An Investigation into the Classification of River Environments Using GIS:

The Case of KwaZulu-Natal Rivers

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Abstract

According to the National Water Act No. 36 of 1998 (DWAF 1999), classification of the water resources in South Africa is the initial step towards the implementation of protection or management programmes. This study reviews different methods and systems of classifying river environments, in order to recommend a convenient, efficient and flexible classification scheme for describing the conditions of river environments. To meet this challenge, the study proposes the use of Geographical Information System (GIS) as a tool to link different controlling variables of river environments and thereafter analyse their spatial relationships.

The study supports the use of GIS in river environment classification, with special emphasis on its functionalities that make it possible to explore and manipulate data interactively and easily. The GIS allows the user a flexible way to analyse the geomorphologic and ecological controlling variables of the river system. Thus, it enables different arrangements of these controlling variables for a number of classification purposes. The methodology used involves the GIS (database) analyses and map analyses to explore the relationships between geomorphologic and ecological controlling variables of the river ecosystem.

A case study of the KwaZulu-Natal Rivers demonstrates that valuable information for river environments could be derived from available geomorphologic and ecological datasets using methods of analyses within the GIS. In addition, the case study illustrates that it is possible to develop a working classification scheme for a particular purpose. The developed classification scheme can be improved by considering influential factors such as, the use of up-to-date datasets, consistent projection parameters and relevant scale.

Preface

This study represents original work done by the author at the Centre of Environment and Development, University of Natal, Pietermaritzburg under the supervision of Drs. F. Ahmed and N. Quinn. The work of others have been acknowledged and referenced accordingly in the study.

This work has not been submitted in any form for any additional degree or diploma to any other institution.

Signed: ....

M.D. Sebake

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LIST OF ABBREVIATIONS

DEM – Digital Elevation Model

DTM – Digital Terrain Model

DWAF – Department of Water Affairs and Forestry

GIS – Geographical Information System

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Chapter 1 Introduction

1.1 Background

The degradation of river ecosystems due to water resource developments is a great concern throughout the world (Rowntree *et al.* 2000). These developments often do not consider the conditions of rivers, consequently causing deleterious impacts on the river ecosystems. This has seen a great need for the individuals and authorities in various countries to maintain the integrity of the abiotic and biotic components of rivers (Rosgen 1994, Snelder *et al.* 1999). Efforts were made to define and understand the controlling variables of the river ecosystems, which resulted in the development of classification systems for river environments.

Classification systems were developed for different purposes (O'Keeffe *et al.* 1994, Rosgen 1994, Snelder *et al.* 1999), which among others included conservation, protection, planning and management of rivers. Most of the authorities took steps in classification and identification of rivers, to encourage protection and proper management of their catchments (Stein *et al.* 1998). Worldwide, a number of projects and programmes were carried out to understand the functioning of river environments, *inter alia*, the Wild Rivers Project in Australia (Stein *et al.* 1998), a classification of natural rivers in the United States, Canada and New Zealand (Uys 1994, Rosgen 1994), and the River Health Programme in South Africa (Brown *et al.* 1996).

In South Africa, advances were made in terms of legislation – in the form of the National Water Act No. 36 of 1998 (DWAF 1999) – to provide for the protection of water resources (Rowntree *et al.* 2000). These changes in legislative framework could be regarded as a watershed in a country that previously had no significant provisions for legal protection of the river environments. According to Rowntree *et al.* (2000), the legislation would be ineffective without a frame of reference, which describes different classes of rivers according to the level of degradation of their environments. Thus, the legislation gives priority to the classification of river environments, prior to the implementation of protection or management programmes.

The legislation also provides for the monitoring of the health of the nation's rivers through the National River Health Programme (Hohls 1996). Consequently, the provinces of South Africa face a challenge to meet the requirement of the legislation, viz. the identification of river classes, in order to prioritise management of the river environments. Despite the necessity for a classification of river environments, there is no existing classification scheme that could be used for this purpose. The reasons for lack of an appropriate classification scheme are manifold, as will be explained in Chapter 2 below. Thus, for the proposed classification scheme to be successful, it should offer a description of river environments using flexible variables to meet requirements for different purposes. According to Snelder *et al.* (1999), the river environment classification that is designed to be 'flexible' will allow the user to analyse and manage a wide range of issues at different spatial scales.

1.2 The concept of river environment classification

River environment classification was mentioned by Snelder *et al.* (1998) in the Eco-classification Working Group formed by the Ministry for the Environment (MFE) in New Zealand. The purpose of the so-called Eco-classification Working Group was to develop an environmental management framework for rivers including a method for developing a core set of environmental indicators to report on the 'ecological health' of rivers.

This framework was based on a top-down classification by a hierarchy of controlling variables such as climate, geology, and landcover that are known to structure river environments. The advantages of the top-down classification over the top-down classification schemes were highlighted by Snelder *et al.* (1998) as follows:

- The classification was based on physical variables that had been previously mapped at a high level of resolution (approximately 1:50000 scale). Thus, classifications could be developed for the entire regions (or an entire country), from data readily available in Geographical Information System (GIS) format.
- The physical variables are arranged in a hierarchy where each subordinate hierarchical level describes the smaller spatial and temporal scale than its higher level. (e.g. substrate is a function of geology, flow regime and topography).

According to Klijn (1994), this has a generic use in resource management as it can be used to examine cause and effect relationships occurring in both biological and physical conditions of river environments.

The concept of physically based river environment classification was developed further by Snelder *et al.* (1998), by applying the approach to different regions in New Zealand. Snelder *et al.* (1998) used GIS techniques to develop a classification of two rivers in each of the regions at a coarse level of spatial resolution. During the course of this project, a number of classification variables and categories within classes have been refined. These variables are illustrated in Figure 1.1 as a web of connected controlling variables (Snelder *et al.* 1999), which shows a hierarchical classification scheme—the physical variables assumed to be affecting the river environments from the regional to river reach scale (Bailey 1996, Snelder *et al.* 1999).

At the top of the hierarchy (as shown in Figure 1.1) are three variables that are not controlled by other variables, which are climate, geology and topography – hence they are referred to as the '*ultimate variables*'. The 'ultimate variables' are connected directly or indirectly to other subordinate controlling factors (also connected to other variables) in the lower levels of scale. It is worthy noting that the interconnectivity of these controlling variables could be more complex than illustrated in Figure 1.1, depending on the purpose of classification for which they are required.

According to Snelder *et al.* (1998), the principle governing the hierarchical classification scheme is that: the lower order variables are the outcomes of higher order variables (often the interaction between one or more higher order variables), e.g. flood regime is the outcome of climate, geology, vegetation and land use. It is evident in this case that the use of hierarchical sets of criteria provides a way of defining similarities (or differences) at different levels of resolution for different purposes. But, combining these controlling variables to develop a practical river classification scheme for a particular purpose, proved to be a great challenge for researchers (O'Keeffe *et al.* 1994, Rosgen 1994, Snelder *et al.* 1999).

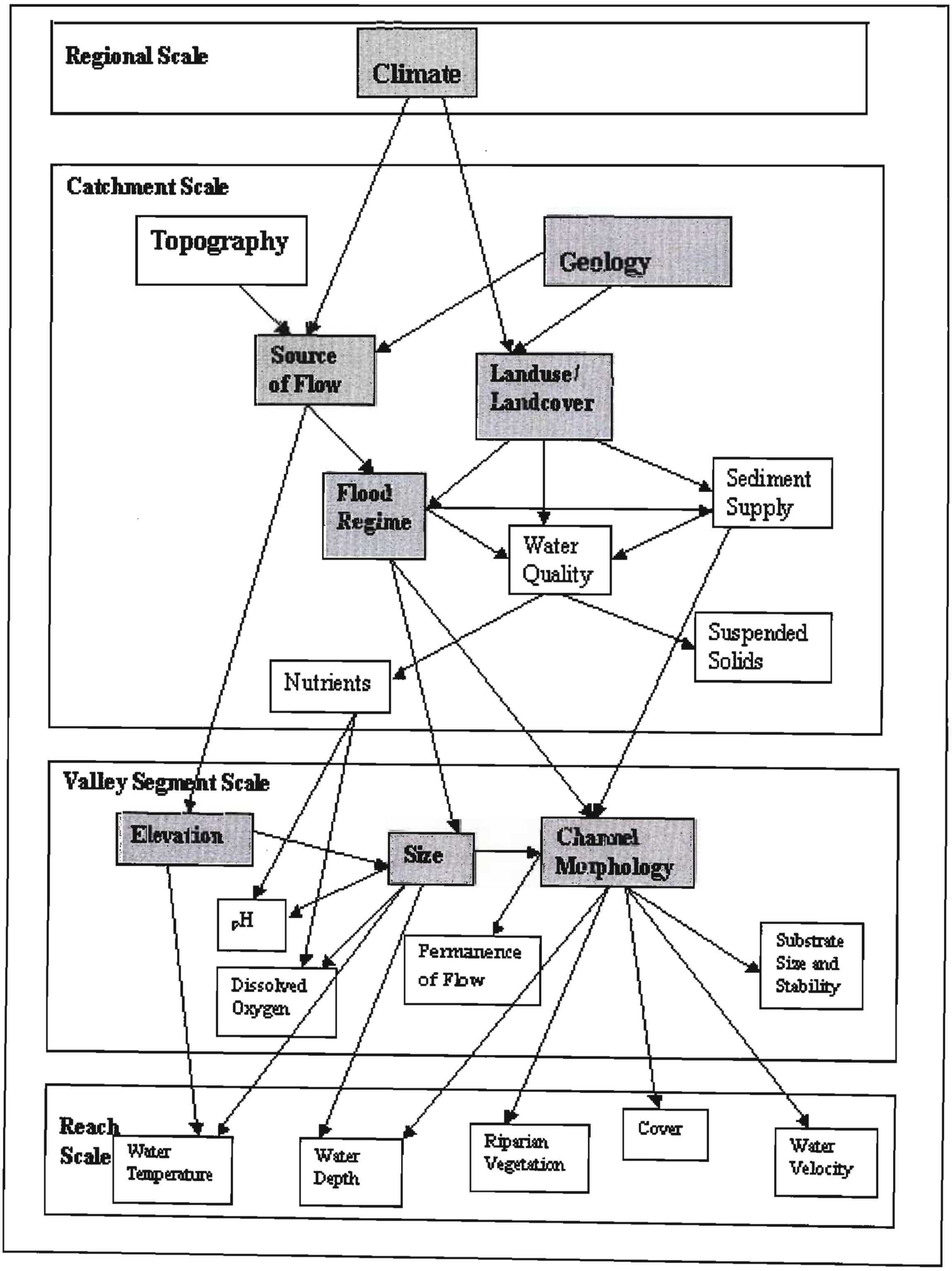

Figure 1.1 Physical variables affecting habitat in rivers, showing ultimate variables (bold), and variables used to classify river environments (shaded). (Snelder *et al.* 1999)

The challenge in developing a river classification scheme (appropriate for river environment classification) lies in the ability to find a means of combining different classification systems, which were originally derived for different objectives and scales. As one researcher has noted:

> 'the different systems have different objectives; however if we were to use a tool like GIS, we may be able to link them – while recognising and maintaining their differences' (Uys 1994, p.83).

This statement forms the basic premise of this dissertation that 'a GIS is one of the important technologies providing spatial data integration and tools for natural resource management' (Sarraf *et al.* 2000). The main focus of this dissertation is to investigate the capabilities of the GIS technology to develop an effective, flexible river environment classification scheme that may be used for different purposes.

1.3 River environment classification developments in South Africa

In South Africa the developments in the National Water Act No. 36 of 1998 (DWAF 1999) – from the precursor Act of 1956 – made provisions for the protection of water resources. These changes in legislative framework could be regarded as a watershed in a country, which previously had no provisions for legal protection of the environment (DWAF 1999). The National Water Act No. 36 of 1998 recognises the 'Reserve', which comprises of basic human needs and ecological needs. The protection of the water ecosystems was related to the identification of the 'Reserve' (Figure 2.1), which is (a factor) dependent on other characteristics such as instream flow, water levels, the presence and concentration of substances in the water, etc.

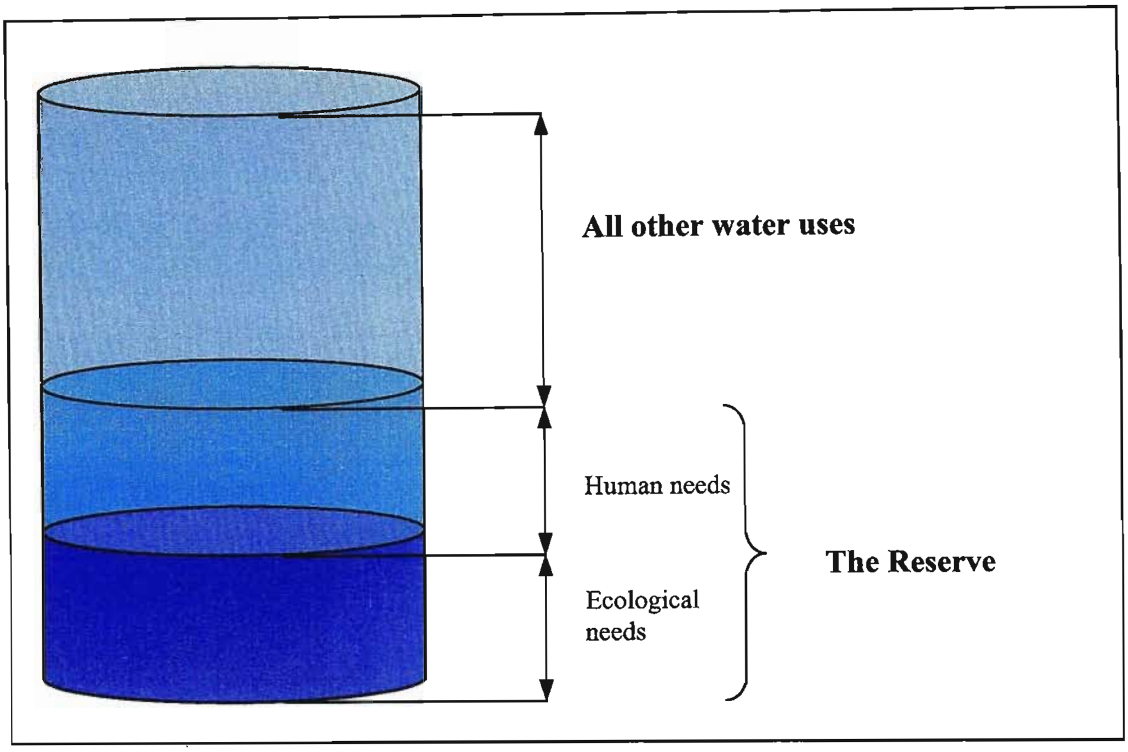

Figure 1.2 The Reserve and other water uses

Basic human needs 'Reserve' refers to the 'quantity and quality of water required to satisfying basic human needs, such as drinking, cleaning, etc' (DWAF 1999, Chapter 1, Sections 1–4). Ecological 'Reserve' means the quantity and quality of water required to protect aquatic ecosystems in order to secure ecologically sustainable development and use of relevant water resource.

Before the ecological 'Reserve' can be determined, the law requires that each water resource unit must be classified in terms of its management class. As discussed by Rowntree *et al.* (2000), the management classes are based on 'the ecological importance and sensitivity of the river system, on the present status, habitat integrity, and whether it is currently degrading due to past or present impacts'.

Rowntree *et al.* (2000, p.164) define habitat integrity as

> 'the maintenance of a balanced, integrated composition of physico-chemical and habitat characteristics on a temporal and spatial scale that are comparable to the characteristics of natural habitats of the region'.

This concept of 'habitat integrity' of river systems is difficult to measure, as the present status of a river ecosystem need to be compared against a reference (sometimes called 'natural') condition in order to determine the magnitude of changes from its original state. A reference condition could only be chosen arbitrarily, as it is as hard (if not impossible) to put an accurate baseline condition to a natural resource with certainty.

Evidently, the issue of reference condition is an open statement, which allows debate on what condition qualifies as 'natural origin' or which 'biological, hydrological and geomorphologic processes' should be taken into consideration in order to make a convincing assessment on the state of a river ecosystem.

As illustrated in Figure 1.1, there is a wide range of biological, hydrological and geomorphologic variables (jointly or separately), which affect the state of river habitats. In this dissertation, much emphasis is put on the physical criteria of classifying river ecosystems. Physical criteria include for instance, the erosion status of the catchment, measures of bed modification due to siltation or erosion and channel modification such as result from a change in flow and bank erosion. In essence, these are all manifestations of geomorphologic processes.

As discussed by Rowntree *et al.* (2000), geomorphologists play an important role in setting environmental flows. This is based on the principle that the geomorphologic processes, which shape the river channel, determine the physical structure of a river ecosystem; and they determine the material from which the river channel is formed, the shape of the channel and the stability of the bed and banks. Hence, geomorphology is seen to provide an appropriate basis of classification for the purpose of describing the physical habitat of riparian and aquatic ecosystems.

1.4 Aim and objectives

The aim of this dissertation is to develop a flexible classification of river environments in KwaZulu-Natal by combining the already existing geomorphologic and ecological classifications within a GIS. This will be achieved through the following objectives:

i *To study the applications of geomorphologic and ecological variables in river environment classification*

This objective entails a literature review of the river classification used abroad and in South Africa. The study is done to establish the importance of geomorphologic and ecological variables as controlling variables in river environments.

ii *To investigate the applicability of GIS in river environment classification*

The relevance of using GIS in combining the geomorphologic and ecological variables of river environments will be investigated; consequently the dissertation will develop recommendations and guidelines.

1.5 Outline of the chapters

Chapter One provides an introduction to the dissertation, describes different concepts in the river environment classification, the relationship of physical river variables at various scales. It gives a brief overview of the development in river environment classification in South Africa, which includes the legislative framework (*viz.* National Water Act No. 36 of 1998), its provisions with regard to the protection of the water resources and the brief developments in both the geomorphologic and ecological classification of river environments. It further outlines the aim and specific objectives of the dissertation. Lastly, it gives an outline of the chapters that constitute the whole thesis.

Chapter Two offers a review of the river environment classification, which highlights the practices internationally and in South Africa. The chapter's focus is on the development of the river environment classification in South Africa – from its legislative framework to different methods and techniques applied. The South African perspectives in this regard are complimented by various international studies on this subject.

Chapter Three gives a full description of the study area with reference to the geographical location of the study area, topography, climatic conditions, soils and natural vegetation.

Chapter Four provides a description of the river environment classification framework, different datasets to be used in the dissertation. It outlines and describes in detail the methods used to acquire, manipulate, analyse and visualize the different datasets in the GIS environment.

Chapter Five presents the results (general and detailed) and the description of the findings. It further discusses the applicability and benefits of the results.

Chapter Six is a concluding statement on the efficacy of the variables used in the river environment classification, the applicability of GIS as a tool and recommendations on how the methodology can be used to be more representative of the river environments.

Chapter 2 Literature review

'The effort to classify rivers is not new' (Rosgen 1994).

