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INTEGRATING STREAM NETWORKS AND LANDSCAPE MOSAICS IN A NEW CONCEPTUALISATION OF SAVANNA LANDSCAPES

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A thesis submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy

Johannesburg, 2014

DECLARATION

I declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



Carola Jane Cullum

10th October 2014

In Auckland, New Zealand

ABSTRACT

Landscapes are highly organised, with recurring patterns of co-varying and interacting biotic and abiotic ecosystem components. Although there is a rising demand for landscape classifications and maps that describe these patterns, emerging conceptualisations of ecosystems as complex, open and inherently uncertain question the existence of geographically definable ecological regions. It is now well recognised that perceptions of ecological patterns are highly subjective, changing with the scale of observation and the particular combination of environmental attributes that are emphasised. Hence many different valid descriptions (and hence maps) of the same ecosystem are possible, each relating to different perspectives and issues.

This thesis aims to develop a conceptualization of the biophysical interactions that fashion the character and behaviour of water-dependent ecosystems in savanna landscapes that can be used to underpin land classifications and maps for transdisciplinary enquiry and the management and allocation of natural resources. Recent analytical approaches in geomorphology, hydrology, soil science and biogeography are synthesised in a heuristic landscape hierarchy that frames hillslopes within the context of a stream network that varies between different geological and climatic settings. Savanna landscapes offer excellent opportunities to develop this new approach, since many hydrological, geomorphic and biotic processes are tightly coupled around the limited availability of water. Thus many biotic and abiotic variables are spatially clustered, forming a biophysical template that constrains the character and behaviour of a wide range of organisms and processes. Maps of these clusters can therefore provide a platform for integrating a similarly wide range of scientific and managerial perspectives.

The credibility and relevance of the conceptualisation is assessed through its application to a land classification in Kruger National Park (KNP), South Africa. The approach is iterative and reflective, endeavouring to reconcile the impossibility of using traditional reductionist approaches to describe complex systems with the need for reductionist generalisations to describe and analyse complex systems. Assumptions and decisions form a narrative that expressly acknowledges the inclusion of normative values and subjective judgements in conceptualisations of complex systems.

Implementation is based around the use of generalised archetypes to navigate between general principles and particular instances and also between conceptualisations and their representation in a map. Rather than using standardised, pre-determined scales and attributes, archetype development is based on the extensive research that exists for KNP, together with observation and analyses that give the landscape a ‘voice’, using concepts such as hillslope catenas and topographic grain. Analytical lenses are reframed to reveal differences as well as similarities, recognising that not all instances of a class are equally similar to the class archetype, so that some locations may conform more than others to the anticipated class character and behaviour.

At regional scales, physiographic zones are characterised by particular geology, patterns of landscape dissection and catchments that contain certain repeating toposequences of catenal elements. Differences in topographic grain have substantial implications for the construction of ecological maps, since the optimum scales of observation for the same level of the landscape hierarchy differ between landscapes. The associated differences in catchment size, hillslope length and stream density also have profound impacts on the nature and scale of many ecological processes, such that differentiation between physiographic zones is vital for good science, modelling and management.

Two study sites were mapped at catchment and hillslope scales, serving to contrast landscape structures in the finely dissected granites and the coarsely dissected basalts. At both catchment and hillslope scales, the basalt site conformed well to the *a priori* archetype that described a vegetation toposequence. However, only about half the area of the granite study corresponded to the archetype. Many of these mismatches did not show any difference in vegetation between midslopes and crests, suggesting they lack the contrasting clay/sandy soils that are typical of catenas in this area. It was therefore concluded that these subcatchments are likely to be generated and sustained by a different suite of processes to those described by the archetype and may therefore warrant the development of new archetypes. These findings illustrate how the explicit mapping of catenal elements allows the variability within an area to be assessed, identifying anomalous areas and hillslopes that are likely to behave differently to the hillslopes that conform more precisely to archetypal conceptual models. Understanding the nature and extent of such variations will improve the performance of broad-scale extrapolations and models based on the behaviour of idealised archetypes.

Ultimately, end users will determine whether or not the conceptualisation of savanna landscapes developed in this thesis is capable of rising to the challenges posed by the complexity and heterogeneity of ecological systems in KNP (and elsewhere). Initial indications are positive, given the early uptake of the approach both by the South African Water Research Commission and South African National Parks (SANParks).

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I am deeply humbled by the experience of developing this thesis and the outstanding support that I have received. *Ego sum a nana gigantum humeris insidentes,* truly I am a dwarf(ess) standing on the shoulders of giants.

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GLOSSARY

Archetype	An archetype, or a set of archetypes, is a conceptualisation of the whole of a category or class of objects. Archetypes can be conceived and represented in many ways: they can be real examples, abstract mental constructs or theoretical concepts.
Catchments	Areas that drain to a tributary junction. Catchments that drain to entire first order streams are called 'first order catchments', those that drain to entire second order streams are 'second order catchments', etc. See also *stream order* below.
Catena	A catena (or toposequence) is a series of soils and associated vegetation linked by their topographic relationship.
Catenal elements	Areas that have distinct hydrological regimes which are both cause and consequence of a particular combination of plant cover, soil, hillslope characteristics (e.g. gradient, curvature and aspect) and hillslope position.
Contributing Areas to Stream Segments (CASSs)	Streams are divided into segments, each of which is a length of channel between tributary junctions (or between a source/ outlet and the first tributary junction). CASSs are the areas that drain into each of these segments. CASSs may be described in terms of the order of the stream that they drain into.
Conceptualisation	Conceptualisations are simplified, abstract views of the world, or part of the world that shape the way we perceive and describe reality.
Drainage network	A drainage network comprises a network of streams and the hillslopes that they drain.
Extent	The total area covered by a map.
Fuzzy classification	In a fuzzy classification, membership values to each class are evaluated. The class with the highest membership value is then assigned to the unit.
Grain	The smallest spatial unit sampled. In a remotely sensed image, grain is equivalent to the resolution (pixel size).
Landscape dissection	The spatial organisation of channels and slopes within a stream network is sometimes referred to as a pattern of 'landscape dissection' or landscape 'texture'. Landscapes with high stream density are 'finely dissected', whilst landscapes with low stream density landscapes are more 'coarsely dissected'.

Landscape grain	The patch size typical of patch mosaics in any given landscape. 'Landscape grain' has broader application than 'topographic grain', which describes landscape dissection in terms of the spacing between major ridges and valleys (Wood & Snell 1960; Pike 1988; Pike *et al.* 1989).
Level of organisation	A vertical level within a hierarchy, associated with a particular spatial and temporal scale domain.
Membership function (curve)	A curve that defines the membership value for each value of a given attribute. Membership functions for different attributes may be combined when defining a class.
Membership value	A value that signifies the likelihood of belonging to a certain class.
Microfeatures	Local associations between hydrology, soils and vegetation that are found within catenal elements.
Minimum Map Unit (MMU)	The smallest area mapped as a discrete unit.
Morphology	The shape of the land surface.
Morphometrics	Measures of hillslope and network characteristics
NDVI	NDVI is the normalized difference between the red and near infra-red bands on a remotely sensed image, often used to indicate of vegetation density.
Patch	Patches are discrete areas, with boundaries that result from discontinuities in environmental conditions.
Physiographic zones	Physiographic zones are areas with distinct patterns of geology and landscape dissection.
Process domain	A process domain is a patch that is characterised by dominant processes that interact to produce the observed pattern.
Prototype	Idealised representations of the central tendency within each class.
Ontology	In philosophy 'ontology' is the study of the constituents of reality, of 'being' and of 'what exists'. Within information science, an 'ontology' is a formal, codeable description of entities, classes, properties and functions that form a particular view of the world.
Scale domain	The range of scales that are characteristic of a hierarchical level and over which landscape patterns change either very little, or change systematically with changes in scale.

Stream order	In the Horton- Strahler method of stream ordering (Horton, 1945, developed further by Strahler, 1957), source streams are defined as 'first order'. When two streams of the same order join, stream order increases by one, such that when two first order streams join, a ‘second order’ stream is formed, when two second order streams join a ‘third order stream is formed and so on.
Supersites	Areas within the Kruger National Park that have been selected as examples of catchments characteristic of a certain physiographic zone. Research projects will be focused on these areas, aiming to construct a holistic, transdisciplinary description and understanding of the ecological processes and interactions that operate within each physiographic zone.
Support	The area or distance over which variables are averaged.

ACRONYMS

CAO	Carnegie Airborne Observatory
CASS	Contributing Area to Stream Segment
DEM	Digital Elevation Model
DSM	Digital Soil Mapping
DTM	Digital Terrain Model
GIS	Geographic Information System
HYSS	Hydrologically Similar Surfaces
KNP	Kruger National Park
LiDAR	Light Detection And Ranging
MAUP	Modifiable Areal Unit Problem
MMU	Minimum Mapping Unit
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra-Red
NSBA	National Spatial Biodiversity Assessment
PNV	Potential Natural Vegetation
PUB	Predictions in Ungauged Basins
SANParks	South African National Parks
SAM	Strategic Adaptive Management
SRTM	Shuttle Radar Topographic Mission DEM (Farr *et al.*, 2007)
SWIR	Short Wave Infra-Red
TPC	Threshold of Potential Concern
TPI	Topographical Position Index

PHOTO CREDITS

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KR Kevin Rogers

CHAPTER 1: WHY A NEW CONCEPTUALISATION OF LANDSCAPES IS NEEDED

1.1 Introduction

Landscape patterns formed by spatially co-varying environmental attributes such as climate, soil, biota and topography have been recognised for centuries, if not longer, and are routinely exploited for a wide range of purposes. Soil surveyors use terrain and vegetation as indicators of soil patterns (e.g. Moore *et al.*, 1993; Park *et al.*, 2001; Ziadat, 2005), whilst hydrological modellers use topography and soils to infer water flows (e.g. Beven & Kirkby, 1979; Chamran *et al.*, 2002; Guntner *et al.*, 2004; Park & van de Giesen, 2004; Lin *et al.*, 2006). Ecologists and vegetation scientists also recognise the coupling of climate, vegetation, soil and topographical patterns in their efforts to map species distributions, resources available to organisms or to model fluxes of materials such as carbon or nutrients (e.g. Franklin, 1995; Bridge & Johnson, 2000; Austin, 2002; Florinsky *et al.*, 2002; Porporato *et al.*, 2003).

