von Bertalanffy, L., 1968: *General system theory : foundations, development, applications*, Penguin Press, London.

White, G.F., 1971: A Perspective of River Basin Development. In Kates, R.W. & Burton, I. (eds.), *Geography, Resources and Environment, Vol.I, Selected Writings of Gilbert F. White*, University of Chicago Press, Chicago & London, p.39-79.

Whole Systems Glossary, 2004: [Online]. Available: www.worldtrans.org/whole/wholedefs.html [2004, September]

Wisconsin K-12 Energy Education Programme, 2004: Definitions. [Online]. Available: www.uwsp.edu/cnr/wcee/keep/Mod1/Unitall/definitions.htm [2004, September].

Wolman, M.G. & Miller, J.P., 1960: Magnitude and frequency of forces in geomorphic processes, *Journal of Geology*, 68, p.54-74.

Zawada, P. & Hattingh, J., 1994: Studies on the palaeoflood hydrology of South African rivers, *South African Journal of Science*, 90, p.567-568.

Other related WRC reports available:

Refinement of geomorphological tools for the sustainable management of the river environment.

Wadeson RA; Rowntree KM

Existing riparian habitat assessment protocols do not directly address the relationship between habitat and the adjacent landscape. Given the values of riparian areas in the landscape, the objectives of habitat rehabilitation should include the reinstatement of such values and functions. This project will develop appropriate protocols.

Report Number: 1181/1/04 **ISBN No: 1 77005 284 4**

TO ORDER: Contact **Publications** - Telephone No. 012 330 0340
Fax Number: 012 331 2565
E-mail: publications@wrc.org.za

Water Research Commission
Private Bag X03, Gezina, 0031, South Africa
Tel: +27 12 330 0340, Fax: +27 12 331 2565
Web: http://www.wrc.org.za

Designed by The Kashan Group K-2102 (www.kashangroup.com)