2.1 Introduction

The need to classify river environments has seen the evolution of methods developed by researchers throughout the world in an attempt to understand and explain the river phenomena (Rosgen 1994). In the development of these various methods, the common principles were evident as outlined by Mosley (1981) that (a) classification should be designed for a specific purpose, and (b) differentiating variables must be important or relevant to the purpose of classification. These principles highlight the difficulty of developing a classification of river environments generally applicable to the range of purposes for river management (Uys 1994, Snelder *et al.* 1999). The failure to produce a universal river classification system is attributed to a variety of constraints, *inter alia*, the spatio-temporal nature of the controlling variables, the differences in river environment contexts, and different purposes for which the rivers were assessed (Rosgen 1994, O'Keeffe *et al.* 1994, Snelder *et al.* 1999). The importance of the above-mentioned constraints will be evident in the underlying literature review on the research undertaken in countries such as New Zealand and Australia.

2.2 International studies

Classification of river environments has been a subject of research worldwide (Mosley 1987, Rosgen 1994), which has led to developments in the methodologies and systems to explain the functioning of the river phenomena. This literature review will highlight the developments pertaining to river environment classification in countries such as New Zealand, Australia, and their link to South African experiences.

2.2.1 New Zealand

The development of a system for classification of river environments in New Zealand was a mandate of the Ministry for the Environment as part of the Environmental Performance Indicators (EPI) programme (Snelder *et al.*1999). As a result, the so-called Environmental Working Group was formed to develop an environmental management framework for rivers, which included a method for developing a core set of environmental indicators to report on the 'ecological health' of rivers (Snelder *et al.* 1999).

Snelder *et al.* (1998) proposed an eco-classification framework, which was based on a top-down hierarchical classification of river controlling variables such as climate, geology and land cover, which are known to structure the river environment (Figure 1.1). This classification scheme was based on physical variables of the river that had been mapped at a high level of resolution (approximately 1:50 000 scale), thus making the classification flexible enough to be developed for entire regions or country, from data readily available in a Geographical Information System (GIS) format (Snelder *et al.* 1999). Snelder *et al.* (1998) applied the classification scheme to different regions in New Zealand, which made it possible for the controlling variables to be refined. The GIS techniques were used to develop a classification of two rivers in each of the regions at a coarse level of spatial resolution. The first step of this classification scheme was to outline the development and classification system at a high spatial resolution, while the second step was to test the system with biological data. Snelder *et al.* (1999) referred to this classification system as river environment classification, i.e. the classification of rivers on the basis of physical variables.

The use of controlling variables to define the overall classification scheme is based on the river continuum concept (Vannote *et al.*1980), which argues that the physical conditions at any point in a river reflect the integrated effects of upstream controlling variables. This concept of river continuum has been widely accepted, and in practice many of the classifications that have been developed use continuous variables – which are divided more or less into a manageable set of groups (Snelder *et al.* 1999).
Snelder *et al.* (1999) outlined components of the technical process required in the classification of the New Zealand rivers, which includes:

- Scale – the river environment classification is designed to be flexible, thus it can be used to analyse and manage a wide range of issues at different spatial scales, regional scale, catchment scale and valley segment scale (as outlined in Figure 1.1).
- Developing a river network – is the first step in applying the classification system. The river network was generated from a digital elevation model (DEM), from contours defined at 20 metre intervals, converted to a 30 x 30 metre DEM grid. Thus, the derived channel network is used to produce a GIS layer consisting of uniquely numbered nodes.
- Data acquisition – is the process of acquiring data for subsequent processing to derive the classification, which uses the GIS and is considered differently according to the scale. For instance, the catchment scale data – comprising layers of elevation, rainfall, geology and land cover data – are extracted using GIS by overlaying the defined polygon.

The river environment classification used the variables that are readily available in the GIS database. As stated by Snelder *et al.* (1999), arbitrary class limits had to be specified for all variables, based on the geomorphologic literature, experience, and examination of 1: 50 000 topographic maps. The researchers faced the challenges of testing the applicability and spatial transferability of the discriminating variables and their class limits with applications in localities of different physiography. It was acknowledged in the research on the New Zealand rivers that the development of a single, all-purpose classification that is nationwide in scope presents many difficulties, and that regional modifications are likely to be required (Snelder *et al.* 1999).

2.2.2 Australia

The problems of Australian rivers were highlighted in a Commonwealth Environment Protection Agency (CEPA) discussion document entitled '*Towards healthy rivers: the ills affecting our rivers and how we might remedy them*' (CEPA 1992, CSIRO 1992). Thus, national approaches were sought to address the plight of rivers, of which the first was to establish a National Water Quality Management Strategy – a cooperative venture between the state and federal governments; and the second was the

Monitoring River Health initiative announced as part of the Prime Minister's environmental statement in December 1992 (Snelder *et al.* 1999, Stein *et al.* 1996). The latter lead to the establishment of the National River Processes and Management Programme – whose key activity was setting up a national programme for monitoring river health (Hart and Campbell 1994 in Uys 1994, pp.177-189).

The water quality management programme and the river-health monitoring programme had their focus on the use of biological indicators to assess the present ecological condition of the nation's rivers (Hart and Campbell 1994). But, the large pool of ecosystem types in Australia was cited as a major constraint for researchers to develop a national ecological river classification scheme (Hart and Campbell 1994). Many proposals for the river classification were made, among others, to establish a river classification scheme for a number of spatial scales (e.g. national, regional, local) and for a number of different end uses. Furthermore, the river classification scheme will be discussed on the basis of the designated use of information (e.g. river type classification or river health classification), or on the approach used (e.g. bottom-up or top-down).

Discussions in a joint workshop between Australian and South African researchers on rivers, made it clear that there is no consensus on what constitutes a river classification scheme, or what its primary use should be (Uys *et al.* 1994). Two point of views were evident: the scientists attending the workshop were interested in classification systems that grouped like systems so that they could be compared equitably, while managers were interested in classifying rivers according to their value (conservation), beneficial uses or condition (ecological health).

Hart and Campbell (1994) distinguished the river classification schemes on the basis of designated use, i.e. river type classification and the approach used, i.e. bottom-up or top-down approaches). The river type classification schemes attempt to classify rivers on a geographic or geomorphic basis (Frisell *et al.* 1986, Omernik 1987, Montgomery and Buffington 1993), which is termed eco-typing. Based on the account of Hart and Campbell (1994), eco-typing classification is necessary for identifying broad geographical limits on river types, but on its own it falls short to answering the questions posed by the managers. The river classification schemes based on geomorphic features (e.g. Leopold *et al.* 1964) have multiplied, and the more recent one recognises a range of spatial scales (e.g. watershed, valley segment, reach, pool/riffle), and focus on the interactions between the catchment and the stream which control the physical nature of the channel (Frisell *et al.* 1986, Montgomery and Buffington 1993).

River condition classification aims to classify the ecological conditions of the river or river health for the purpose of providing important management information (Hart and Campbell 1994). According to these two researchers, such classification answers the questions about what variables of the river should be used in the assessment, and what reference system from which comparison can be done with respect to current conditions. The problems of finding reference system proved to be difficult as spelt out in the definition of a wild or 'near-pristine' river by Stein *et al.* (1998) in the Wild Rivers Project (which was aimed at identifying and classifying the natural or wild rivers in Australia), that

> 'a channel, channel network, or a connected network of waterbodies, of natural origin and exhibiting overland flow in which the biological, hydrological and geomorphological processes associated with the river flow and … have not been significantly altered by modern or colonial society' (Stein *et al.* 1998, p1).

The definition had many shortfalls when it came to developing methodologies for identifying and assessing natural rivers. For instance, the chosen criteria relied on indirect indicators related to factors known to affect the condition and functioning of the river system. Furthermore the absence of adequate baseline information from undisturbed systems that might be used in assessing river condition/river health made it difficult to adopt any of the methodologies with certainty (Stein *et al.* 1998, Hart and Campbell 1994).

Researchers in Australian rivers looked at a number of approaches for classifying rivers, which can broadly be classified into both top-down approaches and bottom-up approaches. The former begins with the full set of rivers or sites to be classified and then divides those using specified criteria, while the latter agglomerates techniques in which data is collected on site and is then used to group sites.

The bottom-up techniques allows the expected number of invertebrate communities to be predicted on the basis of a small number of physical and chemical parameters (developed by Wright *et al.* 1984, Moss *et al.* 1987 for the British rivers).The advantage of the bottom-up approach is the high level of certainty in selecting the appropriate physical variables (controlling the river environments), which are filtered through continuous analysis (Hart and Campbell 1994).

The top-down approach has a main disadvantage of geographical limitations, i.e. when the system is extended over greater geographical distances, the sensitivity is reduced. The top-down approach applied by the researchers for classification of rivers in Australia are derived from the ecoregion concept developed in the United States (Omernik 1987, Omernik and Gallant 1986), which is based on the definition of geographical regions using widely-mapped landscape characteristics (stored in GIS) and assuming that sites within this regions share common characteristics. Ecoregional approaches to river classification developed out of the recognition that management techniques, such as the application of water quality guidelines, could not be applied uniformly over large geographical regions. Thus, Hart and Campbell (1994) supported the development of an ecologically based geographical classification of Australian rivers and streams with addition of the following variables:

- geomorphological,
- hydrological,
- physico-chemical water quality and
- aquatic biological.

2.2.3 Other countries and their contribution to river classification

A review of the literature indicated various contributions made by other researchers in the world on river classification. Some of the approaches and methodologies are overlapping but some are far apart rendering the idea of using them to compliment each other difficult. Table 2.1 shows the challenge of using different approaches to classifying rivers for varied purposes.

Table 2.1 A review of world-wide contributions on river environment classification studies (Snelder *et al.* 1999)

Author	Purpose	Variables
Nevins (1965)	The classification of rivers into torrent phase, shingle phase, silt phase, and tidal phase developed for use by New Zealand river managers. It is based on the principle that a river progressively changes in a downstream direction (i.e. river continuum concept), and is influenced by the sediment load it carries	Channel gradient, position along the channel profile from headwaters to the sea, and channel lithology
Mollard (1973)	It was designed to draw on the aerial reconnaissance and aerial photograph interpretation, i.e. input data are observed planimetric form of the channel from which inferences are made about channel hydrology, stability, and sediment load. Developed for use in northern Canada with flat relief and self-formed alluvial channels	Degree of wandering and braiding of the flowing water within the active channel, channel sinuosity, lateral confinement of the channel by terraces and bedrock outcrops, development of permanent islands
Frisell *et al.* (1986)	A hierarchical system of stream classification developed from a set of variables obtained from GIS and DEM databases	Geological materials, channel gradient, position along the stream profile, valley side slope, adjacent vegetation/soil/ land type
Rosgen (1994)	This classification combines both the bottom-up and the top-down approaches as some of the variables must be observed and others can be derived from topographic maps (i.e. GIS). This was applied to rivers in the U.S., Canada, and New Zealand	Channel entrenchment, width/depth ratio, sinuosity, channel gradient, and sediment
Montgomery and Buffington (1997)	Classification of mountain rivers provides a detailed breakdown of torrent phase identified by Nevins (1965), and overlaps with his shingle and silt phase	Typical bed material, bedform pattern, dominant roughness elements, sediment storage elements, degree of confinement, typical pool spacing – most of these variables can be measured from large scale aerial photographs, only channel confinement can be measured from a topographic map.
Raven *et al.* (1997)	Raven *et al.* (1997) used the Environment Agency's river habitat survey work in conjunction with discriminant and cluster analyses to develop a classification of river types in England and Wales.	Geology, elevation, channel gradient, and flow category – all variables can be derived from a GIS database

2.3 South Africa

2.3.1 Introduction

A review of the river classification literature in South Africa indicates efforts made by a number of researchers to develop methodologies and schemes to classify the rivers for different purposes (Noble and Hemens 1978, Van Niekerk *et al.* 1995, Hohls 1996, Rowntree and Wadeson 1999). Generally, the classification schemes are based on both the top-down and bottom-up hierarchical sets of criteria using the geomorphologic and ecological controlling variables.

Two hierarchical classification schemes have been developed for South African rivers (Rowntree *et al.* 2000). The first is that of Van Niekerk *et al.* (1995), which is deemed a bottom-up approach based on the agglomeration of morphological units into channel types. This approach is field-based, thus it proves to be laborious and time-consuming to undertake (Rowntree *et al.* 2000). The second approach is that of Rowntree and Wadeson (1999) – a top-down approach – based on a combination of desktop and field approaches, which aims to provide a scale-based framework linking various components of the river system, ranging from catchment to the instream habitat (Rowntree *et al.* 2000).

The geomorphologic classification of Rowntree and Wadeson (1999) consists of six levels of scale, which include the catchment, segment, zone, reach, morphological unit, and hydraulic biotope (Table 2.2). Rowntree *et al.* (2000) further categorised the levels into (a) catchment, segment and zone classification, which is derived from desktop studies using available secondary data sources, and (b) reach, morphological unit and hydraulic biotope classifications, which are applied to specific sites, based largely on field assessment backed by reference to large scale maps and aerial photographs.

The catchment is defined as the topographic divide except where groundwater is a major component of streamflow. This falls in line with the principle that the development and physical characteristics of a river are dependent upon the biogeological and climatic conditions in which they reside (Warren 1979, Bailey 1983), the slope and shape of the longitudinal profiles (Hack 1957) and some index of drainage network structure (Strahler 1964).

Table 2.2 Descriptions of geomorphologic classification levels (Rowntree and Wadeson 1999)

Hierarchical unit	Description	Scale
Catchment	The catchment is the land surface, which contributes water and sediment to any given stream network.	Can be applied to the whole river system, from source to mouth, or to a lower order catchment above a specified point of interest.
Segment	A segment is a length of channel along which there is no significant change in the flow discharge or sediment load.	Segment boundaries will tend to be co-incident with major tributary junctions.
Longitudinal zone	A zone is a sector of the river long profile, which has a distinct valley form and valley slope.	Sectors of the river long profile
Reach	The reach is a length of channel characterised by particular channel pattern and channel morphology, resulting from a uniform set of local constraints on channel form.	'00s of meters
Morphological unit	The morphological units are the basic structures recognised by fluvial geomorphologists as comprising the channel morphology and may be either erosional or depositional features.	Morphological units occur at a scale of an order similar to that of the channel width.
Hydraulic biotope	Hydraulic biotopes are spatially distinct instream flow environments with characteristic hydraulic attributes.	Hydraulic biotopes occur at a spatial scale of the order of $1m^2$ to 100 m^2 and are discharge dependent.

The catchment is a source area for runoff and sediment whereas the channels provide the network through which flows of water and sediment are routed. The channel network can be divided into segments, where a segment is a length of channel along which there is no significant change in the imposed flow discharge or sediment load.

Geomorphological zonation is based on downstream changes in the river long profile. In South Africa, longitudinal long profiles of rivers reflect the regional geological events and long-term fluvial action. Rowntree and Wadeson (1999) have developed a zonal classification system for South African rivers (Table 2.2) modified from Noble and Hemens (1978).

For the purpose of the classification, the reach is defined as a length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occurs within identifiable channel patterns (Rowntree and Wadeson 2000). Reach characteristics determine the possible direction of the response to changes in flow and/or sediment load, in particular whether it acts as a source, transfer zone or sink for sediment. These include valley gradient, geology, local side slopes, valley floor, width, riparian vegetation and bank material.

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

Hydraulic biotope is defined as a spatially distinct instream flow environment characterised by specific hydraulic attributes (Wadeson 1994). This level of the hierarchy is the key to successful conservation of rivers to maintain ecological integrity within South African fluvial environments because it provides the crucial link between catchment geomorphology and lotic ecology.

2.3.2 Geomorphologic zonation

The relevance of the geomorphologic zones as a classification tool is that, they can be derived from a desktop exercise (Rowntree *et al.* 2000), e.g. it assumes that channel gradient is a predictor of channel morphology. On many accounts, the Rowntree and Wadeson (1999) geomorphological classification owe much to the Rosgen (1994) classification scheme based on the longitudinal profile of the river system. This can be inferred from topographic maps to serve as the basis for breaking the stream into slope categories that reflect profile morphology (Table. 2.3).

Table 2.3 Descriptions of slope gradient classes (with acknowledgement to Rosgen 1994, Rowntree and Wadeson 1999)

Class	Slope %	Description
Aa+	> 10	Very steep, frequently spaced, vertical drop/scour-pool bed features. High debris transport streams, waterfalls, etc.
A	4 -10	Steep, entrenched, cascading, step/ pool streams. High energy/ debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel.
B, G	2 - 4	B is moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks. G is entrenched 'gulley' step/pool and low width/depth ratio on moderate gradients.
C, E, F	0.5 - 2	C has low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well-defined floodplains. E has low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander-width ratio. F has entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.
DA	0 - 0.5	Anastomising (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable stream banks.

As shown in Table 2.3, the stream types of Aa+ are very steep (greater than 10%), with frequently spaced, vertical drop/scour-pool bed features. They tend to be high debris transport streams, waterfalls, etc. Type A streams are steep (4-10% slope), with steep, cascading, step/pool bed features. Type B streams are riffle-dominated types with 'rapids' and infrequently spaced scour-pools at bends or areas of constriction. The C, DA, E and F stream types are gentle-gradient riffle/ pool types. Type G streams are 'gullies' that typically are step/pool channels. Lastly, the D type streams are braided channels of convergence/divergence process that lead to localized, frequently spaced scour/depositional bed forms.

2.3.3 Ecological river zonation

Ecological river zonation is described by Rowntree *et al.* 2000 as the longitudinal variation of physical characteristics and associated biological distribution down the length of a river. In South Africa, Rowntree *et al.* (2000) introduced this concept of river zonation, which gives a description of physical characteristics and associated biological distributions down the length of a river. The zonal classification developed by Rowntree and Wadeson (1999) was in principle inspired by ecologists' point of view during a biomonitoring workshop held in Cape Town (Brown *et al.* 1996) and as a modification of an ecological classification system by Noble and Hemens (1978).

Longitudinal zonal classifications have been widely adopted by ecologists to explain variations in biotic distributions of aquatic fauna and flora (Hawkes 1975). In South Africa, Harrison and Elsworth (1959), Harrison (1965) and Noble and Hemens (1978) developed a zonal classifications for rivers as summarised in Table 2.4.

From Table 2.4 it is evident that ecologists inadvertently recognised the concurrent changes in both the stream biology and geomorphology that could be related to the river profile. Despite its importance in describing the distributions of river biota, ecological zonation concepts were largely replaced by the river continuum concept (Vannote *et al.* 1980, Rowntree *et al.* 2000).

River continuum was introduced by Vannote *et al.* (1980), which argued that the river ecosystem respond to the flow of energy and matter through the system rather than simply to site-specific variables. Thus, it was an alternative to the concept of zonation, which depicted the river as separate fragments, each of them acting individually from others. According to Rowntree *et al.* (2000, p.165) it was 'undeniable that any point along a river cannot be isolated from the channel and catchment upstream which determines the inputs to that point'.

Nevertheless, river zonation cannot be sidelined in terms of assisting in river classification. In essence, classification demands that systems are divided into their component parts, while zonation provides a framework for classification which can be used to group similar river reaches, but which also retains the idea of a longitudinal change down the system.

The zonal classifications developed by South African ecologists were strongly influenced by the channel geomorphology (Rowntree *et al.* 2000). It makes sense therefore to develop a geomorphological zonal classification that can be used as a first step to classifying the components of a river network.