In recent years, opportunities for automating the classification and mapping of ecological landscape patterns over large areas have increased, as more data sets and more finely-scaled remotely sensed imagery have become available. For example, spatial clusters of environmental attributes have been delineated at various scales by overlaying multiple data sets to produce maps of ecoregions (e.g. Bailey, 1983; Omernik, 1987; Kleynhans *et al.*, 2005; Mucina & Rutherford, 2006; Sayre *et al.*, 2009), habitats (e.g. Varela *et al.*, 2008) and river reaches (e.g. Brenden *et al.*, 2008; Parker *et al.*, 2012). At regional and local scales, these 'ecological' maps are used to stratify biodiversity inventories, assessments and monitoring, whilst at national, continental and global scales they are used to inform an ever-increasing suite of policy applications, including resource allocation, conservation and land use planning, food security and compliance with local and international standards and laws (MacMillan *et al.*, 2003). In the United States, such maps include those produced by Omernik (1987) and Bailey (1983), which were designed to provide a national spatial framework for the inventory, monitoring and management of natural resources such as forests and water. In South Africa, maps of terrestrial, river and marine ecoregions are used to assess regional differences in biodiversity as inputs to national conservation plans (e.g. Driver *et al.*, 2005; Kleynhans *et al.*, 2005). At global scales, biogeographical regions that contain distinct communities of flora and fauna have been identified to guide the setting of global conservation priorities (e.g. Udvardy, 1975; Abell *et al.*, 2012; Olson *et al.*, 2012).

Despite increasing data availability and the entrenchment of ecological maps in the environmental management practices and policies of many countries, there is no generally accepted theoretical basis for the definition of ecological landscape units (McMahon *et al.*, 2004; Omernik, 2004). It appears that technology has outstripped theory (Bishop *et al.*, 2012), fuelled by demands for pragmatic solutions from a wide range of institutions. Most of the conceptualisations that underpin the delineation and classification of ecological landscape units are based on a 'classical' reductionist view of the world that has now been seriously challenged by new ways of conceptualising ecological systems. In this classical view, landscape units are

conceived as structural-functional units that contain more or less discrete ecosystems and locations assigned to the same class are assumed to contain similar ecosystems (Bailey, 1983; Sayre *et al.*, 2009). In this classical view, ecosystems are conceived as either static or at equilibrium, with interactions between system components that are regular and predictable, moving through succession to a climax state. The emphasis is on similarities and universal principles, with local differences in space or time being regarded merely as background noise or as irrelevant and ignorable complications (Pickett *et al.*, 1992). This conceptualisation of the world is very useful, since it provides a rationale for the transfer of knowledge and experience from sample or reference sites to other sites in the same class, allowing spatial models to be constructed and likely responses to management interventions or environmental change to be foresighted and mapped (Bailey, 2009b).

However, this way of viewing the world has been seriously challenged in recent decades by the complexity paradigm, which emphasises the complex and uncertain nature of ecological interactions, the open nature of ecological systems and the importance of local heterogeneity (Perry, 2002; Solomon & Shir, 2003; Urry, 2005). Ecosystems are now widely acknowledged to be complex systems, characterised by emergent properties and behaviour that result from inherently uncertain interactions between system components within and across multiple scales (Funtowicz & Ravetz 1993; Levin 1998; Kay *et al.* 1999; Nowotny 2001; Holling 2001; Pickett & Cadenasso 2002; Ulanowicz 2009). Complex systems conatin many sources of uncertainty, such that even if we had perfect knowledge of the nature of all system components and their possible interactions, attempts to predict certain ecological outcomes by building models based on linear relationships between components are doomed to failure as feedback loops, thresholds, lags and small differences in initial conditions all contribute to the uncertainty of outcomes (e.g. Kay & Schneider, 1994; Scheffer *et al.*, 2001; Wu & Hobbs, 2002). Furthermore, multiple causation and equifinality (different pathways to the same outcome) generate tangled causal thickets', in which it is impossible to clearly identify or separate causal mechanisms (Wimsatt, 1994). Thus even the most complicated process conceptualisations and models often fail to predict ecological outcomes. Not only are ecological surprises common, but they can also be extreme, undermining confidence in extrapolations across space and time and challenging efforts to understand and manage natural resources (Phillips, 2004; Harris & Heathwaite, 2012; Doak *et al.*, 2012).

The complexity paradigm demands new ways of describing, understanding and making decisions about ecological systems (Funtowicz & Ravetz, 1993; Wallington *et al.*, 2005; Lave, 2009, 2012). Not only do the new perspectives of complexity and heterogeneity challenge classical approaches to understanding ecosystem functions and behaviour, the very possibility of agreement on a theoretical basis for the identification and mapping of ecological landscape units is questioned. Rather than seeking to discern and map self-evident ecological units, it is recognised that there are many valid ways of viewing and partitioning landscapes: all conceptualisations of landscapes are contestable from both geographical and functional points of view.

From a geographical perspective, the delineation of ecological regions or landscape units is always contestable, since perceived patterns and spatial associations between environmental attributes depend both on the selection and weighting of attributes (e.g. Behrens *et al.*, 2010) and the scales at which they are observed (Levin, 1992). Thus the definition and delineation of ecological landscape units is inherently subjective, with contestable boundaries that cannot be verified independently of the process of map production. Furthermore, the environmental attributes and scales of observation that are used to define ecological units vary between different regions (Omernik, 2004), such that it does not make sense to formulate a standardised or comprehensive taxonomy of ecoregions. Indeed, the prevalence and importance of contingencies in time and space suggests that every location is potentially unique (Phillips, 2007) challenging the legitimacy of classifying locations in terms of their similarities. As Kennedy put it, we live in a 'naughty' world that often disobeys the 'rules' that we would like to impose upon it (Kennedy, 1979).

From a functional point of view, it is misleading to conceive of ecosystems as more or less closed systems that occupy particular locations. Although Tansley conceived of ecosystems as 'the basic units of nature on the face of the earth' (Tansley, 1935 p. 299), he stressed that such systems are mental constructs that focus on part of a wider system for the purposes of study. He also stressed that ecosystems can be defined at any scale and can consist of any combination of biotic and abiotic components that are of interest and relevance to the observer. Thus the systems that we isolate for study not only form part of larger systems, but also 'overlap, interlock and interact with each other' (Tansley, 1935 p. 300). Unlike closed systems, which have distinct boundaries, ecosystems are always open, relying on inputs of energy to hold them in positions that are often far from equilibrium and so always interacting with the environment in which they occur (e.g. Holling, 1973; O'Neill *et al.*, 1986). Plant and animal species do not necessarily form communities that occupy areas with clear geographical boundaries and interact only within these boundaries. Similarly, fluxes of materials and energy are not confined within discrete locations, but interact across space, time and scales (e.g. O'Neill, 2001; Perry, 2002; Currie, 2011). Ecosystems are in constant flux, in response to stochastic disturbance events that can potentially shift systems into a new state (Turner *et al.*, 1993; Scheffer *et al.*, 2001). In other words, ecosystems are dynamic and are continually changing in space and time, so that the geographical boundaries of ecological units are not fixed. The conceptualisation of multiple, overlapping ecological systems, with interactions and feedbacks operating within and between these open systems over various spatial and temporal scales suggests that there are no definitive ways of delineating ecosystems: no key attributes can be isolated, no optimal scales of observation can be determined and neither functional nor geographical boundaries can be drawn around discrete systems. The implication is that the attributes, scales and boundaries of landscape units can only be justified in relation to specific organisms or processes of interest (Wiens, 1989).

However, the conceptualisation of the world as containing multiple overlapping systems that can be defined only from very specific vantage points leaves us with no tools to describe the regularities that can be seen in many landscapes and at many scales. Landscape structure is neither chaotic nor random (Kay & Schneider, 1994; Mitchell, 2009). Most landscapes are

highly organised, with regularities in time and space that occur at many scales (Holling, 1992; Ulanowicz, 1999): for example, repeating patterns of associated soils and vegetation are often associated with the landforms characteristic of a particular region (Milne, 1935), reflecting their historical co-evolution and the contemporary coupling of ecological functions (Gerrard, 1992; Caylor *et al.*, 2005a).

Although much attention was given to these recurring patterns by naturalists and biogeographers in the late 19th century (e.g. Van Homboldt, 1769-1859, Wallace 1823–1913), such patterns are now rarely studied in an integrated fashion (Proulx, 2007). Instead, most conceptualisations of ecological patterns and processes are developed within a single disciplinary perspective, focussing on a single system component. This component is then treated as a dependent variable which can be described and explained in terms of other, independent environmental attributes. Soil scientists, for example, seek to explain soil properties in terms of attributes commonly known as 'soil forming' factors (Jenny, 1941), whilst vegetation scientists seek to explain plant species distributions in terms of a range of abiotic variables (Franklin, 1995). However, because components of ecological systems co-evolve, forming co-dependencies and tangled relationships, it is misleading to consider single components in isolation or independently of their context.

In light of these considerations, a conceptualisation of landscapes that integrates key system components is needed to describe and understand contextual constraints on ecosystem forms and processes. Such a conceptualisation is not only needed to inform scientific enquiry into ecological processes, but also to relate this knowledge to conservation, land use and environmental management and policy decisions. Many ecological concepts and theories cannot adequately inform public debate or guide the development of environmental policy, land use planning or conservation management since they are too narrowly focussed within single disciplines, or on single species or processes (Funtowicz & Ravetz, 1993; Brewer, 1999; Hadorn *et al.*, 2008). It is neither feasible nor desirable to manage individual system components separately on the same tract of land, since actions that affect one component (e.g. the productivity of forests) have knock-on effects on other components (e.g. water quality and quantity). Land needs to be understood and managed in a holistic manner to avoid or mitigate undesirable side effects, creating an environment that best serves the agreed needs of stakeholders (Zhou & Seethal, 2011).

The different perspectives of terrestrial and aquatic ecologists are a prime example of a disciplinary divide that hinders the application of ecological knowledge to environmental management. Terrestrial and aquatic ecologists tend to be educated separately, using different paradigms and methods to address different questions. They tend to congregate in different societies and at different conferences, read, publish in and cite different journals, be funded by different sources and work for different agencies (e.g. Stergiou & Browman, 2005; Menge *et al.*, 2009). Terrestrial and aquatic ecologists usually have quite different conceptualisations of the same landscape; whilst the former often conceive a landscape in terms of patches that support different species assemblages or respond differently to factors such as fire or herbivory, aquatic ecologists generally think of landscapes in terms of a network of streams in

which hydrological connectivity controls many processes such as the dispersion of species or the spread of pollutants (e.g. Omernik & Bailey, 1997; Abell *et al.*, 2002).

All over the world there are examples of separate ecological classifications prepared from freshwater and terrestrial perspectives, typically accompanied by calls for their integration from environmental management and policy-making agencies. For example, the South African National Spatial Biodiversity Assessments (NSBAs) that are used to determine national priorities for conservation planning are conducted separately for the terrestrial, aquatic and marine realms (Driver *et al.*, 2005). Ecoregion maps have been produced for each realm, each purporting to describe regional contexts in terms of very similar physiographic, geological and climatic differences. Since both terrestrial and aquatic systems are driven and constrained by many of the same processes at these relatively coarse, regional scales, the differences between the maps tend merely to reflect the disciplinary and personal perspectives of the compilers, rather than substantive differences in the constraints applicable to the two realms. The differences between these thus confound decisions about the management or conservation priorities assigned to a particular piece of land, without providing additional contextual knowledge to inform these decisions.

To meet the needs of land managers and planners, a new, integrated way of looking at entire landscapes that addresses the challenges of system complexity and heterogeneity is required. In this thesis I develop a new conceptualisation of savanna landscapes that strives to meet these needs, fusing aquatic and terrestrial perspectives on landscapes and integrating key system components. A conceptual framework is proposed to inform the description, classification and analysis of recurring patterns in savanna landscapes by guiding the selection of scales of observation and appropriate defining attributes for landscape units (or 'patches') at each scale. Classification is based upon fuzzy similarity to a class archetype (an idealised exemplar). Unlike conventional approaches that emphasise crisp boundaries, average values and within-patch homogeneity, the new approach acknowledges local heterogeneity, system complexity and the challenges of indeterminable boundaries. The approach is demonstrated by the classification and mapping of landscapes in the Kruger National Park (KNP), South Africa. I also show how the new conceptualisation can be used to inform management and policy applications.

1.2 The need for conceptualisation to underpin ecological maps

Concepts are generalised and idealised abstractions of any phenomenon that can be experienced or thought of, such as objects, ideas, behaviours, events, people or places. The generalisation and idealisation needed to construct concepts entails the removal of ‘specific’, ‘random’ or ‘unimportant’ features to focus on elements of reality that are considered important for a particular purpose (Pickett *et al.*, 2007). These abstractions form the building blocks of language, culture and science, taming the potentially overwhelming complexity of our experience by ordering our thoughts and perceptions and, in so doing, shape the way we perceive, describe and act within the world. The definition of categories allows objects, ideas or places to be grouped, so that knowledge and experience of one object, idea or place can be

extrapolated to others in the same group. Furthermore, observed similarities in the character or behaviour of objects in the same category can suggest hypotheses about why the objects are similar, how the perceived order has come to exist and whether or not it will persist object (Sokal, 1974). For example, the objects may be hypothesised to have a common origin, be generated and sustained by the same dominant processes, share dependencies or constraints, or be component parts of a larger object (Sokal, 1974; Poole *et al.*, 1997; Goodwin, 1999). Such hypotheses can form the basis of a conceptualisation, in which relationships between concepts are also generalised, summarising the ways in which objects, places and ideas are conceived as relating to each other, within a specified domain or universe of discourse. Such conceptualisations shape our epistemology, providing ways in which we think about the world and organise knowledge. As Rhoads explains:

> *"The way we think about the world shapes human inquiry. The purpose of the categorical concepts we use is to organize thought so that distinctions among ideas about the world can be discerned. Once an initial set of categories has been developed, inquiry becomes possible by associating characteristics of the world with ideas embedded in relevant concepts. Enmeshed within categorical concepts are ontological and epistemological presuppositions, i.e. underlying philosophical notions about the constitution of the world and how specific concepts connect with this constitution." (Rhoads, 2005 p. 131)*

Conceptualisations and conceptual frameworks provide a way of moving between the general and the particular, between abstract idealisations, theories or knowledge and specific instances, observations or experience. Relationships between quantitative (large n) and qualitative (small n) studies also help use to move between the general and the particular: whilst quantitative studies reveal patterns and relationships using random sampling and inferential statistics, qualitative studies suggest mechanisms for these patterns (Wohl 2010). The general applicability of hypothesised mechanisms can then be tested in further quantitative research in an ongoing cycle that refines and elaborates our conceptualisations and explanatory frameworks (Wohl 2010). The interplays between quantitative and qualitative research and between knowledge and experience form a continuing, iterative cycle in the production of knowledge:

> *"Understanding is an objectively determined, empirical match between some set of confirmable, observable phenomena in the natural world and a conceptual construct". (Pickett et al., 2007 p. 29)*

> *“Whatever the truth about the intrinsic orderliness of the world, it is obvious that the order scientifically imposed upon the world is a human invention, a means by which we sustain ourselves. Science is a product of the way we see the world.” (Church, 1996 p. 138)*

> *“Field research, initially focused on understanding specific examples of river process and form, allowed us to perceive underlying patterns that give rise to conceptual models broadly applicable within fluvial geomorphology.” (Wohl, 2013 p. 58)*

The same insight is expressed in linguistics, philosophy and social science in terms of a semiotic triangle, connecting our thoughts (conceptualisations) of the world (reality) with

representations of our thoughts in language, paintings, models and the many other ways we use to communicate with each other about the world we live in (Ogden & Richards, 1923).

Geographic conceptualisations include regionalisation - a type of categorisation in which parcels of land are grouped together according to some perceived similarity. Landscape conceptualisations allow knowledge and experience to be transferred between different places that fall within the same category, or class. Together, spatial classification and hypotheses about the different processes that have generated each class can provide a basis for generalisations across space and time, providing a rationale for detailed, quantitative predictions and/or broader, qualitative foresighting of possible responses to future change. However, the same tract of land can be delineated and classified in many different ways, depending on the similarities and differences that are considered to be important for different purposes and by different groups of people (e.g. Chorley & Haggett, 1967). Each classification is explicitly or implicitly based on a conceptualisation of the landscape that provides a set of terms that defines spatial entities and the presumed relationships between these entities. In other words, every map is theory-laden, expressing the mapper's belief that important differences lie either side of a boundary and that any local differences inside a delineated patch may be discounted (Rowe & Sheard, 1981).

1.3 Integrating the perspectives of different agencies and disciplines

A wide range of agencies responsible for land use policy, planning and management require descriptions, classifications and mapping of landscape units that can be used as a basis for collaboration between different groups of people, each with different priorities and responsibilities. An integrated perspective allows data, knowledge and experience to be shared, avoiding the mismatches of scale that hinder many collaborations (Dollar *et al.*, 2007). It provides a platform for the integration of policies and actions between different agencies responsible for the same tract of land, which also facilitates the application of scientific understandings to management actions and policy decisions (Stirzaker *et al.*, 2011). To meet these demands, landscapes need to be conceptualised in a way that is relevant to many different species and many different ecological processes, integrating disciplinary-based perspectives that deliver fragmented and often contradictory views of the same landscape.

One of the most persistent divides in ecological mapping lies between terrestrial and aquatic perspectives. This divide is rooted in the different purposes for which ecological maps are used by those concerned with terrestrial processes (such as the productivity of forests) and those concerned with aquatic processes (such as the processes controlling water quality and quantity) (Omernik & Bailey, 1997). Whilst the terrestrial perspectives tend to visualise landscapes in terms of static patches, aquatic perspectives emphasise dynamic flows and connectivity (e.g. Omernik & Bailey, 1997; Abell *et al.*, 2002).

Although Wiens (2002) showed how river systems can be usefully conceptualised as a mosaic of patches, he also saw a fundamental difference between landscape and riverscape ecology, in that riverscapes are

> *"…embedded in a medium, water, that exerts a strong and variable physical force on the system and that is also highly directional. Water flow makes the patch structure of riverine landscapes quite dynamic – patches move and change shape and composition as streamflow varies. Floodplain landscapes shift between terrestrial and aquatic phases. The adaptations of many of the organisms that occupy rivers and streams are moulded by hydrology, through its effects on food-resource availability, flood pulses, or simply the physical force of currents (Adis & Junk, 2002; Robinson et al., 2002). The directional flow of water enhances the connectivity of the riverine landscape. In rivers and streams, connectivity is provided by the medium of the landscape more than by the structural configuration of the mosaic itself. On land, this is true only for aerial or wind-borne organisms or materials, and there is little consistency to the directionality of this connectivity. Palmer et al. (2000) have also suggested that patch edges may be more important in riverine than in terrestrial landscapes because they are more effective in intercepting water-mediated flows and trapping moving materials or organisms." (Wiens, 2002 p. 511)*

Although riverine patches are generally dynamic over shorter timescales than their terrestrial counterparts and the distribution of aquatic species is undoubtedly constrained by flow direction and intensity, riverine and terrestrial systems have far more in common with each other than Wiens suggests. Water is one of the most important fluxes through terrestrial landscapes as well as through riverscapes, not only shaping and structuring the landscape itself through erosional and depositional processes, but also structuring the distribution of biota that occupy different niches according to the availability of water and nutrients (Sponseller *et al.*, 2013). The flows of water through the landscape are highly directional, determined by the gradient, curvature and direction of hillslopes as well as by the connectivity of channels in the drainage network (Moore *et al.*, 1991). Sharp terrestrial patch edges can be produced by structures that inhibit flows of water or sediment, such as 'tiger-stripes', where water-dispersed seeding results in striking bands of vegetation with sharp boundaries that reflect the limits of water transport (see Aguiar & Sala, 1999). Another example is a seepline on a catenal hillslope, where a patch with distinct vegetation, soil and hydrology is produced where downslope runoff is blocked by a clay lens (Venter, 1990; Khomo *et al.*, 2011). Sharp edges are often associated with riparian vegetation, which can be conceived as part of both riverine and terrestrial landscapes. Thus the patch connectivity provided through the medium of water is potentially as important on land as it is in streams. Indeed, hillslope flow paths might be viewed as extensions to a stream network.

Division between the aquatic and terrestrial realms is particularly blurred in the case of ephemeral streams. Indeed, these streams are often ignored or overlooked by both terrestrial and aquatic ecologists, despite the important role they play in shaping soil and vegetation distributions and the consequent creation of biophysical diversity. For example, in the study area considered in this thesis, Kruger National Park, aquatic research and management strategy, plans and monitoring have focused on the 600km of perennial rivers, with relative disregard for the 30 000km of seasonal and ephemeral channels (O'Keefe & Rogers, 2003).