Table 2.4 Ecological zonation of South African Rivers (Harrison 1965, Noble and Hemens 1978)

Zone	Physical characteristics	Flow characteristics	Turbidity
High altitude source zone	Source often with sponge or spring. Substream bedrock or humid turf.	Slow flow, often seepage, but may be dispersed with waterfalls	Negligible, even during storms
Mountain stream	Mountain torrents, waterfalls and rapids; little or no true emergent vegetation. Substratum bedrock, boulders and smaller stones. Deposition negligible, stone surfaces clean.	Fast torrential, turbulent, always oxygenated.	Negligible, even during storms
Foothill: rocky bed	Gradient moderate but still noticeable. Substrate dominated by bedrock, boulders and smaller stones, but with occasional patches of gravel and coarse sand. Some epilithic growth. Sparsely distributed emergent vegetation becomes noticeable and islands may form within river channel.	Fast with slow flowing pools	Generally low, turbid during floods.
Foothills: sandy bed	Stony runs alternate with sand or sediment. Marginal riverine vegetation becomes noticeable and islands may form within river channel.	Lower flow velocity but fast in rapids and during floods.	Extremely variable, turbid at least during floods.
Midland river	Further reduction in gradient. Deposition increases. Substratum predominantly sand and finer sediments, but with occasional stony runs. Emergents can become extensive.	Generally slow.	Variable but usually turbid.
Lowland river	Substratum changing to fine silts. Flood plains and meanders can occur or channels may be braided. Islands often present. Emergents usually prominent in channel and on margins.	Flow relatively slow and are discharge dependent.	Usually turbid
Swamp	Area of wet spongy ground with a substratum of fine clays and silts high in organic materials. Channels are braided and usually blind. Emergent macrophytes are dominant and forms dense impenetrable masses.	Generally slow	Negligible to low turbidity except during floods.

2.3.4 Ecological studies in South Africa

In South Africa there are numerous ecological variables developed for a number of reasons. These studies, available in GIS format, include *Acocks Veld Types* (Acocks 1988), *Vegetation of South Africa, Lesotho and Swaziland* (Low and Rebelo 1996), and *South African Landcover Database* (Thompson 1999). These are layers available in GIS formats, which could be used for classification purposes along the river channels. The metadata of these ecological layers are summarised in Table 2.5 below.

Table 2.5 Metadata for *Acocks Veld Types, Low and Rebelo Vegetation Types* and *Landcover Types* (Acocks 1998, Low and Rebelo 1996 and Thompson 1999)

Title of Dataset	**Acocks Veld Types of South Africa (Acocks 1988)**	**Vegetation of South Africa, Lesotho and Swaziland (Low and Rebelo 1996)**	**South African National Landcover Database (Thompson 1999)**
Description	The Acocks Veld Types of South Africa gives a broad idea of the vegetation of South Africa and observations were based on the agricultural potential of the vegetation. The survey was initiated in 1945. A veld type was defined as a unit of vegetation whose range of variations is small enough to permit the whole of it to have the same farming potentialities.	The vegetation of south Africa, Lesotho and Swaziland gives a broad overview of our natural plant resources. Vegetation types were chosen on units with similar vegetation structure, sharing important plant species and having similar ecological processes.	The primary objective of the National Landcover Database project was to provide a standardized landcover database for all of South Africa, Lesotho, and Swaziland. The Landcover has been derived using manual photo-interpretation techniques from a new series of 1: 250 000 scale geo-rectified space maps, based on seasonally standardized, single date Landsat TM satellite imagery captured principally during the period 1994-1995. Landcover classes were based on a standardized hierarchical classification scheme.
Scale	1: 1 500 000	Derived from various scales	1: 250 000
Data Format	Arc/Info Coverage	Arc/Info Coverage	Arc/Info Coverage
Purpose	The database gives an idea of the potential vegetation in South Africa, and observations were based on the agricultural potential of the vegetation.	Need for a baseline vegetation map that can be used for more than agricultural planning. An up-to-date map essential for development planning and conservation.	The database provides a single standardized digital landcover surface for general modelling, statistical and data integration purposes. The usable scale of the data is 1: 250 000 and smaller
Data Quality	Positional accuracy: Vegetation boundaries were drawn on the 1: 1 500 000 Postal Communications Map (1945). Thus the map contains certain inaccuracies.	The boundaries of vegetation types were drawn by hand from geological, pedological, climatological, satellite and other cartographic data known to be relevant to the vegetation type.	Attribute accuracy: Map accuracy =79. 7 % Positional accuracy: varies over 1: 250 000 mapsheets.

2.4 Using GIS in river environment classification

2.4.1 Definition and functions of GIS

In most of the published literature, GIS refers to an organized collection of computer hardware, software, geographical data and personnel designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced information (DoE 1987, Aronoff 1989, Berry 1993). In essence, 'geographically referenced information' can be defined as information linked to specific locations on the Earth's surface at 'real-world scale and in real world space' (Frank 1988), which in GIS terms is referred to as the spatial nature of the data. Spatial is used in this regard to refer to the located data, for objects positioned in any space. Thus, GIS is a tool that provides a spatial representation framework for objects positioned in any space.

Since its conception, GIS has carried the burden of many users' expectations as Goodchild (1993) has suggested that:

> 'GIS is seen as a general-purpose technology for handling geographic data in digital form, and satisfying the following specific needs, among others:
>
> - the ability to preprocess data from large stores into a form suitable for analysis, including such functions as reformatting, change of projection, resampling, and generalization.
> - direct support for analysis and modelling, such that forms of analysis, calibration of models, forecasting and prediction are all handled through the instructions to GIS.
> - postprocessing of results, including such operations as reformatting, tabulation, report generation and mapping' (Goodchild 1993, p.8).

According to Nyerges (1993), a GIS workflow process consists primarily of four steps: (i) problem definition, (ii) data input/capture (with subsequent data storage/management), (iii) data manipulation/analysis, and (iv) data output/display (Figure 2.1).

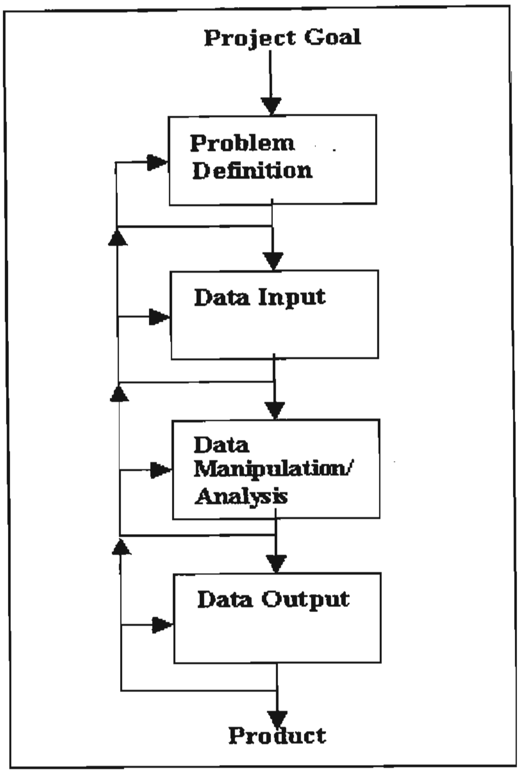

Figure 2.1 GIS as a workflow process from a procedural perspective (Nyerges 1993)

In the *problem definition* step of GIS, one examines what must be done with regard to an understanding of the problem and the needs for information processing.

The data *input/capture* functions support all other processing steps. In data entry step, the data are either converted to digital from hardcopy sources or they are acquired from digital sources and reformatted as appropriate for use. In this case, what counts is to ensure that the digital data set is precisely what is needed. To achieve this, the data management should be in a way that it gives data about the characteristics of the dataset (i.e. metadata). As noted by Nyerges (1993), using the metadata to make an informed decision is an undertaking worth the effort.

Functions to support GIS *data manipulation* focus on preparing data for the analysis phase of processing, i.e. developing and synthesizing of spatial relationships in geographic data to provide answers.

The *display/output* function in a GIS, have a lineage with cartography. Output can be generated in either softcopy or hardcopy form (Nyerges 1993). Softcopy output to the computer monitor is useful for interactive problem solving, while hardcopy output is useful for presentation to a large group of people over an extended period of time.

A successful application of the outlined GIS workflow process to various problem situations is dependent on the relevant questions asked by the users to attain the desired product. Rhind (1990) set out a general classification of the types of generic questions, which a GIS is frequently used to investigate; these relate to location, condition, trend, routing, pattern, and modelling of spatial objects.

The *location* question involves querying a database to determine the types of features, which occur at a given place (e.g. what is the length of a given river stream?) Conversely, the *condition* question aims to find the location of sites with particular characteristics (e.g. where is all the land within 30 km of the river stream which is forest covered?). According to Maguire (1991), this can also be referred to as an 'intersection' question, because it necessitates finding the intersection among more than one type of data sets. The *trend* question involves monitoring of change over a period of time (e.g. what is the change in vegetation cover?).

The *routing* question requires calculation of the best (shortest, most scenic) route between two places. It is *pattern* question, which allows analysts to describe and compare the distribution of phenomena and to understand the process, which accounts for their distribution (e.g. is there some pattern in the distribution of the riparian vegetation which is thought to be caused by the channel slope). The final question deals with *modelling,* which allows different models of the world to be evaluated (e.g. which areas of the riparian zone will be affected by a 20-centimetre increase in quantity of water?).

As noted by Maguire (1991) GIS can be applied to many types of problems. In this dissertation the GIS will be investigated as a tool for the purpose of river classification.

2.4.2 Applications of GIS in river classification

The confidence in using the GIS for studying water resources has been demonstrated by researchers such as Morris and Heerdegen (1988), Downs (1994, 1995a, 1995b). In the consecutive works of Downs (1994, 1995a, 1995b), it was detailed that the use of

GIS in the study of water resources (in particular river basins) might provide at a minimum:

- greater data storage flexibility,
- faster reiteration and modification of parameters once entered,
- the easy and informative display of results, and
- reduction in the repetitive manual calculations, which are common in catchment-based studies.

As previously noted these functionalities of GIS were taken advantage of by different researchers, who envisaged it as a tool of convenience in river classification. For instance, Rosgen (1994) combined both the bottom-up and top-down approaches as some of the variables can be observed and others can be derived from topographic maps within a GIS.

In subsequent studies, Raven *et al.* (1997) used variables such as geology, elevation, channel gradient, and flow category – all of which can be derived from GIS database – to develop a classification of river types in England and Wales.

De Roo (1998) noted that the use of GIS in catchment hydrological and erosion modelling offers considerable potential. This claim was based on the ability of GIS to simulate in great detail topography and other controlling factors of the river channel. In addition, data management and presentation of the results is much easier than when a GIS is not used (de Roo 1998).

In the study of river environments of New Zealand rivers, Snelder *et al.* (1999) proposed different models used to derive the controlling variables for riparian and instream ecosystems (Figure 1.1). The controlling variables included the catchment scale layers of elevation, rainfall, geology and landcover data extracted using GIS by overlaying the defined polygons. Other continuous variables at valley scale level such as channel sinuosity, width, etc. were proposed, as they were obtainable from the GIS databases.

It was discussed by de Roo (1998), that GIS has a potential to derive useful secondary variables (e.g. slope gradient, flow direction, slope length) from basic variables (e.g. digital elevation models). Furthermore, 'these variables can also be used in more complex physically based models either linked to, or integrated in, a GIS (de Roo 1998, p.920).

2.5 Summary

This chapter has reviewed the literature on the studies made on the river environment classification in various outside countries and the relevance they bear to South Africa. It highlights the pros and cons of various river classification systems, the different variables used in river classification criteria, and the importance of GIS as a tool for river classification.

Researchers worldwide have a quest to develop methods in an attempt to understand and explain the river environments. In the development of various methods of river environment classification, there were common principles outlined by Mosley (1981), who succinctly stated that (a) classification should be designed for a specific purpose, and (b) differentiating variables must be important or relevant to the purpose of classification.

In New Zealand, one purpose of river classification was to develop an environmental management framework for rivers, which included a method for developing a core set of environmental indicators to report on the 'ecological health' of rivers (Rutherford 1996). This river environment classification used the variables that are readily available in the GIS database. In this case, the challenges that the researchers faced included: testing the applicability and spatial transferability of the discriminating variables and their class limits, with applications in localities of different physiography. Consequently, the outcomes of the research on New Zealand rivers were that the development of a single, all purpose classification that is nationwide in scope presents a lot of difficulties, and that regional modifications are likely to be required (Snelder *et al.* 1999).

The literature review cited the Australian initiatives, namely, the water quality programme and the river-health monitoring programme, which were aimed at using biological indicators to assess the present ecological condition of nation's rivers (Hart and Campbell 1994). But, the large pool of ecosystem types in Australia was indicated as a major challenge to the researchers, in the development of a national ecological river classification scheme. Many proposals for river classification were made, *inter alia*, to establish a river classification scheme for a number of spatial scales (e.g. national, regional, local) and for a number of different end uses. Some researchers, in particular, Hart and Campbell (1994) distinguished the river classification schemes on the basis of designated use, i.e. river type classification and the approach used, namely bottom-up or top-down approaches. After much research and discussion, Hart and Campbell (1994) supported the development of an ecologically-based geographical classification of Australian rivers and streams with the addition of the geomorphological, hydrological, physico-chemical water quality and aquatic biological variables.

In South Africa there were two hierarchical classification systems developed: the first is that of Van Niekerk *et al.* (1995), which is a bottom-up approach based on the agglomeration of morphological units into channel types. This approach is field-based, thus it is labour-intensive and time-consuming to undertake. The second approach (which forms the basis of this study) is that of Rowntree and Wadeson (1999) – a top-down approach – based on a combination of desktop and field approaches, which aims at providing a scale-based framework linking various components of the river system, ranging from catchment to the instream habitat (Rowntree *et al.* 2000).

The chapter also provides a discourse of a GIS, which is a proposed tool within which a framework of geomorphological and ecological variables (for river environment classification) should be developed. GIS is defined as an organised collection of computer hardware, software, geographic data and personnel designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced information (DoE 1987, Aronoff 1989, Berry 1993). It further outlines the application of GIS to answer the types of generic questions, which are frequently used in the investigations. These are questions pertaining to location, condition, trend, routing, pattern and modelling of different features.

Lastly, the chapter cited the growth in the applications of GIS in river environment classification. This is a trend attributable to the benefits offered by the use of GIS, namely: greater data storage flexibility, faster reiteration and modification of parameters once entered, the easy and informative display of results, and reduction in the repetitive manual calculations which are common in catchment-based studies.

Chapter 3 Study area

3.1 Location

The study area is KwaZulu-Natal province, which is situated between latitudes 27° and 31° S, and longitudes 28° and 33° E (see Figure 3.1). KwaZulu-Natal covers an area of approximately 92 100 km^2 on the eastern part of South Africa. It stretches from the southern borders of Swaziland and Mozambique to the Eastern Cape border in the south. Inland, the Kingdom of Lesotho, the Free State and Gauteng provinces flank it.

KwaZulu-Natal has networks of rivers (both perennial and non-perennial) running through its length, and this has prompted the Province to take initiatives in order to protect the integrity of riparian ecosystems. The selection of this study area is inspired by the strategic goal of the province to classify the river systems, so as to prioritise them for conservation purposes.

The National Water Resource Strategy in terms of Chapter 2 (Part 1) of the National Water Act No. 36 of 1998 (DWAF 1999) provides for the establishment of water management areas nationwide. As a result, 19 water management areas were established country-wide (Figure 3.2). KwaZulu-Natal province was demarcated into three water management areas. These are:

1. *Usuthu to Mhlatuze*, major rivers include Usutu, Pongola, Mhlatuze, Mfolozi and Mkuze;
2. *Thukela*, with major river as Thukela;
3. *Mvoti to Umzimkulu*, major rivers include the Mvoti, Umgeni, Umkomazi and Umzimkulu.

Thus, the study covers both perennial and non-perennial rivers in these 3 water management areas.