Furthermore, terrestrial and aquatic systems are so interdependent that it makes little sense to separate them when considering ecological systems as a whole, as opposed to considering

them as isolated system components. Not only does the character and behaviour of rivers depend on the nature of their catchment, catchments are also shaped by their rivers (Hynes, 1975). Fluvial erosion literally shapes the landscape in many settings and the gravity-induced movement of water and sediment down and through hillslopes is a major control on the distribution of soils and vegetation (e.g. Coughenour & Ellis, 1993; Witkowski & O'Connor, 1996; Baldeck *et al.*, 2014). In turn, soils and vegetation affect water movement, such that terrestrial and aquatic landscapes are interdependent, co-evolving to produce the patterns observed at a particular moment in time (e.g. Jenerette *et al.*, 2012). Both terrestrial and aquatic systems are driven and constrained by many of the same processes. At coarser scales, both systems operate within the boundaries set by local geology and climate. At finer scales, patterns of production, transport and storage of sediment and water, on hillslopes and through channels, control the structure and dynamics of both landforms and biotic assemblages. In turn, these patterns are determined by the configuration of hillslopes and channels within a drainage network (e.g. Benda *et al.*, 2004; Bellmore & Baxter, 2014).

This line of argument suggests that despite the challenges of uniting a network perspective of streams, in which the focus lies on the connectivity along linear pathways, with a terrestrial patch perspective in which the focus is on a mosaic of areal units, the integration of riverine and terrestrial perspectives is fundamental to the framing of integrated perspectives of landscape patterns and processes.

1.4 Spatial clustering of ecological attributes and processes

A conceptualisation that is able to inform a wide range of applications needs to be grounded in theory that relates the observed character of landscape units to a wide range of ecological processes. In many landscapes, this is very challenging, since the environmental processes that generate landscape patterns do not necessarily co-vary in time and space (Su *et al.*, 2004; Heino, 2010). In the extreme case, where the spatial domains of different processes never coincide, this means that different landscape units would be delineated for each different process considered.

However, in many landscapes, there is a tendency for biophysical attributes to cluster around a small number of recurring scales and values, forming distinct patches where many different attributes and processes are spatially aligned. This clustering can be explained in terms of co-evolution, where coupling and feedbacks between different ecological processes have resulted in a 'lumpy' (Holling, 1992) or 'granular' (Ulanowicz, 1999) ecological surface. For example, in semi-arid systems such as savannas, a lack of water frequently places severe constraints on ecosystem composition, structure and dynamics (Rodríguez-Iturbe & Porporato, 2004). Since many ecological and geomorphological processes are water-limited, they can only occur at places and times when sufficient water is available and often occur at rates and to degrees that are also dependent upon water availability (Coughenour & Ellis, 1993; Scholes & Walker, 1993; Sankaran *et al.*, 2005). This means that in savanna ecosystems the distributions of many ecological attributes are tightly coupled to the distribution of water and hence co-vary in space to form distinct landscape units (Caylor *et al.*, 2005a). In such systems, it is possible to detect

'lumps' or 'patches' at various scales that represent ecological structural-functional landscape units.

A classic example of landscape patches that represent ecological structural-functional units is seen on semi-arid savanna hillslopes, where repeating sequences of soils and vegetation recur down hillslopes, forming 'catenas' (Milne, 1935). Each patch in the hillslope sequence can be conceived as a distinct functional unit, or 'process domain' (*sensu* Montgomery, 1999), with a water budget that both arises from and controls interactions between water inputs, soils, vegetation, animals and humans (Figure 1.1). By definition these landscape units integrate a wide range of highly interdependent system components. For example, not only do soil and climate affect the type and biomass of vegetation, but vegetation affects soil texture and structure through organic inputs, root systems and the actions of fauna (micro and macro) that are associated with the plant community (Jenny, 1941; O'Connell *et al.*, 2000; Caylor *et al.*, 2006). Vegetation structure, functional type and life form not only influence the partitioning of rainfall into infiltration, evapotranspiration and runoff, but also influence climate through atmospheric gas exchange and albedo (Solomon & Shugart, 1993). Lithology, vegetation and climate interact to produce weathering and erosion regimes that are largely responsible for topography (e.g. Howard, 1967; Bull & Kirkby, 2002; Marston, 2010; Osterkamp & Hupp, 2010).

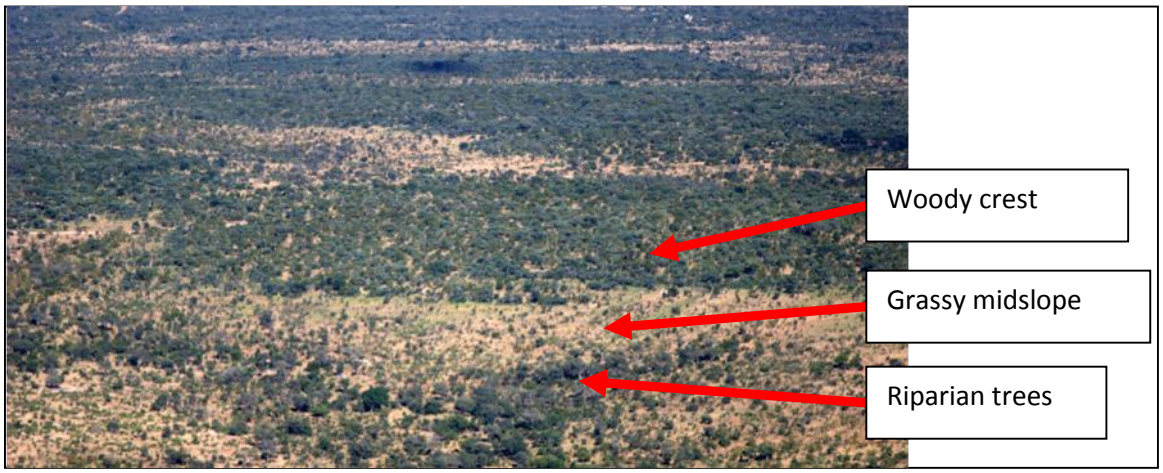


Figure 1.1: Catenal patterns in granitic landscapes in southern Kruger National Park.
Although the same pattern is repeated on many hillslopes, in some cases the pattern is much clearer than in others and there are also many exceptions to the general rule. Photo: KR Apr 2009.

Similarly scaled conceptualisations could be used to describe the same landscapes from a geomorphological perspective. The repeating (often fractal) patterns found in stream networks complement the patterns found on the intervening hillslopes. As Davis said over a century ago:

> *"Although the river and hill-side waste do not resemble each other at first sight, they are only extreme members of a continuous series, and when this generalisation is appreciated, one may fairly extend the 'river' all over its basin and up to its very divides. Ordinarily treated, the river is like the veins of a leaf, broadly viewed it is like the entire leaf." (Davis, 1899 p. 495)*

Mapping the mosaic of these complementary hillslope and channel units can therefore potentially provide a geographical platform for the integration of knowledge and experience across disciplines and between environmental science, management and policy.

1.5 Selecting scales of observation and the attributes used to define patches

Perhaps inevitably, mapping integrative landscape units is not straightforward, since the mosaic of patches that is observed varies with the scale of observation (Wiens, 1989; Levin, 1992; Wu & David, 2002) and the environmental attributes used to define patches (e.g. Behrens *et al.*, 2010). Much effort has been devoted to the determination of optimum scales for observation of landscape patterns, using techniques such as wavelets, minimum variance and various measures of spatial autocorrelation (e.g. Marceau, 1999; Hay *et al.*, 2003; Wieland & Dalchow, 2009) to discover the scales at which correlations between attributes such as vegetation cover and hillslope position are strongest. However, results to date are inconclusive, and no standardised approach to the detection of optimum scales for landscape analysis has emerged (Hengl, 2006). This reflects several facts. Firstly, landscapes themselves have different levels of heterogeneity at any given scale. Whilst some landscapes are homogenous over large distances, others show large variability over short distances (Fryirs & Brierley, 2009). Secondly, results can vary with the combinations of environmental attributes that are considered (Deng & Wilson, 2006). Thirdly, results may be confounded by differences in the abruptness of patch boundaries and the amount of contrast between adjacent patches, both of which often vary considerably both within and between landscapes (Burrough, 1989).

One way of resolving scale issues is to agree on the definition of the spatial entities that are to be mapped (Openshaw, 1984; Fotheringham, 1989). In the case of ecological mapping, these entities are structural-functional landscape units or 'patches'. For example, if a definition of 'riparian forest' is agreed, then a suitable mapping scale can be determined based on the dimensions of the riparian forests to be mapped and the required boundary precision. Basic units (e.g. pixels) can be aggregated so as to identify individual patches of riparian forest, producing a map that corresponds to a shared perception of reality which can be verified by groundtruthing. If no such agreement exists, such that some people conceive riparian forests as having a continuous canopy cover, whilst others define these patches in terms of a minimum density of trees over a certain height, then the appropriate mapping scale and the reference for groundtruthing will remain contested. Furthermore, the definition of a hierarchy of landscape units allows the identification of multiple appropriate scales of observation, each associated with different hierarchical levels (Allen & Starr, 1982).

Assuming such a hierarchy of landscape units is agreed, the next challenge is to select attributes appropriate for describing these units, given the limitations of data availability. This is challenging, since the environmental attributes that can be used to distinguish between different ecological landscape units change in different locations, at different scales and over time (Omernik, 2004). For example, in one place aspect may be an important determinant of hillslope soils and vegetation, but in another, gradient or altitude may be far more important. At fine scales the presence of termitaria influences soil moisture distribution (Asawalam *et al.*,

1999) and can be associated with hillslope position (Levick *et al.*, 2010), whilst at coarse scales geology is often a more important indicator of the distribution of soils and vegetation (Klijn & Haes, 1994; Gillson, 2004). The relative importance of different attributes also varies in time, changing for example, according to seasonal vegetation cover or the amount and intensity of rainfall in a particular year. Thus the conceptual models linking form and process (and therefore the attributes are relevant to the delineation of ecological structural-functional units) not only change between locations, but also over spatial and temporal scales (e.g. Church, 1996).

Spatial and temporal differences mean that standardised approaches to ecological classification that are designed to be universally applicable (e.g. Sayre *et al.*, 2009) initially deliver poor descriptions of many landscapes and require critique and adjustment by panels of local experts prior to publication (Omernik, 2004; Driver *et al.*, 2005). Thus while standardised approaches claim legitimacy through the use of supposedly objective methods, they ultimately rest upon subjective appraisals and adjustments. Whilst the endorsement of experts can lend credibility to a map amongst those who respect the experts, opinions are usually undocumented and based on tacit, intuitive judgements rather than on explicitly documented rules or reasoning.

A more defensible approach is to use a conceptual framework to guide the selection of scales of observation and defining attributes, articulating the reasoning for each decision (Audouin *et al.*, 2013). Whilst this approach does not claim to be objective, delivering the only possible solution, the transparency of method means that changes can be made as arguments are won or lost and new knowledge and data become available. This transparency is built through narratives that justify the adoption of a particular conceptualisation of the world, seeking a consensus that allows the conceptualisation to be shared by a wide range of scientists, managers and policymakers.

1.6 Legitimising a landscape conceptualisation

For end-users to reach consensus on a conceptualisation of landscapes that can inform the selection of the appropriate scales and variables for the mapping of ecological landscape units, all need to agree on a way of conceptualising the world.

Users judge if a particular conceptualisation is helpful for the purpose at hand in terms of credibility and utility (Cash *et al.*, 2003). Such judgements can be therefore be influenced by arguments and statistics that demonstrate the credibility and utility of a particular conceptualisation.

The *utility* of a particular conceptualisation of landscapes to land management agencies, planners and policy makers can be demonstrated in terms of its ability to:

- Integrate many system components and processes, so that the conceptualisation is relevant to a wide range of applications, integrating the perspectives of different agencies and disciplines to avoid fragmented approaches to ecological science, management and policy making.

- Provide a basis for extrapolating site behaviour across time and space, so that observations, experience and foresighted responses from sample and monitoring sites can be transferred to other locations. This requirement implies that the conceptualisation must be process-based, relating observed features used for classification to the contemporary processes that sustain them and determine their future trajectory (e.g. Surian *et al.*, 2009).
- Be adaptable, so that spatial units can be tailored to accommodate the various scales and attributes characteristic of individual landscapes.

The environmental attributes that structure both landscapes and riverscapes vary between locations (e.g. Omernik, 2004). Subtle variations that can be disregarded in one context can be important elsewhere, such that it can be appropriate to split or clump classes in different ways in different settings. Furthermore, some landscapes contain unusual features and processes that are not common elsewhere. The scales appropriate to describing landscape patterns also differ between settings. For example, fine resolution imagery is needed to capture the difference in vegetation associated with catenas in finely dissected landscapes with comparatively short hillslopes, whereas coarser resolution imagery may suffice in areas with low stream density and long hillslopes.

- Thus standardised classifications that are intended to be universally applicable (e.g. Rosgen, 1994) can omit or downplay local or historical factors that are locally important in driving or controlling the processes of interest (Simon *et al.*, 2007).

A conceptualisation of landscapes can achieve *credibility* amongst end-users, by:

- Being grounded in accepted theory. The conceptualisation should include models that describe the processes that have generated the observed patterns and the drivers and controls on future developments. Such a model not only provides a basis for extrapolations and forecasts, but also lends it credibility. The choice of attributes used to define and classify landscape units can also be justified in terms of the conceptual model, thus transferring credibility to classifications based upon the conceptualisation.
- Acknowledging the inherent uncertainties associated with dynamic, complex and heterogeneous ecosystems, offering new tools and heuristic devices that are consistent with these new perspectives.
- Being repeatable, with transparent methods that are contestable and open to further refinement and development. It is not sufficient to rely solely on expert judgement, since not all communities of end-users necessarily respect the same experts. Furthermore, explicit documentation of the theoretical basis for the conceptualisation and the rationale for decisions allows iterative refinements and development as new knowledge is acquired and new data become available. Although subjective decisions are often needed, if the rationale for these decisions is documented, then it becomes possible both to critique and improve the approach. In addition, explicit arguments

and the documentation of decisions and methods provide a sound basis for communication and training (Brierley *et al.*, 2013).

- Being consistent with empirical observations in a variety of landscapes. Using the conceptualisation to develop and apply classifications of different landscapes is a way of demonstrating this correspondence with reality. Whilst there are sure to be anomalies that do not fit well into any of the described classes, a classification can claim consistency with empirical observations if a large proportion of the test landscape can be described reasonably well.

1.7 Thesis aims, objectives and methods

The aim of this thesis is to develop a conceptualisation of savanna landscapes that can be used to inform the description and mapping of biophysical patterns in savanna landscapes in a way that integrates many components of ecological systems and so is relevant to a wide range of applications in environmental science, management and policy development. The conceptualisation is designed to underpin a wall to wall landscape classification in which the entire landscape is partitioned into classes that can be mapped at least semi automatically from remotely-sensed imagery within a GIS system.

Specific objectives are to:

a) Identify potentially useful approaches through a review of existing landscape conceptualisations.
b) Develop a new conceptualisation of savanna landscapes that incorporates:
    i. Consideration of the nature of the mapped entities and how they are to be observed and represented.
    ii. Construction of a hierarchy of these entities, defining the spatial domains appropriate to each level of organisation considered.
    iii. Consideration of how the conceptualisation can be implemented to classify and map savanna landscapes.
c) Demonstrate the application of the conceptualisation and the approach to landscape classification by mapping selected areas of the Kruger National Park (KNP).
d) Evaluate how well the conceptualisation and approach to landscape classification worked, in terms of how well the landscape patterns correspond to the archetypes suggested by the hierarchy and in terms of progress towards addressing the challenges posed by system complexity, heterogeneity and dynamics.

The conceptualisation of savanna landscapes presented in the thesis is designed to interface between the mapping, science and management of ecological systems, providing a platform for the integration of knowledge and experience. KNP is a particularly good place to develop such a conceptualisation. For the last 20 years an adaptive management approach has been used that relies heavily on close cooperation between scientists and managers, and both groups are committed to finding new ways of addressing the challenges arising from an appreciation of system complexity and heterogeneity (Venter *et al.*, 2008; Biggs & Roux, 2013). This thesis

responds to these challenges, developing new tools and heuristic devices for the description, analysis and management of savanna landscapes that are compatible with adaptive management approaches and which acknowledge scientific understandings of the complexity and heterogeneity inherent in ecological systems.

This thesis is concerned mainly with approaches to the description of landscape pattern rather than with explaining the processes responsible for the observed patterns. It therefore lies outside the scope of the thesis to describe detailed applications of the conceptualisation in either science or management or to establish either its acceptability or shareability amongst groups of potential end-users. Thus generalised conceptual models that could be used to link observed forms to generative processes are only briefly outlined and are not fully developed. Instead, emphasis is placed upon conceptual and methodological developments that support the generation and potential uptake of integrative landscape tools.

The theory- and value- laden nature of geography is recognised within the emerging school of critical geography (e.g. Lave *et al.,* 2014), which is complemented by the practice of critical mapping (Crampton, 2001, 2010). Recognising that there are many valid ways of describing and mapping landscapes, the conceptualisation is supported by narratives that seek to legitimise its utility and credibility, carefully articulating the rationale for decisions at each step and identifying uncertainties, strengths and weaknesses along the way. The approach is inspired by 'critical complexity' (Preiser & Cilliers, 2010), which attempts to reconcile the impossibility of using traditional reductionist approaches to describe complex systems with the need for reductionist generalisations to describe and analyse these systems.

1.8 Thesis structure

Literature review
In the next chapter (***Chapter Two***), I review existing approaches to the integrated description of landscape patterns and processes in terms of the criteria for utility and credibility presented in this chapter (Section 1.6).

Method
In ***Chapter Three***, I present the central elements of the new conceptualisation, constructing the ontology of a geographic conceptualisation of landscapes that can be used to inform the description and mapping of savanna landscapes. The chapter starts with describing the broad perspective of the approach, followed by the presentation of a heuristic landscape hierarchy. Lastly, methods appropriate to applying this schematic hierarchy to particular landscapes are introduced and discussed.

Study Area
The study area, Kruger National Park is introduced and described in **Chapter Four**.

Results
The results section of this thesis is differentiated into three chapters, developing and analysing an approach to savannah landscapes at hillslope (catenal), subcatchment and regional scales

(**Chapters Five to Seven**). These chapters build upon each other in a nested hierarchical manner, framed around the conceptualisation developed in Chapter Three. These applications are performed for example granite and basalt landscapes of KNP (as outlined in Chapter Four). Procedural steps used to derive classes are considered in each of the results chapters. Because the approach adopted is inherently iterative and reflective, methods and results are often intertwined in the narratives forming these chapters of the thesis.

Discussion

Lastly, in ***Chapter Eight***, I review the narratives that I have constructed to demonstrate the credibility and utility of the new conceptualisation developed in this thesis. I consider the contributions made by each of the various perspectives that have been woven together to create this new way of looking at savanna landscapes. Particular attention is paid to the ways in which credibility is built and how the challenges of complexity, dynamics and heterogeneity are addressed. I review the implementation of the conceptualisation as a framework for the classifications of KNP landscapes, reflecting on how the approach played out, noting ways in which the framework advances the description, mapping and explanation of semi-arid, savanna ecosystems. Key themes that emerge from the thesis are discussed and contextualized in relation to the international literature. Potential future research needed to develop and strengthen this new approach is outlined, together with reflections on the limitations of the conceptualisation. Lastly, I explore how the framework can be used (and is being used) to integrate knowledge across disciplines in a way that is useful and relevant to savanna science as well as to conservation policy and management.