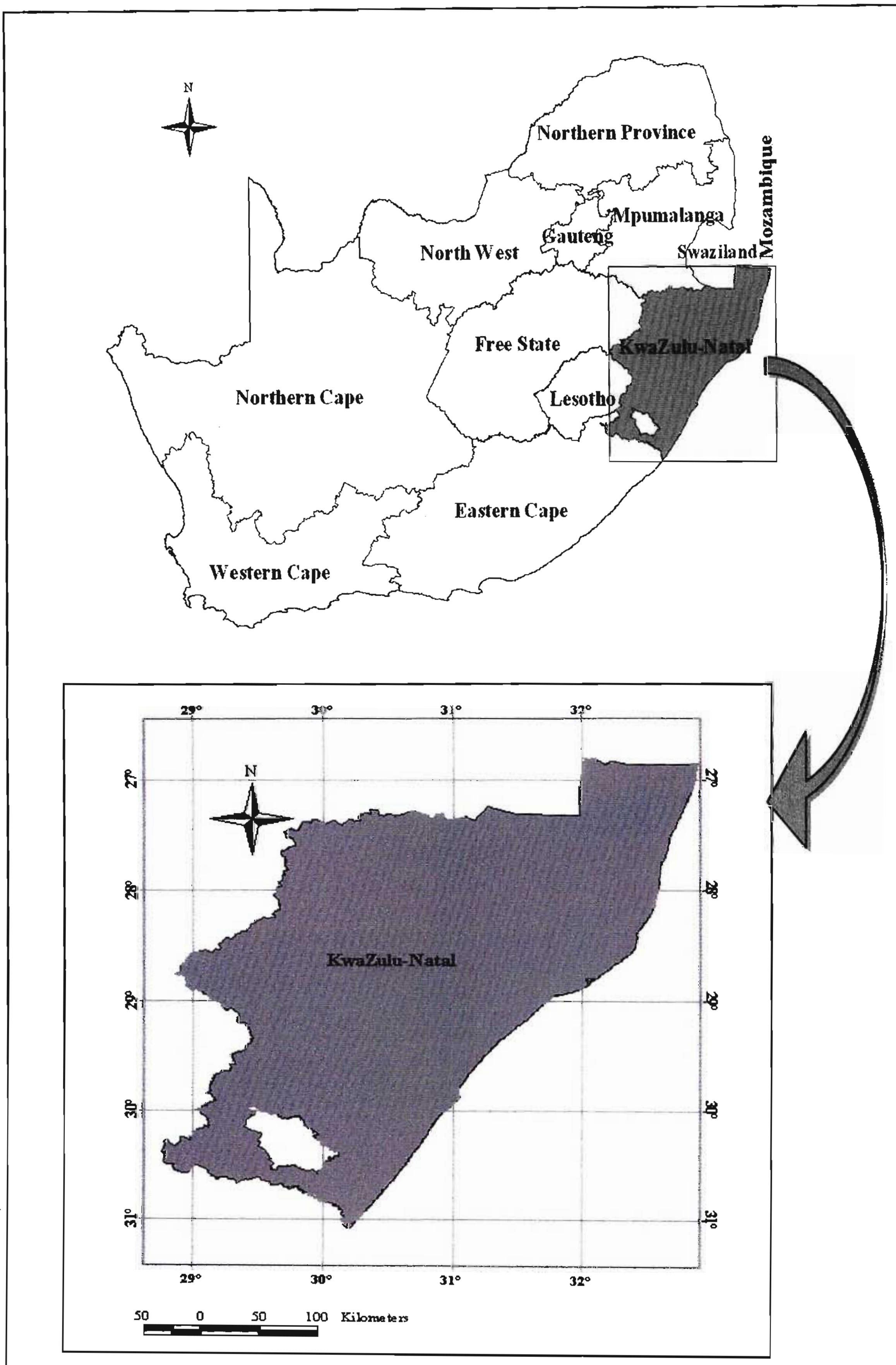

Figure 3.1 Location of the study area, KwaZulu-Natal Province

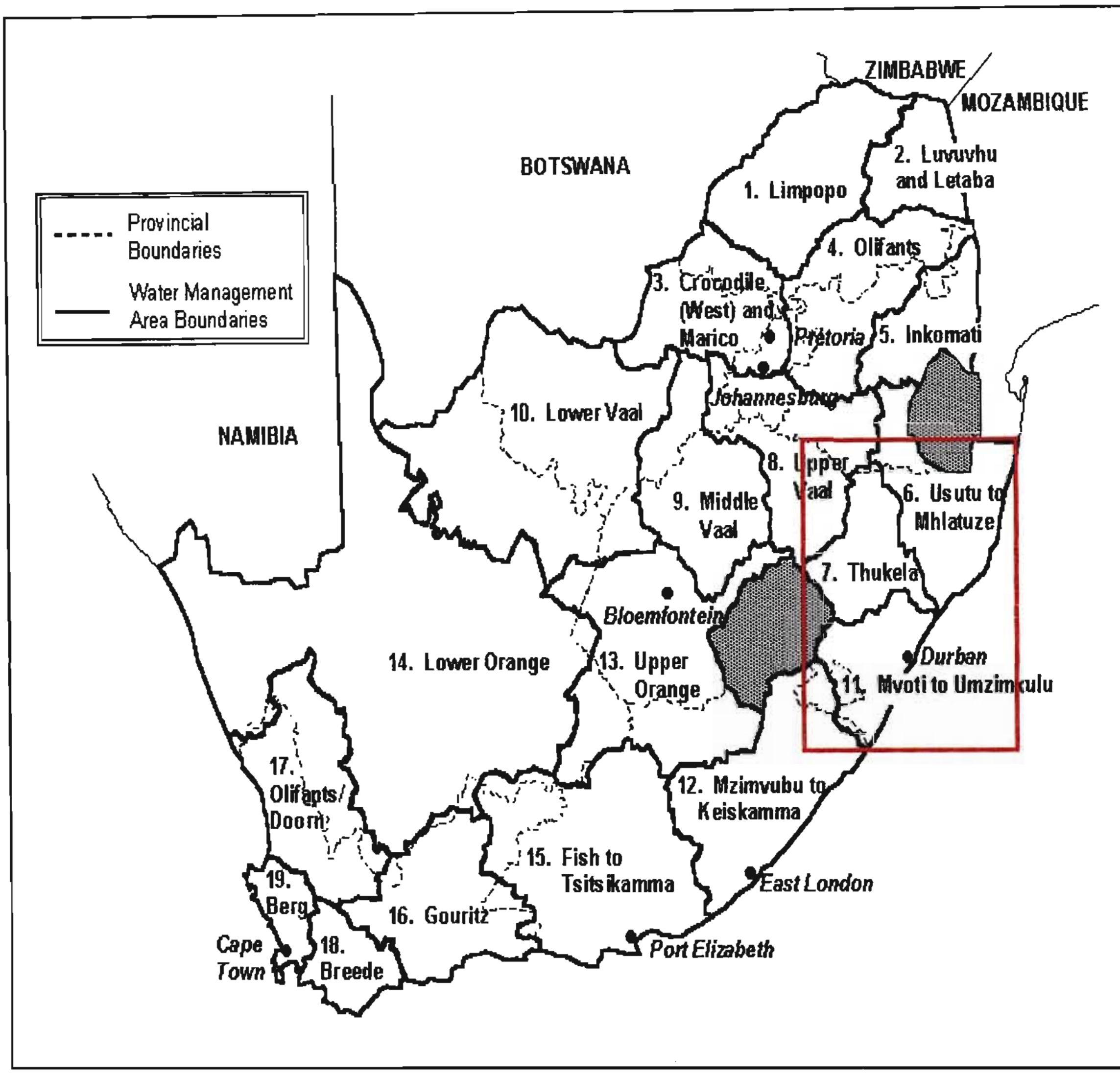

Figure 3.2 Water management areas of South Africa. Note Usuthu to Mhlatuze (6), Thukela (7) and Mvoti to Umzimkulu (11) in KwaZulu-Natal Province (Source: DWAF)

3.2 Topography

Acording to Schulze (1997) topography is part of the terrain morphological units. Topography is an invariate feature of the landscape, which is described by altitude (*per se*) as well as the rate of change of altitude over distance (Schulze 1997). The altitude in KwaZulu-Natal ranges from 0 to 3292 metres, which gives the province a high variability of altitude. As a result, topography has a major influence on other controlling variables, such as climate, and hence on hydrological and land use responses (Snelder *et al.* 1999).

Schulze (1997) discussed that altitude acts as a barrier for air movements, as a consequence, altering the rainfall patterns, e.g. the moist air is forced to rise and the windward facing slopes to experience more rainfall. It was noted by Schulze (1997) that, this incidence of more rainfall – due to the effect of high altitude – occurs in the KwaZulu-Natal side of the Drakensberg, where it shares the border with Lesotho (Figure 3.1) in summer.

According to Schulze (1997), the dominant terrain morphological units in KwaZulu-Natal are as follows:

1. *High mountains* on the south eastern side of KwaZulu-Natal, where it shares the border with Lesotho;
2. *Low mountains* are spread over the length of KwaZulu-Natal;
3. *Highly dissected low undulating mountains;*
4. *Mountains and lowlands;* and
5. *Irregular undulating lowlands with hills.*

3.3 Climatic conditions

Climatic conditions in this case refer to annual temperature and annual precipitation. The mean annual temperature of KwaZulu-Natal is 18.1°C, with minimum and maximum values of 2.2°C and 22.7°C respectively (Schulze 1979). These moderate mean temperatures are induced by topographic variations, i.e. the altitude ranging from 0 to 3292m.

KwaZulu-Natal experiences the highest annual precipitation in South Africa, with a mean value of 845mm (Schulze 1979). Precipitation is concentrated on the rainy seasons in mid summer (peak concentration in January month), with incidences of daily thunderstorms at times. This occurrence of heavy rainfall within a short period is attributed to soil erosion, which causes siltation in the streams.

3.4 Natural vegetation

Vegetation mapping and research in South Africa was based for many years on the research and work conducted by Acocks (1988). These maps had been established as the standard by which all national vegetation changes were measured.

In KwaZulu-Natal there is a broad similarity between the boundaries of terrain morphological units and vegetation types defined by Acocks (1988). This similarity could be attributed to the cause-and-effect relationship between terrain morphological units and vegetation types as discussed by Snelder *et al.* (1999) on the hierarchical classification scheme (see Figure 1.1), whereby the higher-level controlling variables (e.g. topography) affect the lower-level controlling variables (e.g. vegetation).

According to Acocks (1988), the most prominent vegetation types in KwaZulu-Natal are:

1. *Coastal Forests and Thornveld*, which runs along the coast;
2. *Ngongoni Veld;*
3. *Highland Sour Veld and Dohne Sour Veld;*
4. *Southern Tall Grassland;*
5. *Valley Bushveld*, which runs along the rivers;
6. *Ngongoni Veld of Natal Mist Belt;*
7. *Northern Tall Grassveld; and*
8. *Zululand Thornveld.*

Chapter 4 Materials and methods

4.1 Introduction

This chapter outlines the methods used to acquire, manipulate, analyse and visualize the datasets in the GIS environment. These methods are primarily derived from the research studies reviewed in Chapter Two.

The initial stage of this chapter gives the description of the parameters of the GIS as a tool for handling different datasets in the river classification scheme. Lastly, it discusses the requirements of the datasets and their usage in the steps of the methodology as outlined in Figure 4.6.

4.2 GIS tool

Most of the data used in the dissertation were compatible with the GIS application, i.e. they were either in shapefile or grid formats supported by GIS databases. In this dissertation, GIS serves as a tool for data input, management, manipulation and data output/ display (see Figure 2.1).

For the purposes of consistency, a common projection system is used in the GIS to spatially register geographic data for the same area. Some of the datasets were primarily in *Geographic (Lat/Lon)* projection, but for the purpose of calculation of the area, the *Universal Transverse Mercator* projection system was commonly used. The parameters of the *Universal Transverse Mercator* projection system pertaining to the location of KwaZulu-Natal province are given in Table 4.1.

Table 4.1 Projection parameters used for all datasets

Parameter	Value
Projection	Universal Transverse Mercator (UTM)
Spheroid	WGS 84
Units	Metres
Zone	36°

4.3 Controlling variables for river classification

As shown in Figure 1.1, there are a number of controlling variables for river ecosystems. The controlling variables in the classification systems on which this dissertation is based were identified and captured into a GIS database. This section gives a description of the GIS layers used in the dissertation, namely: river network, slope gradient, vegetation and landcover layers.

4.3.1 River network

The first step in applying the classification system is to obtain a river network of Kwazulu-Natal's major rivers. According to the Agricultural Information System (AGIS) metadata, the river network used in the dissertation was developed from 1: 50 000 topographic maps. The river network was acquired in an ArcView shapefile format, and its topology was established, i.e. cleaning and building the relationship between the line segments. The KwaZulu-Natal river network is shown in Figure 4.1 and its accompanying tabular data (Table 4.2)

Table 4.2 below indicates the *River_ID*, *Name* of the river and *Class*. The importance of the *River_ID* is its usage in the GIS processes such as buffering and calculation of length or area. The *Name* of the river is of optional use in this dissertation, because the focus is on all the major rivers of KwaZulu-Natal and not a specific river. The *Class* of river, which is whether the river is perennial or non-perennial, is of significance in the early stages when the selection is made between the perennial or major rivers and non-perennial rivers.

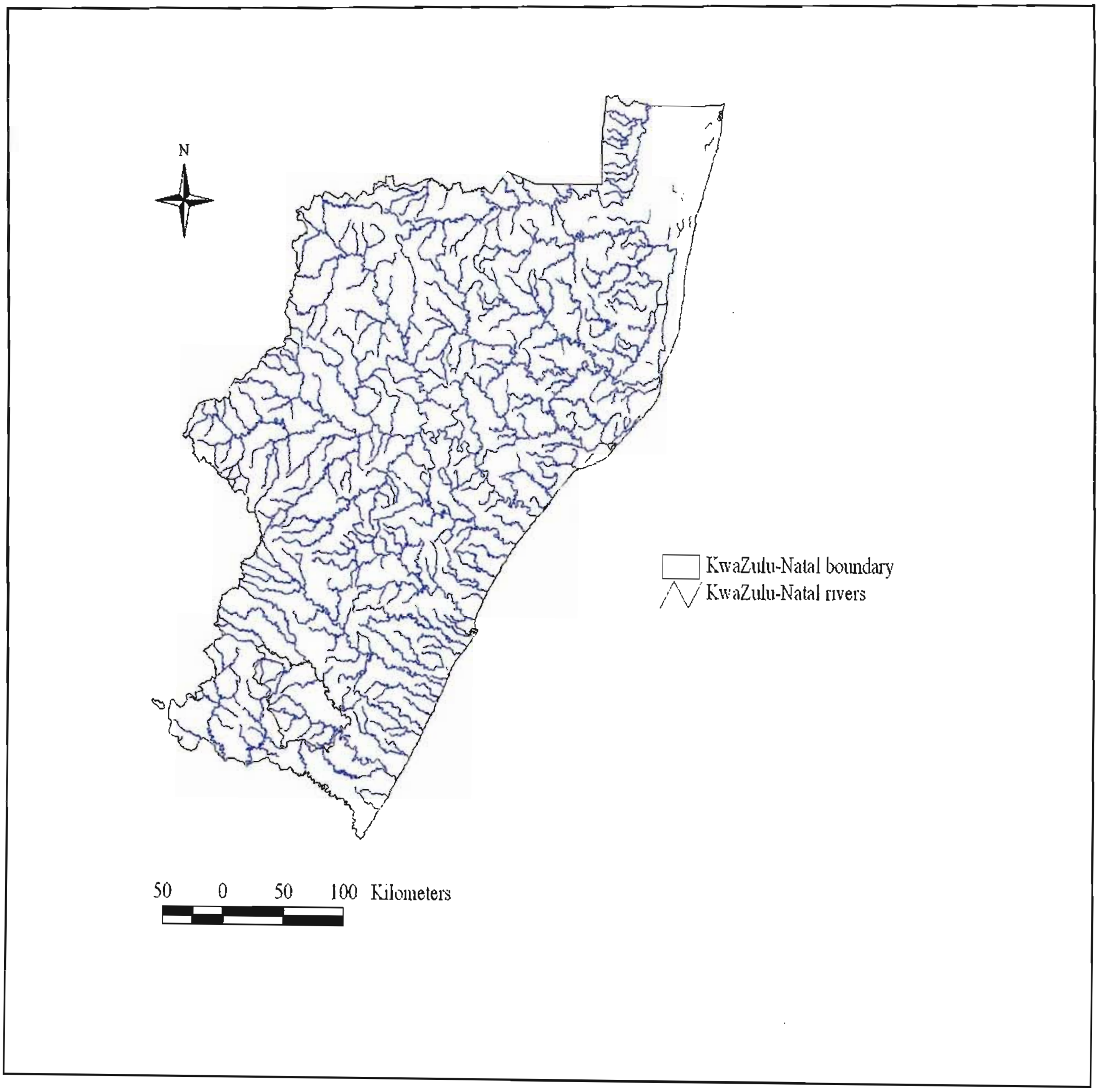

Figure 4.1 River network of KwaZulu-Natal Province (Source: Agricultural Research Council)

Table 4.2 River network tabular data

River_ID	Name	Class
326	BRAAMHOEKSPRUIT	Non_pernl_river
145	DORINGSPRUIT	Perennial_river
304	DWARSRIVIER	Perennial_river
523	ISIKHEHLENGA	Perennial_river
22	LUBAMBO	Non_pernl_river
948	MALUKOKA	Perennial_river
396	MANGENI	Perennial_river
495	MANYANE	Non_pernl_river
70	MFONGOSI	Non_pernl_river
23	MFONOS	Perennial_river
692	MGENI	Perennial_river
930	MHLABATSHANE	Perennial_river
120	MHULUMBELE	Perennial_river
721	MQATSHENI	Perennial_river
2	MSUNDUZI	Non_pernl_river
526	MTONTWANES	Perennial_river
322	MVALO	Non_pernl_river
255	MZINYASHANA	Non_pernl_river
882	NDONYANE	Perennial_river
215	NGWENI	Non_pernl_river
417	NHLANYANGA	Perennial_river
706	NHLATHIMBE	Perennial_river
841	NHLAVINI	Perennial_river
174	NSONTO	Perennial_river
319	NYALAZI	Perennial_river
269	NZIMANE	Perennial_river
4	PONGOLO	Perennial_river
410	SAND RIVER	Perennial_river
275	STERKSTROOM	Perennial_river
328	TATANA	Perennial_river
379	TOLENI	Perennial_river
442	TUGELA	Perennial_river

4.3.2 Slope gradient

A critical component of the river ecosystem classification is a factor of slope gradient (Rosgen 1994, Rowntree *et al.* 2000). This factor helps in the delineation of river channels into different morphological zones. The slope gradients of the river channel are generated from the digital elevation models (DEMs) of the area. The procedures of creating the DEMs – also known as the digital terrain models (DTMs) – are reviewed by Weibel and Heller (1991). In this dissertation, the grid-based format of the DEM was used to derive the slope gradients.

The 100-metre DEM available for the dissertation was obtained from the Agricultural Research Council's archives. This 100-metre DEM was used to derive a slope gradient (in percentages), and thereafter manipulated to reflect the Rowntree and Wadeson (1999) classes of slope ranges (Figure 4.2). Its accompanying tabular data shows the *Slope %*, the *Class type*, *Area* covered by these classes by square metres (m^2) or hectares (ha) in KwaZulu-Natal (Table 4.3).

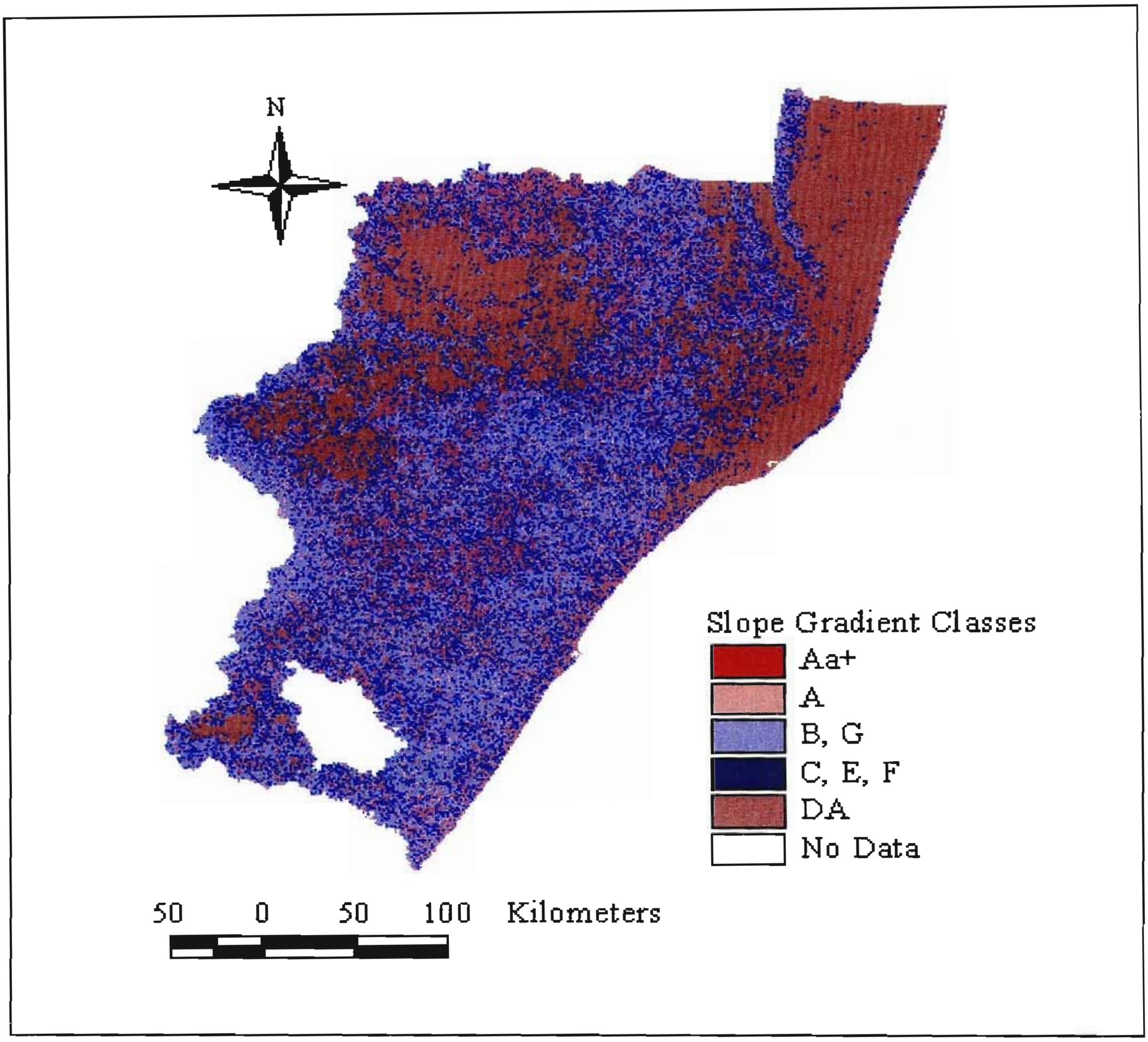

Figure 4.2 Slope gradient classes (after Rowntree and Wadeson 1999) derived from 100-metre DEM. Source: Agricultural Research Council

Table 4.3 Slope gradient classes (Rowntree and Wadeson 1999) derived from 100-metre DEM

GridCode	Slope %	Class_type	Area(m²)	Area(ha)
1	0 - 0.5	DA	339881216.93	33988.12
2	0.5 - 2	C, E, F	192304784.24	19230.48
3	2 - 4	B, G	240883090.05	24088.31
4	4 - 10	A	7813529.24	781.35
5	>10	Aa+	2075.77	0.21

4.3.3 Vegetation and Landcover layers

Vegetation and land-cover layers are secondary variables, which prove to be valuable for river environment classification (Snelder *et al.* 1999, Rowntree *et al.* 2000 and Rosgen 1994).