CHAPTER 2: EXISTING APPROACHES TO THE INTEGRATED DESCRIPTION OF LANDSCAPE PATTERNS AND PROCESSES

Various approaches to the integrated description of landscape patterns are reviewed to assess their potential contributions to a new integrated conceptualisation of savanna landscapes that can serve as a platform for collaboration between ecological scientists, managers and policy makers. After reviewing the more general approaches from hierarchy theory, landscape ecology and ecoregion mapping, I turn to conceptualisations that have emerged from specific disciplinary foci on individual system components: vegetation, soil, topography and water. Whilst developments in the American school of landscape ecology have delivered useful descriptive and analytical tools and concepts, it has also led to increasingly fragmented perspectives. Although the European school of landscape ecology offers an all-encompassing vision of landscapes and those mapping ecoregions have developed useful tools, both approaches lack robust conceptual foundations that can justify a particular way of partitioning ecosystems that are inherently open, with indeterminable boundaries. Somewhat counter-intuitively, it emerges that the disciplinary perspectives offer more useful approaches to the specification of integrated spatial entities than do the cross-disciplinary perspectives. Rather than producing maps and classifications based on statistical correlations among a dealer's choice of environmental attributes and scales, soil maps, hydrological catchment classifications and geomorphological river classifications are all grounded in conceptual models that link observed features and/or gradients to generative processes. All offer valuable insights into strategies and techniques that facilitate interplay between empirical field observations and general principles and theory, allowing place based understandings to be constructed by careful adaptation of idealised mental models. Furthermore, there is an increasing convergence between disciplinary- based approaches, all of which seek identify and describe geographical complexes of interwoven, co-evolved ecological attributes that are both cause and consequence of the spatial organisation of landscapes. Although no single approach satisfies all the requirements of an integrated perspective of landscapes that meets the challenges posed by system complexity, heterogeneity and dynamics, each of the approaches reviewed has something valuable to contribute to a new conceptualisation of savanna landscapes.

2.1 Introduction

In this chapter I review various conceptualisations of landscapes, seeking ways to resolve the tension between the demand for objective, spatially explicit classifications that integrate a wide range of biotic and abiotic environmental attributes and the challenges to such generalisations that arise from understanding the importance and value of local heterogeneity and that ecological systems are inherently open, with indeterminable boundaries.

The conceptualisations reviewed are all widely used to underpin wall to wall landscape classifications in which the entire landscape is partitioned into classes that can be mapped at least semi automatically within a GIS system. All can take advantage of the increasing availability of high resolution satellite data to capture environmental gradients, reducing the

need for extensive field surveys that are both expensive and impractical over large areas. Lastly, they are all applied in land and conservation management and planning.

I start by reviewing *hierarchy theory*, a general conceptualisation that underlies many of the other approaches reviewed, either implicitly or explicitly. This conceptualisation is somewhat different to the other perspectives reviewed, presenting an empty framework through which landscapes can be viewed rather than suggesting the entities, scales and attributes that can or should be used to describe them.

I then turn to the theory and practice of describing, analysing and mapping landscape patterns and processes from integrated, cross-disciplinary perspectives. Theoretical approaches used in *landscape ecology*, the field of ecology that specifically focuses on the description and analysis of landscape patterns and processes are reviewed before considering the practice of *ecoregion mapping,* which aims to map these patterns to inform inter-agency policy and management decisions relating to the use of natural resources and land.

Next, I consider framings that have emerged from specific disciplines that aim to describe and predict the spatial distribution of the key system components: vegetation, soil, topography and water:

- *Vegetation* mapping, habitat modelling and mapping land cover
- *Soil*-landscape models, landform mapping, land systems, *topography* and soil delineation are so closely related that I consider them together
- *Water*:
    - Hydrology: Predictions in Ungauged Basins (PUB)
    - The spatial organisation of river systems

Each approach is considered from the point of view of its potential contribution to the development of a new, integrated conceptualisation for savanna landscapes. Lastly, I assess each approach against the criteria that such a conceptualisation must meet if it is to serve as a platform for collaboration between ecological scientists, managers and policy makers.

2.2 Hierarchy theory

2.2.1 Overview

Hierarchy theory is a dialect of general systems theory that describes how systems self-organise into structures and patterns as a result of interactions between system components that are constrained by their horizontal and vertical position in a hierarchy (Allen & Starr, 1982). At each level within the hierarchy, system components can be decomposed into their parts, which form separate units at a lower level. Alternatively, hierarchies can be assembled bottom up, by considering the composite units formed by interactions between lower-level components. The character of components at a particular hierarchical level is largely determined by processes that occur at lower hierarchical levels, within a range of variability that is contextually constrained by higher level units (Allen & Starr, 1982; Salthe, 1985). Higher

levels are characterized by emergent characteristics and behaviour that is evident at coarse spatial and temporal scales. Although emergent properties result from lower-level interactions, they cannot be predicted from knowledge of their component parts. Each level of organization within a given system is associated with a characteristic spatial and temporal scale domain, determined by the rates of the processes that produce the observed patterns. Higher levels are characterized by patterns and processes that operate at relatively slow rates. Faster processes characterize lower levels of organization and are responsible for the patterns observed at finer scales (Allen & Starr, 1982; Salthe, 1985; O'Neill *et al.*, 1989) (Figure 2.1).

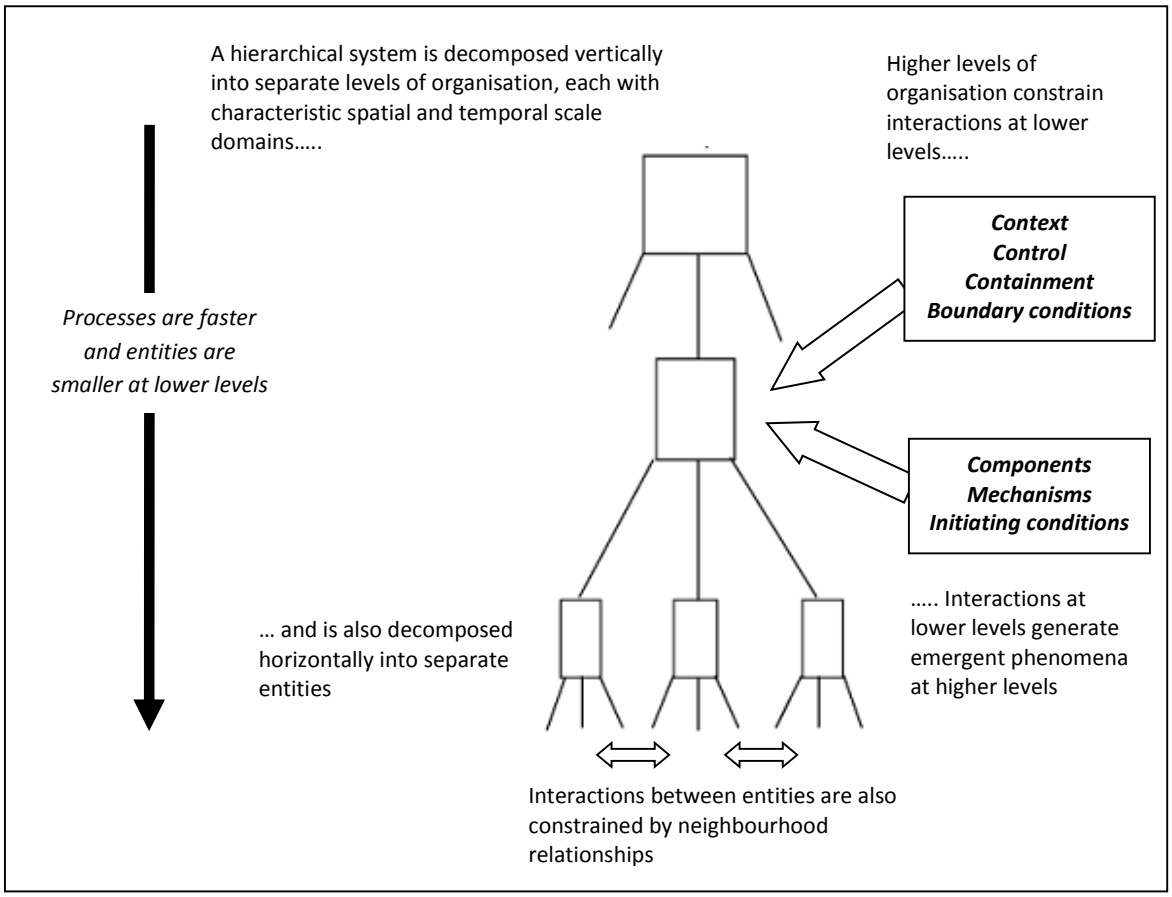


Figure 2.1: Illustration of the key concepts in hierarchy theory.

Hierarchical systems are at least approximately decomposable in both vertical and horizontal dimensions. Hierarchies describe the relationships between entities within and between each hierarchical level. For example, spatial entities at lower levels of organisation are contained within higher level entities and are adjacent to other entities at the same level. The character and behaviour of these entities is contextually constrained, both horizontally by neighbourhood relationships and vertically by top-down and bottom-up relationships (Wu, 1999).

2.2.2 Hierarchical frameworks define spatial entities and guide selection of scales and attributes

Hierarchical frameworks help to address issues of scale and attribute selection by specifying the different types of entity that are visible within different scale domains. An appropriate scale of observation can be determined by agreeing upon the objects of geographical enquiry (i.e. the spatial entities that are to be mapped) (Openshaw, 1984; Jelinksi & Wu, 1996; Fotheringham *et*

al., 2002). For example, if the focus is on individual trees, then a suitable mapping scale can be determined based on the dimensions of the trees and the required boundary precision. Basic units (e.g. pixels at appropriate resolution) can be aggregated so as to identify individual trees, producing a map that corresponds to a shared perception of reality which can be verified by ground truthing. However, individual trees can then be combined in many different ways to form clusters, so unless clusters are defined as having a particular size and shape, then scales of observation must again be agreed at this new scale of analysis. Thus, when there is agreement as to the nature and meaning of the entities to be mapped, then the selection of the data needed to delineate the entities and the choice of mapping scales is clarified.

Hierarchy theory has been widely adopted as a way of describing and analysing ecological systems (e.g. Allen & Starr, 1982; Levin, 1998; Wu & David, 2002). Students of ecology are often introduced to the subject by way of a hierarchy ranging from cells, with their constituent molecules and atoms, though organisms and populations to ecosystems, landscapes and biomes (Potochnik & McGill, 2012). Each level of this hierarchy occupies a distinct scale domain, within which different methods and conceptualisations are appropriate. Similarly, hierarchy theory is widely applied in hydrology, soil science and geomorphology to separate spatial domains within which different types of models and methods are appropriate (e.g. de Boer 1992; Schroder 2006; Dollar *et al.* 2007). For example, Church (1996) explains how different approaches are needed for the study and management of natural phenomena such as sediment transport on river beds at different levels of organisation. At very small space and time scales, such as the microseconds and millimetres associated with turbulent flow and the movement of individual grains of gravel on a river bed, the precise path of an individual grain is inherently unpredictable and almost random. Statistical methods must be used to describe the probability of a grain being found in any given location at a given time. Viewing the same system at a higher level of organisation and considering an entire eddy at scales of metres and seconds, recurring patterns can be related to the development of erosional and depositional features in the channel. These emergent features cannot be predicted from observation of the movements of individual grains of gravel or threads of water. However, the movement of grains and water in a particular location and time period can be predicted at this scale with reasonable accuracy, so deterministic models can be applied. At a higher level of organisation again, the development and movement of channels can be observed at scales of tens of metres and hours. Averaging mean flow, sediment load and stream power allows reasonable predictions of channel morphology, even though the precise location of erosional and depositional features cannot be predicted. At even higher levels of organisation, the development of meanders and floodplains over kilometres and decades becomes unpredictable again, due to the influence of local contingencies such as the history of flood events and the location of bedrock outcrops. The development of the river system can only be described in a narrative at this level of organisation. Church's explanation of scale-delimited theory echoes hierarchy theory and is reinforced by more philosophical demonstrations of the need to bound discourse within a specified domain to generate and communicate meaning and understandings (Cumming & Collier, 2005; Cilliers, 2005b).