In this dissertation, the vegetation layers include Acocks Vegetation Types (Acocks 1988) in Figure 4.3, and *Low and Rebelo Vegetation Types* (Low and Rebelo 1996) in Figure 4.4. These layers are used in order to give a varied description of the vegetation occurring in KwaZulu-Natal and also to showcase the opportunity to use the vegetation layers readily available in GIS format to analyse different hierarchies in the river classification system.

The accompanying tabular data of *Acocks Vegetation Types* and *Low and Rebelo Vegetation Types* (both in Table 4.4 and Table 4.5 respectively) contain the fields of *Vegetation_ID*, *Vegetation_Type*, *Area* (m^2) and *Area (ha)*. The data contained in these tables help in the quantification of the vegetation types and their spatial distribution.

Landcover Types (Figure 4.5) is an additional layer which is of the same ilk as the above-mentioned, but instead of solely dealing with vegetation types, it embraces other land cover features such as waterbodies, mines and quarries, bare soil, etc. The use of this layer gives a picture of land use in the areas, hence important for conservation and development purposes.

Table 4.6 contains the fields of *Landcover_Code*, *Landcover_Type*, *Area* (m^2) and *Area (ha)*. It is worth noting that The *Landcover_Type* field complements the *Vegetation_Type* field in *Acocks Vegetation Types* and *Low and Rebelo Vegetation Types* in that it gives the kind of land use, such as irrigation, mines and quarries, built-up areas, etc. The link of vegetation types and land-use could be important in decision making, for instance, whether a particular vegetation type need to be protected or conserved with reference to the land use in the area.

The metadata for the layers of Acocks Vegetation Types, Low and Rebelo Vegetation Types and Landcover Types are presented in Chapter 3 (Table 2.5). These describes the layers in detail: issues of scale, data format, purpose for which the layer was developed, and data quality – which is dependent on the manner in which the data was handled up to its end.

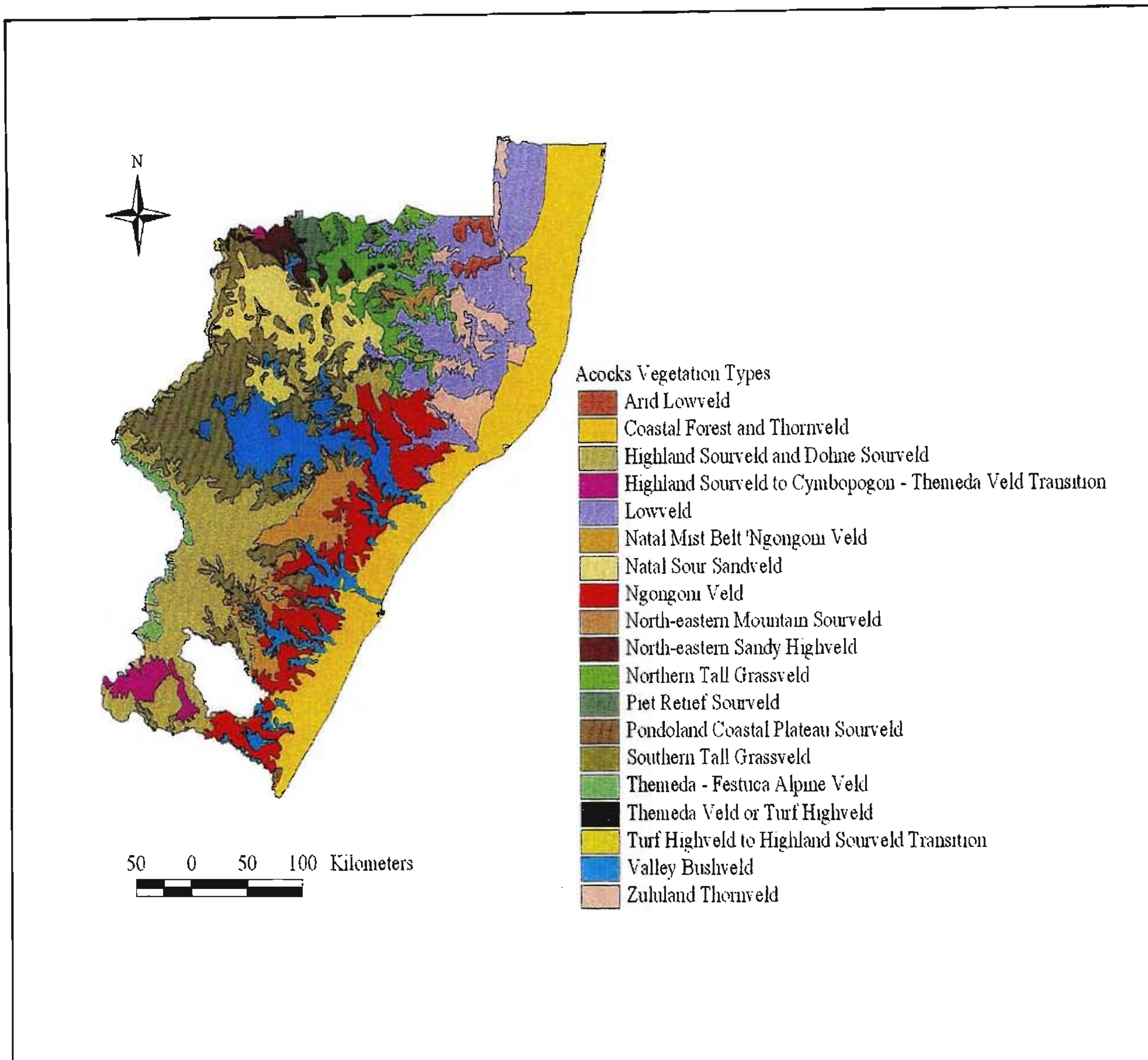

Figure 4.3 Acocks Vegetation Types of KwaZulu-Natal. The legend shows the description of veldtypes. Source: Institute of Soil, Climate and Water

Table 4.4 ***Acocks Vegetation Types*** **of Kwazulu-Natal**

Vegetation_ID	**Vegetation_Type**	**Area(m^2)**	**Area(ha)**
1	Coastal Forest and Thornveld	16224154020.84	1622415.40
3	Pondoland Coastal Plateau Sourveld	69040770.86	6904.08
5	Ngongoni Veld	8221142182.59	822114.22
6	Zululand Thornveld	3279189341.54	327918.93
8	North-eastern Mountain Sourveld	524391777.06	52439.18
10	Lowveld	10732190581.68	1073219.06
11	Arid Lowveld	725332661.22	72533.27
23	Valley Bushveld	7811823881.21	781182.39
44	Highland Sourveld and Dohne Sourveld	12766403343.09	1276640.33
45	Natal Mist Belt 'Ngongoni Veld	3863985097.62	386398.51
52	Themeda Veld or Turf Highveld	33406240.07	3340.62
54	Turf Highveld to Highland Sourveld Transition	33214893.60	3321.49
56	Highland Sourveld to Cymbopogon - Themeda Veld Transition	1266963515.61	126696.35
57	North-eastern Sandy Highveld	1068972048.21	106897.20
58	Themeda - Festuca Alpine Veld	930256737.63	93025.67
63	Piet Retief Sourveld	1221269524.14	122126.95
64	Northern Tall Grassveld	4995201286.22	499520.13
65	Southern Tall Grassveld	12287088255.61	1228708.83
66	Natal Sour Sandveld	6040737772.41	604073.78

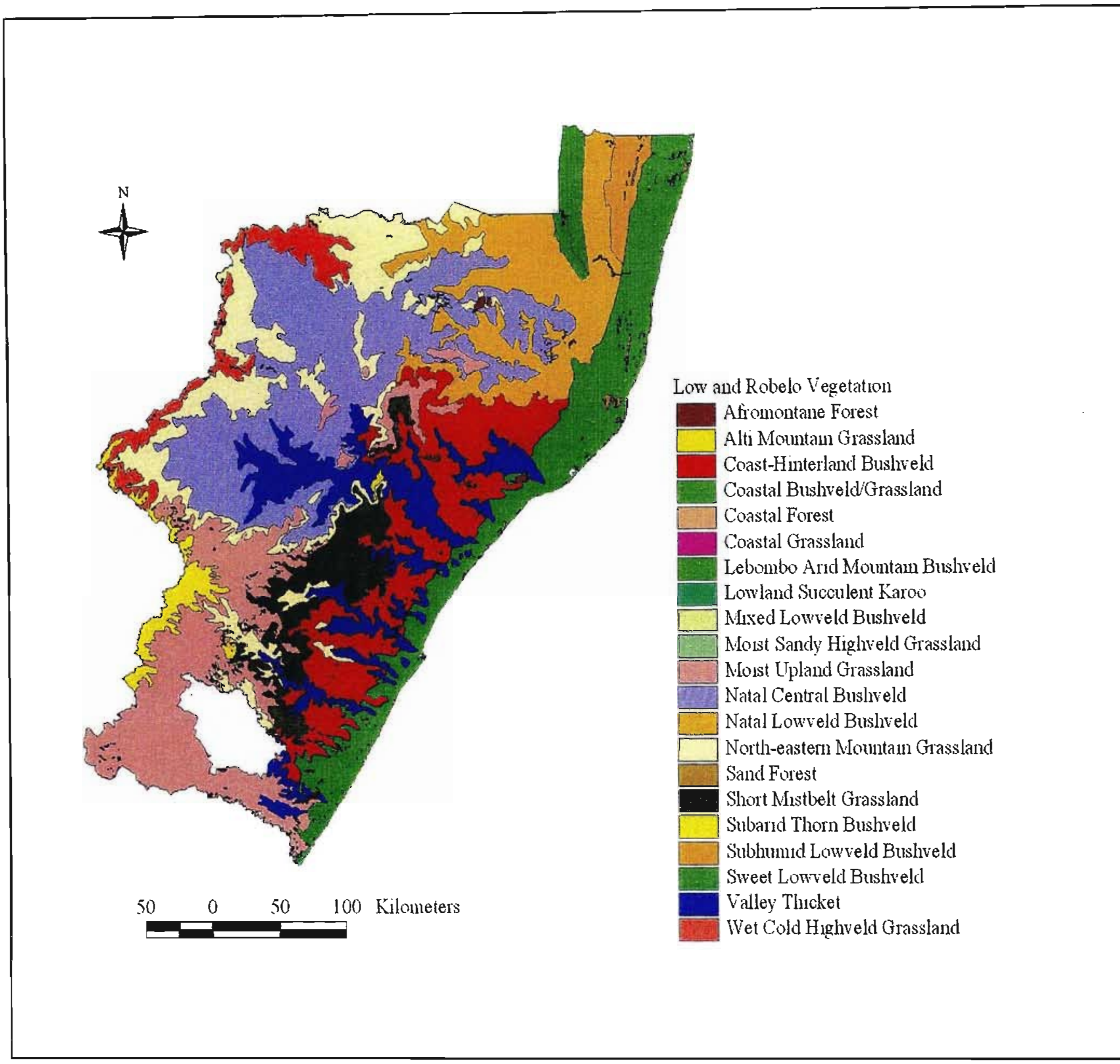

Figure 4.4 ***Low and Rebelo Vegetation Types*** **of KwaZulu-Natal. The legend shows the description of veldtypes. Source: Institute of Soil Climate and Water**

Table 4.5 Low and Rebelo Vegetation Types of KwaZulu-Natal

Vegetation_ID	Vegetation_type	Area(m^2)	Area(ha)
30	Natal Lowveld Bushveld	10027908138.92	1002790.81
32	Subarid Thorn Bushveld	82731069.56	8273.11
48	Coast-Hinterland Bushveld	5077835999.98	507783.60
50	Short Mistbelt Grassland	296750190.63	29675.02
52	Wet Cold Highveld Grassland	2872070505.70	287207.05
53	Valley Thicket	3965139920.39	396513.99
54	Alti Mountain Grassland	1704824281.42	170482.43
57	Moist Upland Grassland	263270912.79	26327.09
59	Natal Central Bushveld	17036413111.55	1703641.31
60	Coastal Grassland	29742.16	2.97
63	Subhumid Lowveld Bushveld	1359488573.23	135948.86
66	North-eastern Mountain Grassland	2831816745.53	283181.67
69	Mixed Lowveld Bushveld	527303.51	52.73
70	Sweet Lowveld Bushveld	323691471.95	32369.15
73	Coastal Bushveld/Grassland	11317678335.49	1131767.83
75	Lebombo Arid Mountain Bushveld	1141217072.40	114121.71
83	Moist Sandy Highveld Grassland	8429778.83	842.98
93	Lowland Succulent Karoo	1786218.14	178.62
111	Sand Forest	585639.76	58.56
112	Afromontane Forest	637898.73	63.79
120	Coastal Forest	1802441.59	180.24

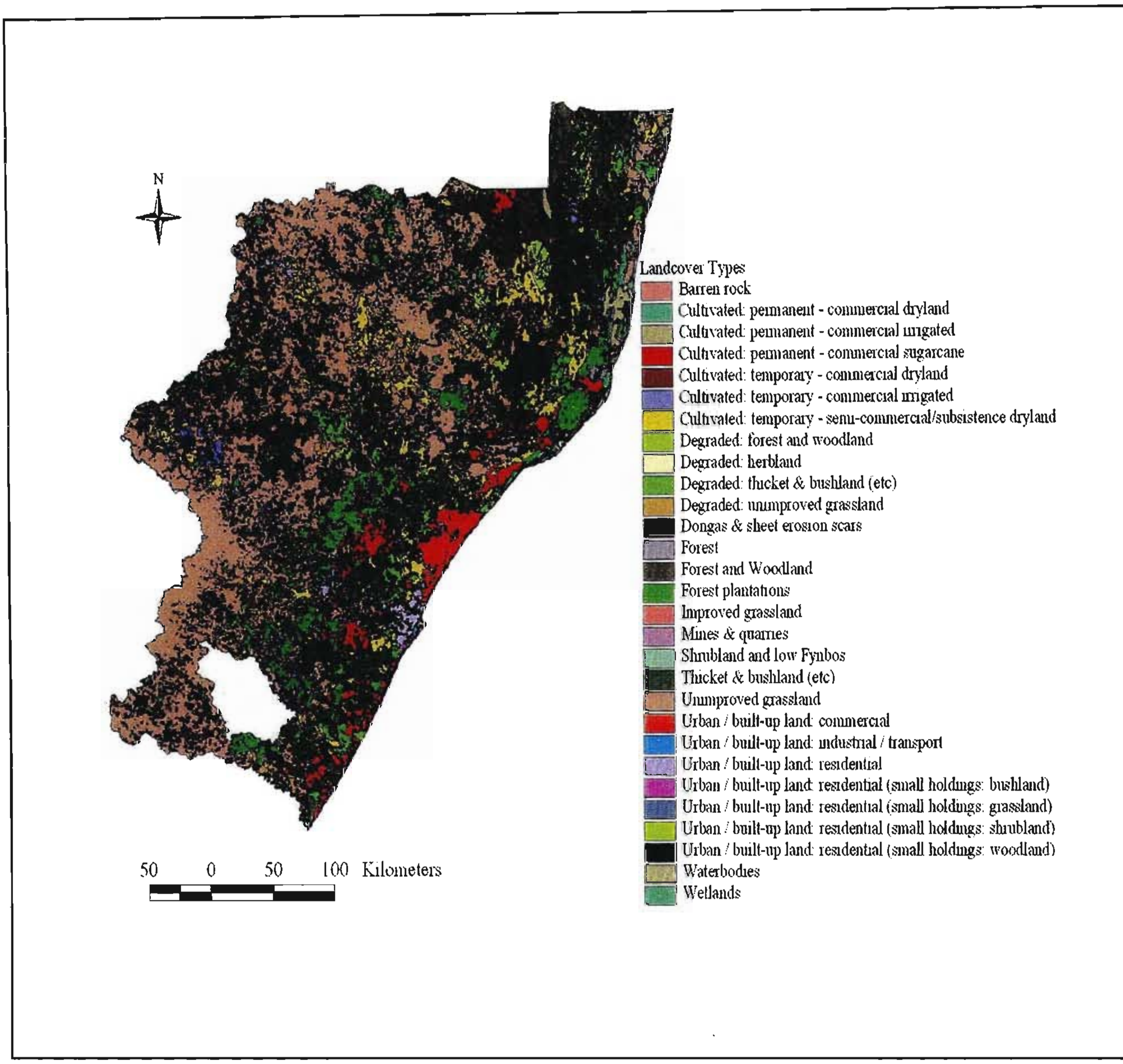

Figure 4.5 *Landcover Types* of KwaZulu-Natal extracted from the National Landcover Database. Source: Institute of Soil, Climate and Water

Table 4.6 ***Landcover Types*** **of KwaZulu-Natal**

Landcov_ Code	**Landcov_Type**	**Area(m^2)**	**Area(ha)**
1	Forest and Woodland	6061194175.25	606119.42
2	Forest	1226965444.57	122696.54
3	Thicket & bushland (etc)	16196454799.83	1619645.48
4	Shrubland and low Fynbos	76301052.08	7630.11
6	Unimproved grassland	35937900768.72	3593790.08
7	Improved grassland	237116102.42	23711.61
8	Forest plantations	6186539058.97	618653.91
9	Waterbodies	993364860.31	99336.49
10	Wetlands	766969646.23	76696.96
11	Barren rock	62043607.17	6204.36
12	Dongas & sheet erosion scars	279970599.29	27997.06
13	Degraded: forest and woodland	958098268.98	95809.83
14	Degraded: thicket & bushland (etc)	2778586409.31	277858.64
15	Degraded: unimproved grassland	3284689697.04	328468.97
17	Degraded: herbland	578375.60	57.84
18	Cultivated: permanent - commercial irrigated	27473193.85	2747.32
19	Cultivated: permanent - commercial dryland	81532855.33	8153.29
20	Cultivated: permanent - commercial sugarcane	4114558168.25	411455.82
21	Cultivated: temporary - commercial irrigated	1320913162.02	132091.32
22	Cultivated: temporary - commercial dryland	2370043449.53	237004.34
23	Cultivated: temporary - semi-commercial/subsistence dryland	7909678311.18	790967.83
24	Urban / built-up land: residential	1060773550.09	106077.36
25	Urban / built-up land: residential (small holdings: woodland)	171475.72	17.15
26	Urban / built-up land: residential (small holdings: bushland)	140830113.50	14083.01
27	Urban / built-up land: residential (small holdings: shrubland)	2435258.49	243.53
28	Urban / built-up land: residential (small holdings: grassland)	27472816.43	2747.28
29	Urban / built-up land: commercial	39818909.83	3981.89
30	Urban / built-up land: industrial / transport	88935999.49	8893.60
31	Mines & quarries	74666983.46	7466.70

4.4 Map analysis

4.4.1 Introduction

Three analyses were performed using the geomorphologic and ecological databases of the KwaZulu-Natal major rivers. These analyses were divided into three main steps (Figure 4.6). The first step pertains to the geomorphologic analyses, the second step represents the ecological analyses, and the third step analyses the combination of multiple layers of slope gradient, vegetation and landcover.