Management framings based upon hierarchical conceptualisations of river systems have been widely implemented (e.g. Frissell *et al.*, 1986; Naiman *et al.*, 1992; Petts & Amoros, 1996; Brierley & Fryirs, 2005) and are discussed below in Section 2.7.2.

2.2.3 Hierarchy theory reconciles reductionist and complexity perspectives

By introducing the concept of top-down constraints and bottom-up mechanisms, hierarchy theory neatly reconciles perspectives that stress system complexity and potentially unique combinations of spatial and temporal contingencies with perspectives that emphasise conformity to general laws and principles (Mitchell, 2009). As Phillips (2007) explains:

> *"Landscapes are circumstantial, contingent outcomes of deterministic laws operating in a specific environmental and historical context. A landscape is only one possible outcome of a given set of processes and boundary conditions, which is determined by a specific, perhaps irreproducible set of contingencies. However, the possible outcomes are strongly constrained by the applicable laws. While it is legitimate and useful to conduct research focussed on either global laws or local contingencies, the ultimate goal of explaining landscape evolution requires the integration of global and local approaches." (Phillips, 2007 p. 166)*

To extend Church's example of sediment movement on a river bed, the trajectory of a single grain is complex, potentially unique and nigh impossible to predict precisely, even though individual movement obeys Newtonian laws of motion. However, the range of possibilities is subject to both horizontal and vertical contextual constraints (Figure 2.1). Horizontal constraints arise from relationships with other entities on the same organisational level: grain movements are constrained by the character and dynamics of neighbouring grains. Vertical constraints, on the other hand, are imposed by higher level entities, such as the speed and direction of eddies. Since these constraints favour some movements over others, potential exists for the development of a self-organising system and the development of recurring patterns that can be observed at higher levels of organisation (see Favis-Mortlock, 2013 for an overview of self-organising systems). The recurrence of these patterns means that they are somewhat predictable and can be described in terms of general principles. These contextual constraints are sometimes described as a range of variability within boundary conditions (Landres *et al.*, 1999; Brierley & Fryirs, 2005).

The concept of emergence within hierarchical framings helps to explain why some landscape patterns appear to be regular at broad scales, but irregular at finer scales. This phenomenon results not only from smoothing associated with simplifications and generalisations introduced in broad scale observations, but also from differences in the dominant processes at different hierarchical levels of organisation. For example, whilst the movement of water in turbulent flow is chaotic at the level of individual packets of water, the same movements can appear as regular eddies when observed at a higher level of organisation (see Burrough 1983; Culling 1988; Phillips 1995; Church 1996).

2.2.4 Critique

Although hierarchy theory provides very useful insights into how reductionist and holistic perspectives may be reconciled and can be very helpful in guiding the selection of objects of

study and the appropriate scales for their observation, there is much confusion around both the ontology and the epistemology of hierarchies of natural phenomena. Ontological issues centre on the nature of the entities described in the hierarchy, whilst epistemological issues are concerned with ways of knowing and understanding them.

The description of natural systems as a hierarchy ranging from cells to biomes is usually presented as though it consists of real, discrete objects that are universally arranged in levels of organisation (Potochnik & McGill, 2012). Entities at each level are aggregates of lower-level entities, but have emergent properties that make them more than the sum of their parts and which demand modes of observation, measurement, explanation and manipulation that are different to those applicable at lower or higher levels.

However, whilst all entities up to and including the level of organisms are discrete units with clear boundaries, higher levels such as populations, communities and ecosystems are aggregates of individuals. Units in these aggregates are far more loosely coupled to each other than are elements at lower levels of organisation, having the ability to move between groups and to associate with more than one group at a time. In other words, at lower levels the hierarchy is constitutive, with lower level elements forming constituent parts of higher level elements. At higher levels there is a different kind of relationship between parts and wholes, based on increasingly subjective conceptual groupings, with boundaries that are far from self-evident (Wimsatt, 1994; Hay *et al.*, 2002).

Ascending through the classic ecological hierarchy (Odum, 1953), the identity of individual entities becomes increasingly less self-evident and more contestable: which populations should be included in a community? Which communities should be included in an ecosystem? The level of 'landscape' is particularly problematic, since it is envisaged as consisting of an aggregate of ecosystems. Given that individual ecosystems are mental constructs, in which observers are free to draw lines around whatever collection of components and interactions best suit a particular purpose (Tansley, 1935; Kay & Schneider, 1994), the grouping of ecosystems into landscapes becomes a dealer's choice from almost infinite possibilities.

Following Raper and Livingstone (2001) and others, I adopt a weak realist view of landscapes, in which the world exists independently of human perception and cognition, but can be partitioned in many different ways. Under this perspective, both mind and matter play a part in constructing landscape units, with the dominant role shifting between the two as theory is modified by experience and observation (Raper & Livingstone, 1995, 2001). From this point of view, hierarchies are best conceived as heuristic devices that provide a framework to structure communication, knowledge and action.

However, people working within different disciplines, working within different paradigms and with different interests and perspectives generate different hierarchical frameworks of the same phenomena (Kuhn, 1962; Dollar *et al.*, 2007). Without agreed definitions for landscape entities and levels of organisation that determine appropriate scales of observation, it becomes difficult, if not impossible, to share knowledge and experience in a meaningful manner. Ultimately, successful interdisciplinary research and collaborative management and planning

depend upon the adoption of a shared landscape conceptualisation (Pickett *et al.*, 2007; Stirzaker *et al.*, 2011).

However, for a framework to be shared in collaborative projects, the underlying ontology needs to be seen as contestable, so that explicit narratives that demonstrate the credibility of the framework, its relevance to the purpose(s) in hand and the legitimacy of its sources need to be produced and accepted by all end-users (Cash *et al.*, 2003).

2.3 Landscape ecology

2.3.1 Two schools of landscape ecology

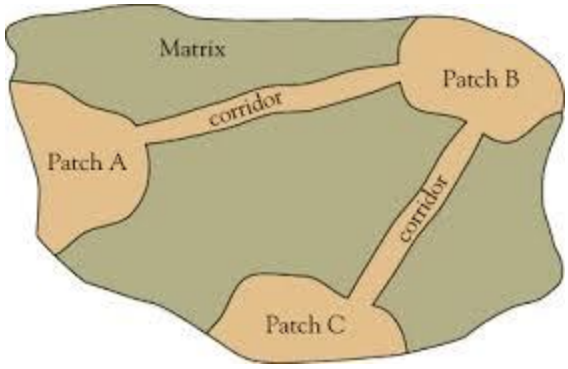
Hierarchy theory is widely adopted as a framework for landscape ecology, the discipline that focuses on spatial patterns generated by ecological systems (Turner *et al.*, 2001; Currie, 2011; Mace *et al.*, 2012). Landscape ecology is founded on Carl Troll's vision of a marriage between geography and biology (Troll, 1939). However, the union is not complete, since the discipline is deeply divided into two schools that offer very different perspectives on landscapes (Bastian, 2001; Wu & Hobbs, 2002; Wu, 2012). The 'American' school is rooted in biological science. It seeks to describe and understand the effect of spatial heterogeneity in abiotic and biotic attributes on the character, behaviour or dynamics of particular organisms or ecological processes (e.g. Turner *et al.*, 2001). By contrast, the European school has a more geographical focus. This reflects its origins in the 1940s as a tool for agricultural and land use planning by central and local governments in Eastern Europe (e.g. Neef, 1967; Haase, 1989).

2.3.2 The American school of landscape ecology

Overview: Patches, matrices and mosaics

Drawing on the conceptualisation of landscapes developed in MacArthur's theory of island biogeography (McArthur, 1972), landscapes have been conceived within the American school of landscape ecology in terms of 'patches' connected by 'corridors' and embedded in a neutral or hostile 'matrix' (Forman & Godron, 1981, 1986). In this conceptualisation (Figure 2.2a), it is assumed that the matrix surrounding patches of interest is homogeneous, containing no differences that influence relationships between the variables considered and the organism or process of interest (McGarigal & Cushman, 2005). Such conceptualisations do not describe an entire landscape, but only those parts deemed relevant to a particular organism or process of interest. An alternative, wall-to-wall view of landscapes as patch mosaics draws on Watts (1947) description of a vegetation community forming a dynamic mosaic of patches at different stages of succession (Cushman *et al.*, 2010b). In this conceptualisation the entire landscape is decomposed into an exhaustive set of discrete and mutually exclusive patches (Figure 2.2b). Each patch corresponds to an area that is conceived as internally relatively homogeneous and differing from its surroundings in some relevant respect.

a) Patch- corridor-matrix



b) Patch mosaic with wall-to-wall coverage of the entire landscape

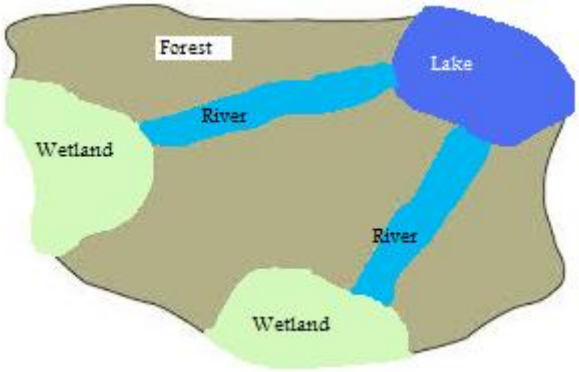


Figure 2.2: Two conceptualisations of landscapes used within the American school of landscape ecology. a) Patches of habitat suitable for an organism of interest, located within a matrix of undifferentiated hostile habitat. Patches are connected by corridors that can potentially connect different populations. b) The entire landscape is divided into a mosaic of patches, defined in terms of scales and variables relevant to a particular organism or process. Boundaries may shift over time.