The following sections discuss the details of the geomorphologic and ecological analyses, the methods and processes used.

4.4.2 General GIS map analyses

To analyse the map layers, GIS (cartographic) modelling was used to combine desirable features on each map to produce single resultant maps. GIS modelling uses the binary logic, i.e. it codes as 1's all the preferable features on the map, whereas the non-preferable features are coded as 0's.

In the geomorphologic and ecological analyses (Figure 4.6), the multiplicative operator of the GIS databases was used. This operator ensures that only locations with preferable features on both maps are shown on the resultant maps, e.g. as shown in Figure 4.6 the combination of *Classified Slope* and *River Channel* results in a *Slope in Channel* layer, which shows slope percentage within the river channel.

On the other hand, combinations of geomorphologic and ecological layers are done using the additive operator, also known as crosstabulation (i.e. *crosstab* in Figure 4.6) or cross-classification. The result is a new combination layer that shows the locations of all combinations and categories in the original layers. Thus, the cross-classification produces a map representation of all non-zero entries in the cross-tabulation table.

The following diagram (Figure 4.6) summarises the dataflow and processes used to produce the geomorphologic and ecological maps in this dissertation.

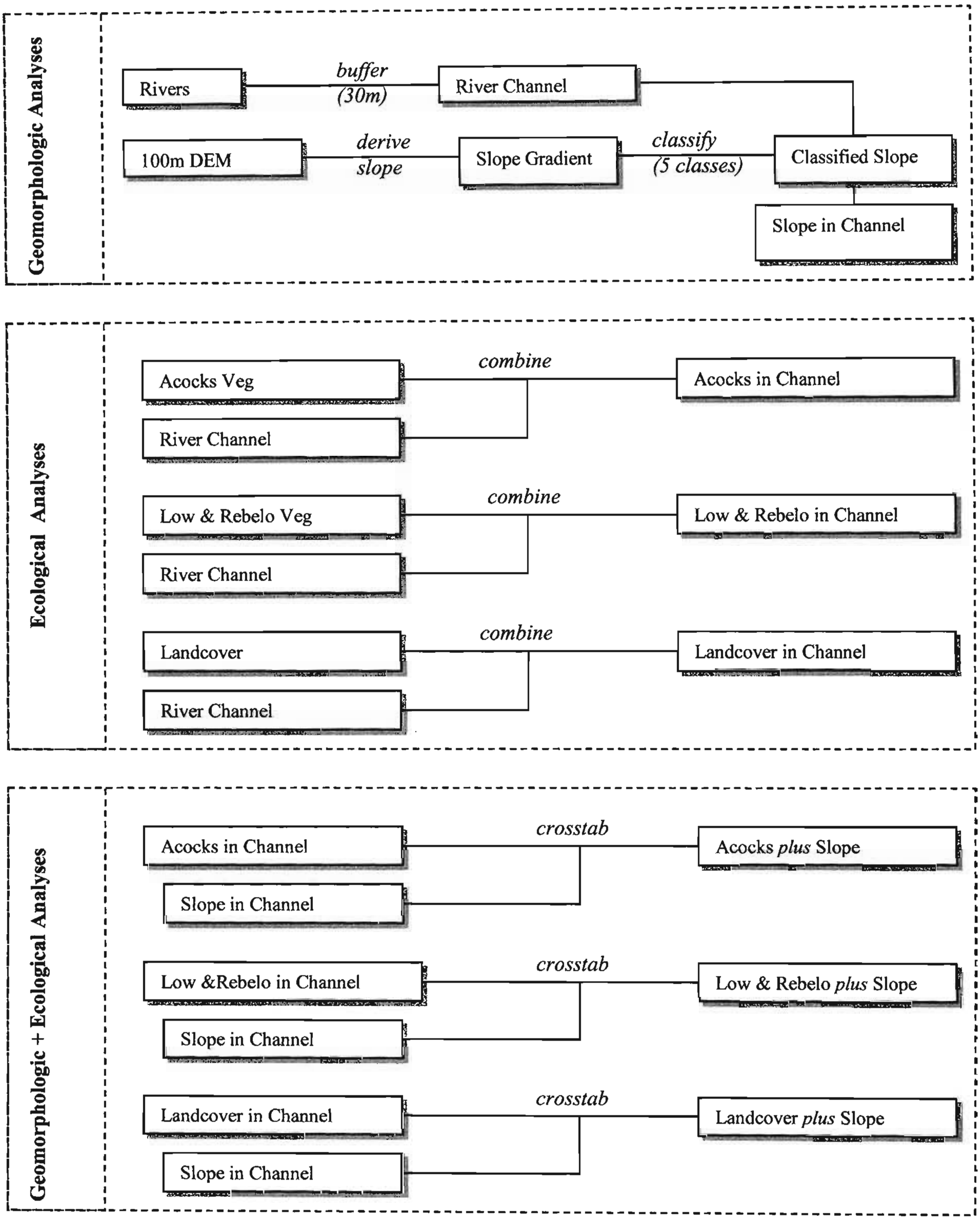

Figure 4.6 A dataflow diagram of the study.

4.4.3 Geomorphologic analyses

In the geomorphologic analyses the river map is used to demarcate the area of the river channel. In the dissertation, the river channel is defined as the area 30m on both sides of the river segments. This definition corresponds with the definition of a river reach (Table 2.2) that it is '*a length of channel characterised by a particular channel pattern and channel morphology, resulting from a uniform set of local constraints on channel form, which extends '00s meters from the river*' (Rowntree *et al.* 2000, p. 164). The resultant map is the *River Channel*, which forms the basis of all the consequent analyses (Figure 4.6). The derived map from the 100m DEM is reclassified to take the form of *Classified Slope*, which denotes the slope gradient classes in percentages (Table 2.4).

The classification adapted in Table 2.4 is simplified such that the original classes sharing the same slope gradient are grouped in order to enable classification in a GIS, e.g. a combination of B and G classes into a single class (B, G class), because of their sharing of similar slope gradient of 2-4%. Nevertheless, the descriptions of these classes indicate that even though they share the same slope gradient class, their morphology could still differ, which includes factors such as sinuousity, entrenchment and width/depth ratio.

4.4.4 Ecological analyses

In the ecological analyses, the maps of *Acocks Veg*, *Low & Rebelo Veg* and *Landcover* layers were combined with the *River Channel* to create the maps of Acocks in Channel, *Louw & Rebelo in Channel*, and *Landcover in Channel* respectively (Figure 4.6). The function of intersection in GIS was used to overlay the layers with each other in order to produce the combined database of their attributes. These layers represent the vegetation in terms of *Acocks* (Figure 4.3), *Louw & Rebelo* (Figure 4.4) as well as the *Landcover* types (Figure 4.5) within 30m on both sides of the river channels.

4.4.5 Geomorphologic plus ecological analyses

In these analyses, geomorphologic and ecological layers are combined using a crosstabulation operation. This operation combines the layers in question, which results in a map showing the locations of all combinations in the original layers. Simultaneously, a cross-tabulation table is created, in which the attributes of both layers are presented. The corresponding legend shows classes comprising of these combinations, thus resulting in a map representation of all non-zero entries in the cross-tabulation table.

For instance, in the above-illustrated dataflow diagram (Figure 4.6), a crosstabulation of *Acocks in Channel* and *Slope in Channel* produce a map designated as *Acocks plus Slope* (see the map in Figure 5.6). This resultant map shows a combination of *Acocks Vegetation Types* classes (Figure 4.3 and Table 4.4) and *Slope* gradient classes (Figure 4.2 and Table 4.3). In the corresponding legend the combination of these layers is illustrated, e.g. a class such as '*Lowveld/A*', which implies that '*Lowveld*' class of *Acocks Vegetation Types* combines with '*A*' class of *Slope* gradient.

Chapter 5 Results and discussions

5.1 Introduction

The previous three analyses in Chapter 4 described the resultant layers generated from the combination of 30m-buffered *River Channel* (Figure 5.1) and the layers of *Slope in Channel* (Figure 5.2), *Acocks in Channel* (Figure 5.3), *Low and Rebelo in Channel* (Figure 5.4) and *Landcover in Channel* (Figure 5.5). The *River Channel* – measured 30m on both sides of the river line – was used to describe the riparian zone, which formed the basis of the analyses in the dissertation.

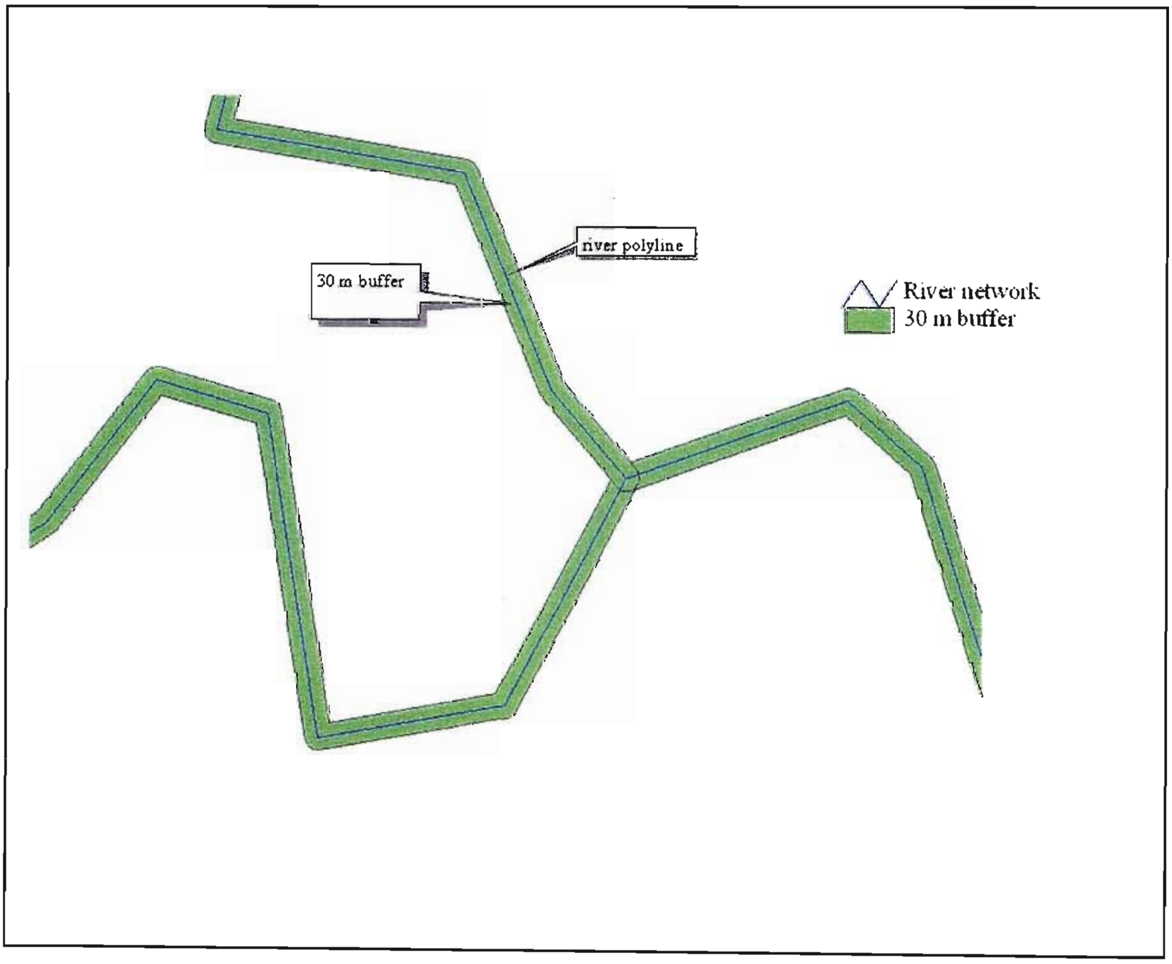

Figure 5.1 The River Channel showing the 30 m buffer on both sides of the river line

In order to give a detailed view of the analyses, approximately 15 km x 15 km area was selected as a sample to demonstrate the classes of resultant layers. As a consequence, this chapter presents the analyses of the sampled area, and discussions on the resultant layers developed.

5.2 Geomorphologic layer

5.2.1 Description of *Slope in Channel*

Slope in Channel (Figure 5.2) is a resultant layer that represents the slope gradient classes according to Rowntree and Wadeson (1999). This layer has been developed from the 100m DEM using the GIS functions of slope generation. The same techniques have been used by Grant *et al.* (1990), Rosgen (1994) de Roo (1998) and Stein *et al.* (1998) to develop the classification schemes for different applications.

In its description of the river environment, *Slope in Channel* depicts the stratification of the *River Channel* (i.e. 30 m on both sides of the river channel polyline) according to their slope gradient classes (Table 5.1). Table 5.1 represents the slope gradient classes, the ranges of slope percentages and the associated description of the classes. The use of *Slope in Channel* layer in the river classification system is based on the works of Grant *et al.* (1990), which endorsed the inference of slope gradients from topographic maps. Thereafter, the inferred slope gradients serve as the basis for stratifying the river channel into slope categories that reflect its geomorphologic units.

The geomorphologic units referred to in the tabular data of the *Slope in Channel* (Table 5.1) are derived from Rowntree and Wadeson (1999), which were modified into classes according to the slope percentage ranges. This implies that classes falling into the same slope range were grouped together as a single class, e.g. classes '*B*' and '*G*' were amalgamated to form '*B, G*' class because they fall into the same slope percentage range of '*2 – 4%*'.

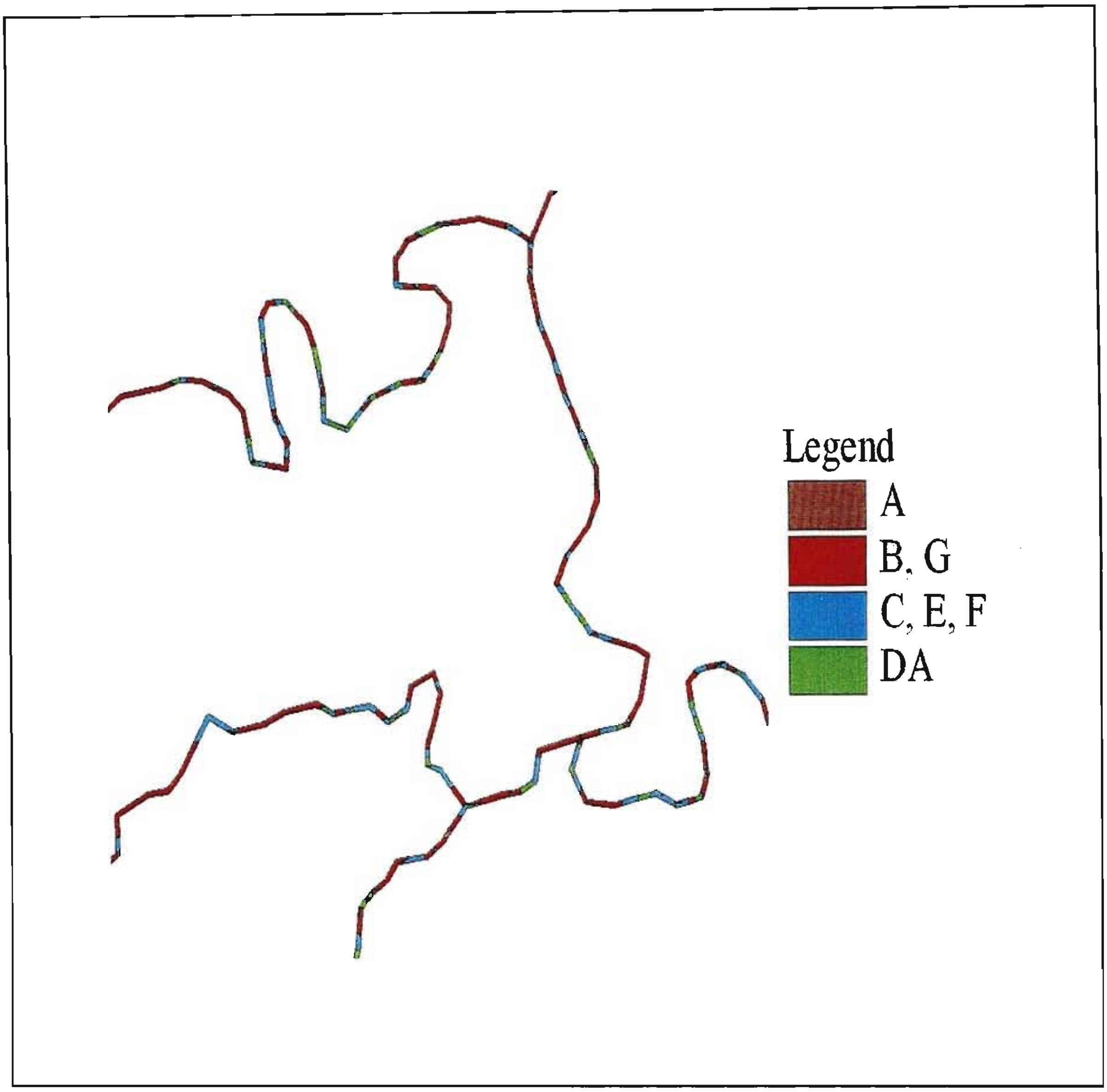

Figure 5.2 ***Slope in Channel*** **layer showing the stratification of the river channel according to slope classes**

Table 5.1 Tabular data of *Slope in Channel* layer

Gridcode	Class	Slope %	Area (m^2)	Area (ha)
1	DA	0 - 0.5	1977.73	0.20
2	C, E, F	0.5 - 2	10177.64	1.02
3	B, G	2 - 4	956709.93	95.67
4	A	4 - 10	6201.91	0.62

5.2.2 Importance of *Slope in Channel* in the classification scheme

The value of *Slope in Channel* layer is its ability to highlight the status of the whole river system, thus making it possible to:

- make groupings of geomorphologic units of the river channel at a later stage;
- evaluate relationships between the slope gradient and other controlling variables, such as source of flow, vegetation types, etc.; and
- predict the river channel morphology.

Nevertheless, the *Slope in Channel* layer does not provide a high degree of resolution, but at this stage, its generalized values make it possible to delineate or select the areas of study along the river channel for appropriate levels of resolution.

5.3 Ecological layers

5.3.1 Description of the ecological layers

As described in Chapter 4, the ecological layers such as *Acocks in Channel* (Figure 5.3), *Low and Rebelo in Channel* (Figure 5.4) and *Landcover in Channel* (Figure 5.5) originate from the combination of thematic maps of their base layers and the *River Channel*, as explained previously in the methodology in Figure 4.6.

5.3.1.1 *Acocks in Channel*

Acocks in Channel (Figure 5.3) describes the veld types along the river channel according to Acocks (1988) vegetation classification. The layer was developed using the vegetation type field in *Acocks Vegetation* tabular data (Table 4.4) to highlight vegetation type, and thereafter it was combined with *River Channel* layer. This combination resulted in the layer of *Acocks in Channel* (Figure 5.3), which is made up of classes such as '*Ngongoni Veld*', '*Valley Bushveld*', etc (Table 5.2)

As a descriptor of river channel, *Acocks in Channel* provides indicator classes for areas with similar soil types, moisture regime and other factors controlling the occurrence of such a veld type along the length of the river (Acocks 1988). It is noteworthy that these classes are not detailed enough to provide species and sub-species for conservation purposes.

Furthermore, the original classes of *Acocks in Channel* could be manipulated according to the requirements of a classification system to suit a specific purpose, which implies amalgamating veld types sharing the same characteristic into subjective classes, such as 'highly disturbed', 'moderately disturbed' or 'less disturbed'.

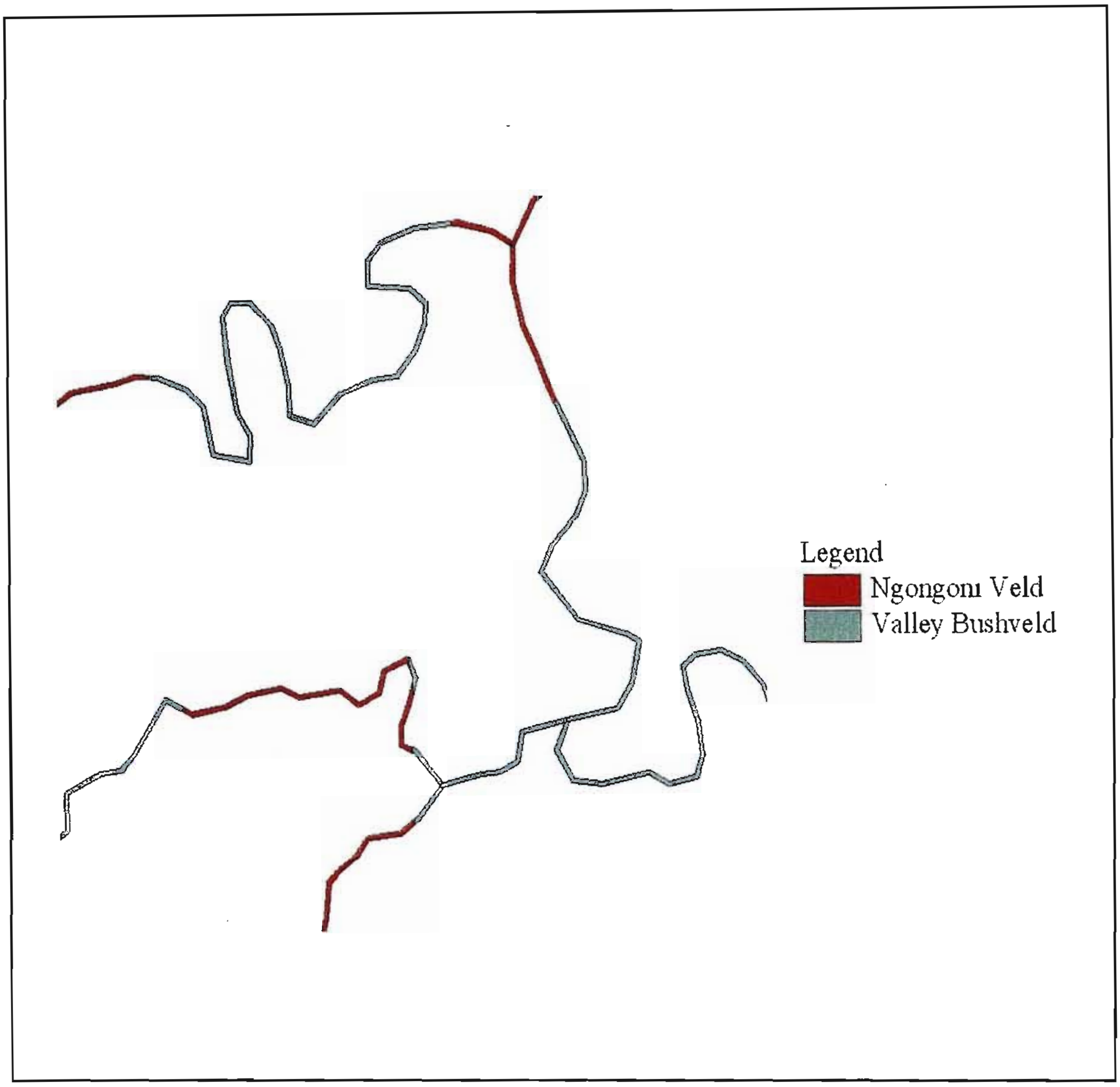

Figure 5.3 ***Acocks in Channel*** **showing the vegetation types of '*Ngongoni Veld*' and '*Valley Bushveld*' along the river channel**

Table 5.2 Tabular data of *Acocks in Channel* layer

Class	Area (m^2)	Area (ha)
Ngongoni Veld	1440771.08	144.05
Valley Bushveld	39161.84	3.92

5.3.1.2 *Low and Rebelo in Channel*

Low and Rebelo in Channel (Figure 5.4) illustrates the vegetation types chosen on units with similar vegetation structure, sharing important plant species and having similar ecological processes along the river channel (Low and Rebelo 1996). This layer was generated by combining the *Low and Rebelo* vegetation (Figure 4.4) and the *River Channel* layers, and it denotes the vegetation classes as presented in Table 5.3, such as *'Coast-Hinterland Bushveld'* and *'Valley Thicket'*.

As an indicator of ecological processes in river classification, *Low and Rebelo in Channel* describes the portions along the river channel with particular groupings of plant species influenced by more or less same ecological processes (Low and Rebelo 1996). Although it is not detailed enough to explain some of these ecological processes, it provides the general understanding about the river channel in this instance. At this level of resolution, the ecological assessment of the river channel could be done using the distribution of the vegetation classes along the river.

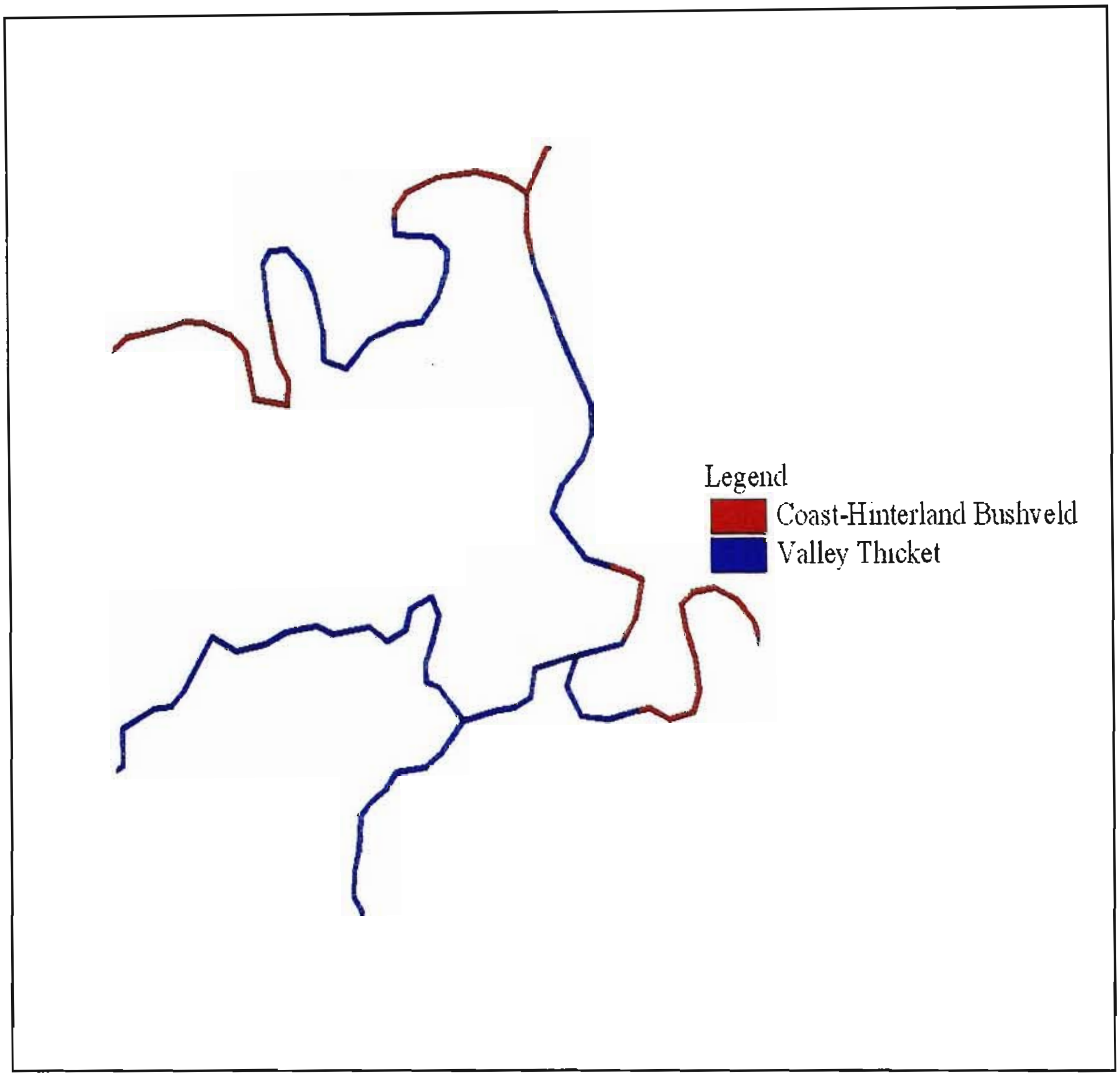

Figure 5.4 ***Low and Rebelo in Channel*** **layer showing the vegetation types of '*****Coast-Hinterland Bushveld*****' and '*****Valley Thicket*****' along the river channel**

Table 5.3 Tabular data of *Low and Rebelo in Channel*

Class	Area (m^2)	Area (ha)
Coast-Hinterland Bushveld	2015409.92	201.54
Valley Thicket	656163.01	65.62

5.3.1.3 *Landcover in Channel*

Landcover in Channel (Figure 5.5) is a layer developed from the *Landcover* and *River Channel* layers, which is different from other ecological layers discussed previously. The difference is due to its combination of landcover (i.e. vegetation cover, soils, water etc.) and its correlate, landuse, which is indicated in the tabular data of *Landcover* (Table 4.6) with classes such as '*Mines and Quarries*' and '*Urban/Built-up land*'.

As a controlling variable in the ecological processes of the river channel, *Landcover in Channel* is significant in processes controlling nutrient enrichment, suspended sediment supply and flow variability and therefore on biological assemblages. Furthermore, *Landcover in Channel* layer – due to its component of landuse – could be of use in identifying the areas of potential human development and activities.

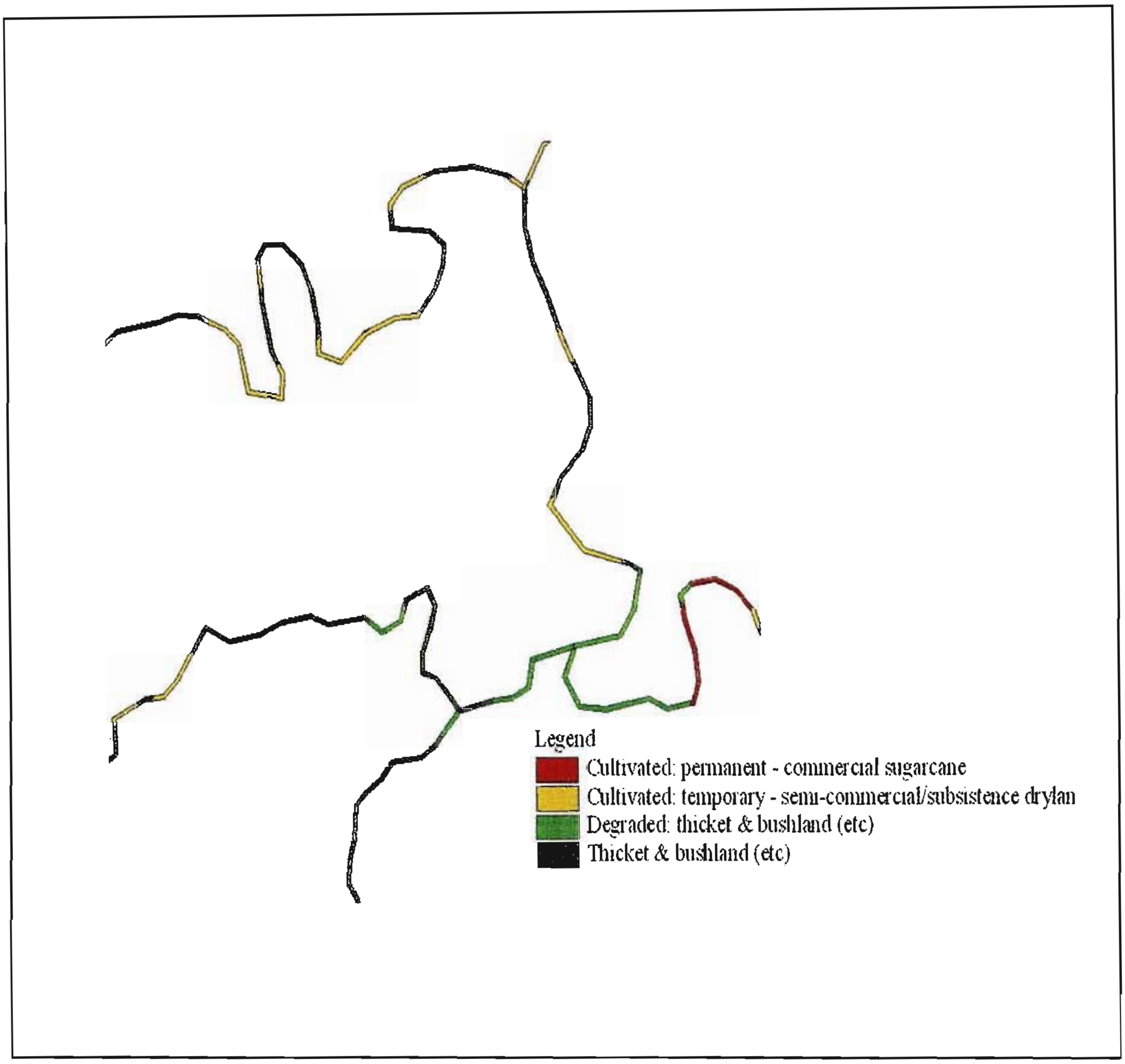

Figure 5.5 *Landcover in Channel* layer showing the legend with some of the classes in its tabular data.

Table 5.4 Tabular data of *Landcover in Channel* layer

Class	Area (m^2)	Area (ha)
Cultivated: permanent - commercial sugarcane	2653986.34	265.41
Cultivated: temporary - semi-commercial/subsistence dryland	74072.78	7.41
Degraded: thicket & bushland (etc)	26698.49	2.67
Thicket & bushland (etc)	742915.15	74.28

5.3.2 Importance of ecological layers in the classification scheme

In the river environment classification, these ecological controlling variables such as '*landuse/landcover*', '*riparian vegetation*' and '*cover*' occupy different spatial scales in the hierarchy (see Figure 1.1). For instance, '*landuse/landcover*' is found in the upper level of the hierarchy (catchment scale), while '*riparian vegetation*' and '*cover*' are found at the lowermost level of the hierarchy (reach scale). Despite the difference in the spatial scales, these ecological layers overlap when it comes to describing the conservation status, ecological health, and sensitivity of the river channel.

The ecological layers of *Acocks in Channel* (Figure 5.3), *Low and Rebelo in Channel* (Figure 5.4) and *Landcover in Channel* (Figure 5.5) depict separate fragments of the river channel, i.e. illustrations of the stratified river channel, with zones of different vegetation or landuse classes. These are *in situ* classifications of the river channels, without signifying the purpose of classification. Thus, these ecological layers serve as preliminary step for classification of the river channel for a specified purpose, such as conservation.

As part of the classification scheme, these layers could play a pivotal role in

- identifying sites for detailed studies of river channels, i.e. homogenous and non-homogenous,
- creating ecological basemaps for temporal and spatial analysis of the ecological layers, i.e. continuously monitoring change of these variables, and
- appraising the degradation potential of the river channel by using the vegetation types and the landuse/ landcover layers as a baseline.

These ecological layers illustrated in Figure 5.3, 5.4 and 5.5 could be useful in a number of developed river classification schemes in South Africa and abroad (Wadeson and Rowntree 1994 in Uys 1994, pp. 49–67). But, the authors indicated that the true value of these methodologies appear to be the ability to highlight areas of potential disturbance and to focus attention in an objective manner on various aspects of the river system.

5.4 Geomorphologic plus ecological Layers

5.4.1 Description of the geomorphologic plus ecological layers

These are layers resulting from spatial combinations of ecological and geomorphologic layers, for instance, the combination of *Acocks in Channel* and *Slope in Channel* yield a resultant layer of *Acocks plus Slope* (Figure 5.6). In *Acocks plus Slope* layer, the attribute databases of *Acocks in Channel* (Figure 5.3 and Table 5.2) and *Slope in Channel* (Figure 5.2 and Table 5.1) are merged to describe a new layer in which the spatial features of both are represented. This combination is evident in the legends of Figure 5.6, 5.7 and 5.8, which show fusions of these layers, e.g. '*Ngongoni Veld/ DA'* in *Acocks plus Slope* (Figure 5.6). As described in the methodology in chapter 4, crosstabulation operation was used to amalgamate these layers in order to arrive at classes that show the spatial coincidence of the geomorphologic layer and the ecological layer.

It is evident in the legends of Figure 5.6, 5.7 and 5.8 and the accompanying tabular data (Table 5.5, 5.6 and 5.7) that large number of data could be generated with the increase in the layers combined. But, the flexibility of the GIS makes it possible for easy management of large databases, such that classes within each controlling variable could be amalgamated to produce general classes for specific management purposes. For instance, landcover/ landuse may be classified as '*highly disturbed*', '*moderately disturbed*' or '*less disturbed*' in more advanced descriptive maps (Berry 1991 in Maguire *et al.* 1991, pp. 285-295).

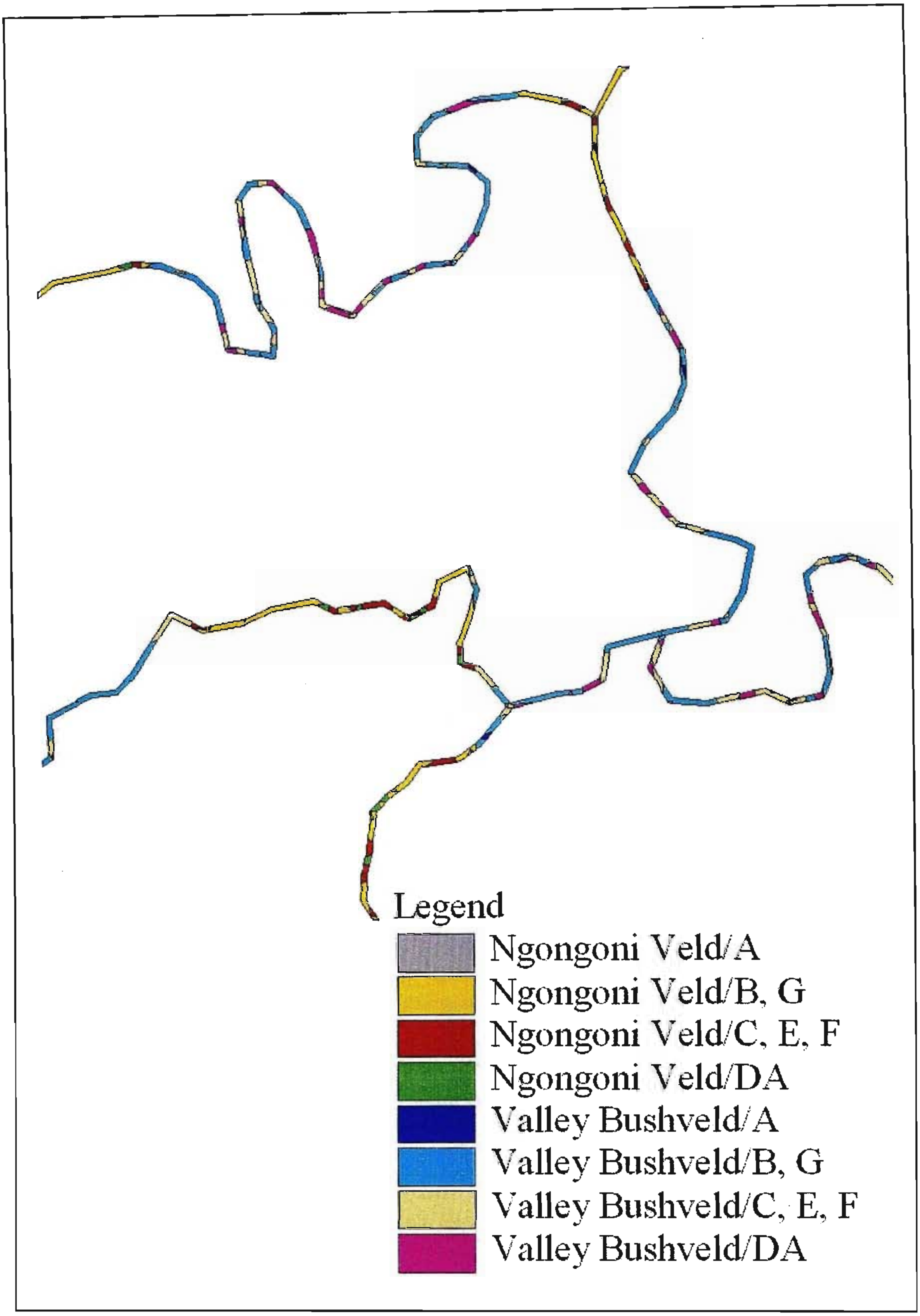

Figure 5.6 ***Acocks plus Slope*** **layer with a legend showing the classes in its tabular data**

Table 5.5 Tabular data for *Acocks plus Slope* layer

Class	**Slope**	**Area (m^2)**	**Area (ha)**
Ngongoni Veld/A	4 - 10	312.09	0.03
Ngongoni Veld/B, G	2 - 4	869240.59	86.92
Ngongoni Veld/C, E, F	0.5 - 2	15378.74	1.54
Ngongoni Veld/DA	0 - 0.5	7527.19	0.75
Valley Bushveld/A	4 - 10	6201.91	0.62
Valley Bushveld/B, G	2 - 4	4917.65	0.49
Valley Bushveld/C, E, F	0.5 - 2	17651.61	1.77
Valley Bushveld/DA	0 - 0.5	4956.94	0.50

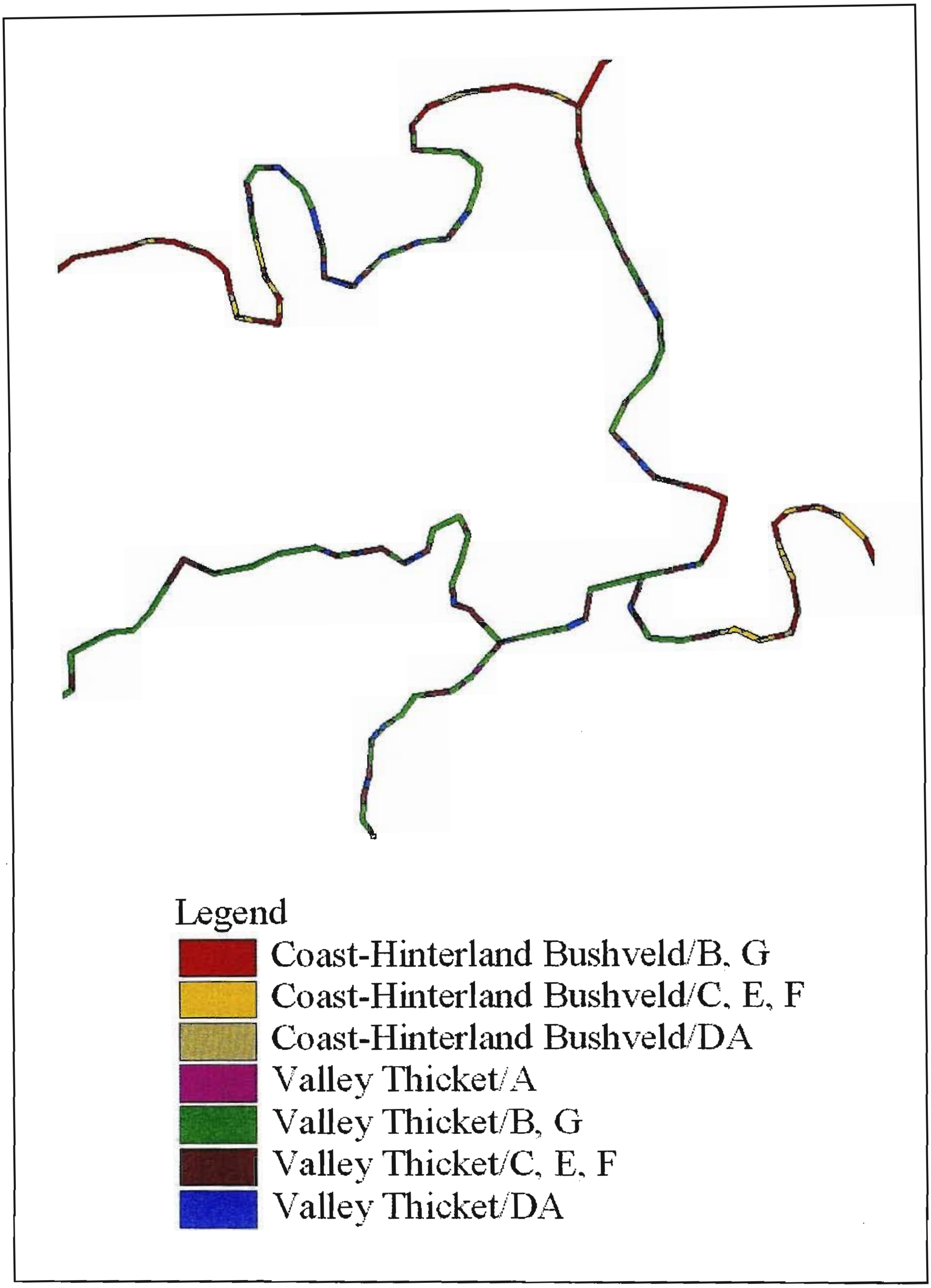

Figure 5.7 ***Low and Rebelo plus Slope*** **layer showing classes in its tabular data**

Table 5.6 Tabular data of *Low and Rebelo plus Slope* layer

Class	**Slope %**	**Area (m^2)**	**Area (ha)**
Coast-Hinterland Bushveld/B, G	2 - 4	2411.95	0.24
Coast-Hinterland Bushveld/C, E, F	0.5 - 2	5291.15	0.53
Coast-Hinterland Bushveld/DA	0 - 0.5	801.10	0.08
Valley Thicket/A	4 - 10	2913.08	0.29
Valley Thicket/B, G	2 - 4	956709.93	95.67
Valley Thicket/C, E, F	0.5 - 2	0.27	0.00
Valley Thicket/DA	0 - 0.5	4981.67	0.50

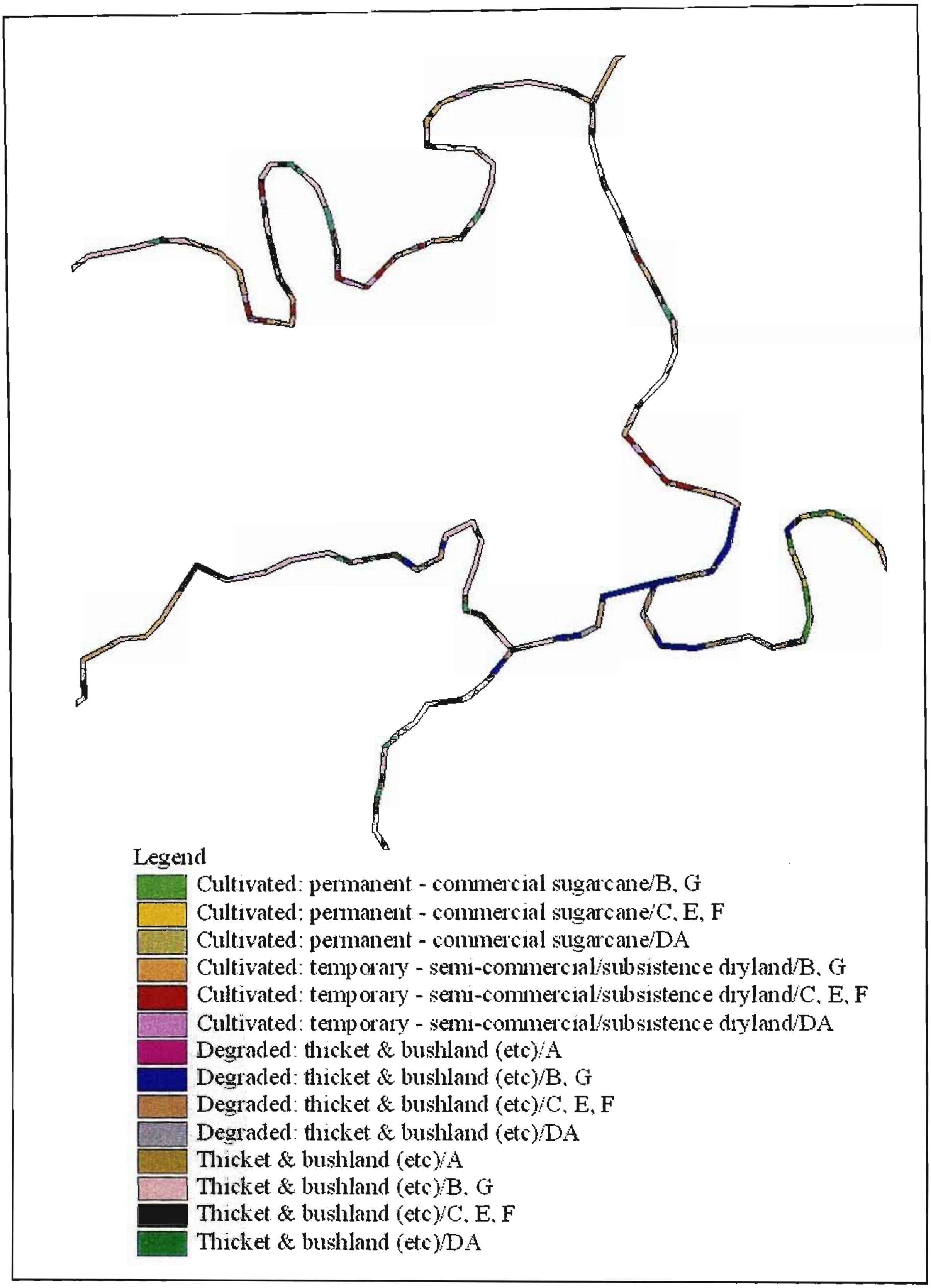

Figure 5.8 *Landcover plus Slope* layer showing the classes represented in its tabular data along the river channel

Table 5.7 Tabular data of *Landcover plus Slope* layer

Class	Slope	Area (m^2)	Area (ha)
Cultivated: permanent - commercial sugarcane/B, G	2 - 4	784185.96	78.42
Cultivated: permanent - commercial sugarcane/C, E, F	0.5 - 2	3577.86	0.36
Cultivated: permanent - commercial sugarcane/DA	0 - 0.5	3443.13	0.34
Cultivated: temporary - semi-commercial/subsistence dryland/B, G	2 - 4	579976.34	58.00
Cultivated: temporary - semi-commercial/subsistence dryland/C, E, F	0.5 - 2	1034.59	0.10
Cultivated: temporary - semi-commercial/subsistence dryland/DA	0 - 0.5	2972.71	0.30
Degraded: thicket & bushland (etc)/A	4 - 10	6201.91	0.62
Degraded: thicket & bushland (etc)/B, G	2 - 4	784185.96	78.42
Degraded: thicket & bushland (etc)/C, E, F	0.5 - 2	19434.28	1.94
Degraded: thicket & bushland (etc)/DA	0 - 0.5	6317.06	0.63
Thicket & bushland (etc)/A	4 - 10	195.97	0.02
Thicket & bushland (etc)/B, G	2 - 4	579976.34	58.00
Thicket & bushland (etc)/C, E, F	0.5 - 2	11364.97	1.14
Thicket & bushland (etc)/DA	0 - 0.5	6268.07	0.63

5.4.2 Importance of the geomorphologic plus ecological layers in the classification scheme

The geomorphologic and ecological layers, such as illustrated in Figure 5.6, 5.7 and 5.8 could be of significance in the creation of various levels of classification, and that would be guided by:

- the purpose of the classification,
- the scale of the classification,
- the number of controlling variables to be included in the classification,
- the usability of the controlling variables as GIS layers, i.e. can be viewed and manipulated in GIS programmes.

According to the previous discussions, these above-stated factors affect the integrity of classification schemes, and caution should be taken to ensure that some information is not compromised in the amalgamation of various controlling variables.

These geomorphologic plus ecological layers could be of great use in the evaluation of the status of the river channel *viz.* the interrelationship between the controlling variables along the river channel could easily be established. Accordingly, various levels of classification could be achieved by successively aggregating subsequent layers in the analyses (Snelder *et al.* 1999). The analyses are flexible, thus enabling the categories in each controlling variable to be amalgamated to produce broader classifications, e.g. in the *Landcover plus Slope* layer (Figure 5.8 and Table 5.7), classes sharing the same slope range could be grouped together in the evaluation of erosion potential or other purposes.

The use of the geomorphologic plus ecological layers could be a great step to understanding and classifying the river systems. The classification of the water resources is the first step required in the protection of the water resources, which is provided for in of the National Water Act No. 36 of 1998 (DWAF 1999) that: '…the first stage in the protection process, which is the development by the Minister of a system to classify the nation's water resources' (Chapter 3, Part 1).

Chapter 6 Conclusions and recommendations

6.1 Conclusions

6.1.1 The controlling variables in river environment classification

The dissertation showed that the analyses of geomorphologic and ecological layers could provide a synoptic view about the potential conditions of the river channels. In essence, it can be regarded as the first step to generate ideas about how the controlling variables along the river channel interrelate across different levels of scale (Figure 1.1). The combination of geomorphologic variables (e.g. slope) and ecological variables (e.g. vegetation types and landcover) makes it possible to predict the physical phenomena of the river system. This dissertation showed that it is possible to combine different controlling variables of river channel, which implies that each point along the river channel could be classified. As a consequence, the contributions of these controlling variables (either individually or together) to the conditions of the river channel could be determined with ease.

In accordance with the objectives of this dissertation, the criteria for choosing the controlling variables were based on their availability in a GIS format and their influence in the river environment. For instance, topography as a high-level controlling variable in the hierarchy for catchment scale studies (Snelder *et al.* 1999) is available for analysis and manipulation in GIS. The same applies to ecological layers such as *Acocks* veld types, *Low and Rebelo* vegetation types and *Landcover* types, which are all available in GIS formats. These geomorphologic and ecological layers are important indicators of the state of the river channel as they are related to the processes controlling nutrient enrichment, suspended sediment supply and flow variability and therefore on biological assemblages.

The use of these geomorphologic and ecological layers is given credence by their ability to appraise the status of the river ecosystem at a coarser scale (in the works of Stein *et al.* 1998 and Snelder *et a*l. 1999). But, it should be noted that this is not a substitute for the study of the instream variables affecting the river channel. These instream variables such as stream-flow rate, stream bank stability, sediment supply and water quality (Figure 1.1) are crucial in the fine scale planning. Thus, the analyses of geomorphologic and ecological layers should be taken as a preliminary stage in the understanding of the whole river systems, which could serve as a basis for selection of sites for studying at a fine scale.

6.1.2 Applicability of GIS in the river environment classification

In this dissertation, it is demonstrated that GIS could be used to analyse different geomorphologic and ecological layers due to its ability to spatially relate the data.
In the GIS, data can be arranged, rearranged, whereas data representations can be edited and updated immediately and interactively. For instance, the derivation of slope percentages from the digital elevation models (DEMs), which was inconceivable in the past, is made possible through the GIS functions. Then, the derived slope percentages served to be an important aspect of river classification in this dissertation, as it helped in developing geomorphologic classes as outlined by Rowntree and Wadeson (1999).

De Roo (1998) noted that the use of GIS in catchment hydrological and erosion modelling offers considerable potential. This claim was based on the ability of GIS to simulate in great detail topography and other controlling factors of the river channel. In addition, data management and presentation of the results is much easier than when a GIS is not used, as demonstrated in this dissertation.

On the same note, this dissertation demonstrated that valuable information for river environment classification could be extracted from available base datasets using spatial analysis tools of GIS. Various controlling variables of the river channel could be used in more complex analyses within a GIS, which eventually lead to generation of new knowledge about the relationships between them. This has been demonstrated by the successful combination of geomorphologic and ecological layers in the dissertation, which gave a clear view of their inter-relatedness along the river channel.

The resultant combined layers had new spatial databases and feature descriptions, which were obtained with as minimal as possible data loss.

In short, this dissertation served to highlight the imperatives of delineating the river environments using the spatial analyses within the GIS. The applicability of these analyses is supported by promising results presented in this dissertation. Both theoretical and practical discourses in the dissertation are in favour of the applicability of the GIS-based analyses for river environment classification.

6.2 Recommendations and guidelines

These recommendations are based on the observations made during this dissertation, in particular, the use of the GIS for analyses of geomorphologic and ecological layers along the river channel:

- The use of updated geomorphologic and ecological layers is recommended for thorough appraisal on the status of the river environment within the GIS. This ensures that there is data compatibility – for both geomorphologic and ecological layers, which is a critical factor in determining the quality of the results.
- The use of standard scale and projection parameters in the GIS should be observed to ensure compatibility of the datasets to be analysed. It is easy to confuse between projection systems, spheroids and datums, which could upset the geographical position of the data. The data integrity could also be lost during the transformation of one projection system to another. If the datasets are not treated the same, they tend to behave differently, thus making the linking of these datasets uneventful.
- This river environment classification should be used in the context of other river classification systems in South Africa and abroad. Its true applicability would be to highlight disturbances in the areas of interest and to focus on various controlling variables of the river channel at different levels of scale. It is not considered to be an ultimate classification system, but a 'working' classification that could be improved further.

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