In both conceptualisations, observed patterns and processes are highly dependent upon the scale at which they are viewed (Turner, 1989; Wiens, 1989). Multi-scale analysis is common, wherein different patterns observed in the same landscape are described at scales associated with different levels of organisation within a hierarchy (Gillson, 2004).

A focus on ecological patches has drawn attention to patch boundaries, the challenges of determining them and their role in facilitating or preventing inter-patch connectivity (Cadenasso *et al.*, 2003; Strayer *et al.*, 2003; Post *et al.*, 2007). Concepts of boundary permeability to organisms, materials and energy and patterns in changes to this permeability over time and space advance our understanding and ability to describe and analyse inter-patch connectivity.

The patch-corridor-matrix conceptualisation has provided useful ways of describing landscape connectivity and fragmentation, which is of particular importance to wildlife population survival, and biodiversity conservation (Fahrig & Merriam, 1985; Taylor *et al.*, 1993; Tischendorf & Fahrig, 2000; Briers, 2002). It has also underpinned conceptualisations of rivers as corridors

that are rich sources of biodiversity and ecosystem services for surrounding regions (Naiman *et al.*, 1993) and which provide pathways from numerous socio-ecological processes, ranging from human settlement to the propagation of disease and the dispersion of nutrients, plants and animals (Johansson *et al.*, 1996; Reiners & Driese, 2004; Rodriguez-Iturbe *et al.*, 2009).

The patch mosaic conceptualisation is more relevant to this thesis than is the patch-corridor-matrix conceptualisation, since it offers the capability of partitioning the whole landscape into units that are potentially relevant to scientific enquiry and/or land use management and planning. This conceptualisation deals with issues of system dynamics, complexity and heterogeneity by conceiving the mosaic as shifting continually in response to disturbances and environmental change. Indeed, the variability within and between landscape patches is often explained in terms of local differences in susceptibility to various disturbances and/or the history of past disturbances (Turner *et al.*, 2001).

The patch mosaic concept has been extended to describe aquatic systems (Pringle *et al.*, 1988; Ward *et al.*, 2002; Poole *et al.*, 2004). In these conceptualisations, patches are seen as dynamic, with hydrological connectivity varying in time and space over multiple scales (e.g. Poff *et al.*, 1997; Fryirs *et al.*, 2007).

Heterogeneity and complexity

Heterogeneity is also a central concept in the American school of landscape ecology. Indeed, in the report of the 1984 workshop that is often considered as laying the foundations for the American school (Wu, 2013), the whole discipline was described as the study of the effects of spatial heterogeneity on ecological processes:

> *Landscape ecology focuses explicitly upon spatial pattern. Specifically, landscape ecology considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity…. The relationship between spatial pattern and ecological processes is not restricted to a particular scale…. Ecological processes vary in their effects or importance at different scales. (Risser et al., 1984 p. 7).*

Heterogeneity is not considered as an inconvenience, to be smoothed out by averages and categorical groupings, but rather as lying at the very heart of the diversity and functioning of the ecosystems we seek to protect (Turner & Chapin, 2005). For this reason, heterogeneity has come to be seen as valuable in its own right and a target for conservation. Under the heterogeneity paradigm of conservation that has been adopted in the Kruger National Park (KNP), it is recognised that conserving biodiversity involves more than maintaining species richness, but entails protection of an entire spectrum of ecological system components and generative processes in a dynamic space-time mosaic over multiple scales that range from genes to entire landscapes (Rogers, 2003).

Interactions between systems components are not usually conceived as simple, linear, cause and effect relationships, but as a tangled web typical of complex systems (Ryan *et al.*, 2007). A whole new field of probabilistic ecological modelling has emerged, simulating multiple

outcomes, lag and threshold effects and emergent properties, using techniques such as computer automatons and individual based modelling (see Molofsky & Augspurger, 1992; DeAngelis & Mooij, 2005 for reviews). Although many of these models are constructed in artificial space, many have also been constructed in real landscapes, using bottom-up approaches to study how ecosystems affect individual organisms as well as how system level properties emerge from the adaptive behaviour of individuals (Grimm, 1999; Grimm *et al.*, 2006).

Synthesising hierarchy theory, complexity theory and the patch mosaic concept from the American School of landscape ecology, Wu and Loucks (1995) developed the paradigm of 'hierarchical patch dynamics'. They suggested that the temporal and spatial heterogeneity of ecosystems could be described in terms of observable mosaics of patches generated by the dominance of different processes in different areas of a landscape and at different scales. If the nature and rate of the dominant process(es) is (are) similar across the whole patch, then the patch will appear homogenous. Patches at higher levels are conceived as being larger in area and changing more slowly over time than patches at lower levels.

2.3.3 Critique

The conceptualisation of landscapes as a mosaic of internally relatively homogeneous patches underlies many other approaches to the delineation of landscape units. Although this conceptualisation is both pervasive and useful (Turner, 2005), it is founded on the assumption that the world can be divided into discrete, non-overlapping polygons. This way of viewing the world truncates the internal heterogeneity within patches and between patches belonging to the same class, losing information about how variables change through space and time to summarise information in terms of rigidly bound, internally homogenous patches (Cushman *et al.*, 2010b). Although clearly bounded, discrete, internally homogenous units are easy to represent, analyse and manage, they are poor reflections of reality. Not only are patch transitions are often blurred, but small within-patch variations can have large effects both on the distributions of individual species and on overall patch character and behaviour (Phillips, 2004; McGarigal & Cushman, 2005).

Despite these drawbacks, the American school of landscape ecology offers many insights into the nature of a conceptual patch mosaic, and the potential effects of patch configuration on process (Turner *et al.*, 2001). A suite of tools has been developed to describe patch composition and configuration, including measures of patch size, shape, differences between patch edges and interiors, the heterogeneity of patches *per se,* the nature and permeability of boundaries and the connectivity between patches (Forman & Godron, 1981; Turner *et al.*, 2001; McGarigal *et al.*, 2012). These tools are commonly used to examine the effect of landscape fragmentation on species distributions and biotic processes such as dispersal or predation as well as informing efforts to optimise reserve design for the conservation of rare species (e.g. Brosofske, 2006; Boitani *et al.*, 2007).

However, emphasis tends to be placed upon pattern *per se*, examining the effects of patch configuration on particular processes and organisms of interest. Patch composition is generally

described only in terms of components and interactions that affect the focal processes and organisms. All other attributes that make up the background matrix and interactions between or within either set of variables are either ignored or treated as constant in time and space (Cushman *et al.*, 2010b). This means that contextual influences upon the character and behaviour of the studied organism or process are often ignored, so that results are not transferable to other locations. For example, the potential distribution of a particular species is often inferred from the spatial distribution of environmental attributes associated with locations where the species actually occurs (Franklin, 1995). The ability of a rare species to travel or disperse along corridors that connect patches of suitable habitat can then be overlaid on this template to inform plans to conserve the species. In these examples, the nature of the matrix is not considered to affect the corridors, nor is the ability of organisms to influence and shape their own habitat considered (Jones *et al.*, 1994; Moss, 2000). Although these perspectives on landscape patterns include many different variables and draw on expertise from many different disciplines, the approach is not truly integrative, since the only interactions considered are those between the target organism or process and individual dependant variables (Bastian & Steinhart, 2002).

Since the conceptual models that define the scales and variables of interest relate to a particular organism or process, these scales and variables do not vary between landscapes. Thus because the American school has no way of conceiving landscape patches independently of particular organisms or processes, there is also no way of ensuring that patch definitions capture contextual differences between landscapes that shape future patch behaviour.

In summary, although the American school of landscape ecology provides useful insights, concepts and tools (including discussions of scale, heterogeneity, dynamics and boundaries, the notion of patch mosaics, and tools for describing and analysing spatial pattern), landscapes can only be described and analysed in fragmented ways that relate to particular organisms or processes. Since all these perspectives use different scales and attributes, they cannot easily be combined to provide a unified description of a landscape that can be used to inform other scientific studies or decisions about the management of a particular tract of land.

2.3.4 The European school of landscape ecology

Overview: Holistic perspectives

Whereas the American school of landscape ecology focuses on the responses of individual organisms or processes to a spatially heterogeneous environment, the European school focuses on the coupling of biophysical variables to generate an integrated, holistic view of landscapes in which abiotic attributes, plants, animals and humans are intimately interconnected (e.g. Neef, 1967; Zonneveld, 1989; Naveh, 2000; Bastian & Steinhart, 2002). The European approach to landscape ecology reflects its development as a tool for mapping the potential human uses of different areas, to inform centralised land use planning in heavily populated areas of Eastern Europe. By contrast, the American school tends to focus on wilderness areas, considering landscapes as providing resources for biota, with little or no human influence (Pickett & Cadenasso, 1995).

Socio-ecological systems

Within the European school, relatively internally homogenous landscape patches are seen as the spatial expression of socio-ecological systems, with boundaries determined by the spatial extent of each patch. In this view, humans are considered as integral parts of the system, rather than as an external factor that 'impacts' upon the system. Ecological regions are considered to be structural-functional units that are the net result of the interplay of all the biological, physical and cultural features and processes that occur in a particular geographical area. People and their artefacts are included alongside abiotic features such as relief, soil, climate and water and biotic features such as plants and animals. All of these elements are conceived as interdependent, so that if one thing changes, knock-on effects may impact upon other elements. Landscape ecology is positioned as a science that can help us to describe, explain and predict these changes to understand the environmental impacts of the human use of natural resources in different geographical settings, so that the potential for sustainable exploitation can be assessed (Naveh, 2004).

Gestalt perceptions of landscape units

Landscape units are considered to be self-evident, perceived holistically by the brain as a gestalt, rather than as a collection of individual parts (Naveh, 2004). A strong atomistic tradition within the school conceives ecological units as real entities that are made up of small, building blocks, called 'Naturuum' (Neef, 1967), or ecotopes (Zonneveld, 1995) that result from the particular ecosystem processes occurring in each location. These biophysical units are then overlaid with human artefacts and culturally dependent values and meanings (Troll, 1939; Naveh, 2001). This position is probably linked to the way early European landscape ecology developed from the interpretation of aerial photographs of agricultural landscapes in Eastern Europe (Bastian & Steinhart, 2002). Large areas were assiduously mapped using this approach, overlaying ecotopes derived from aerial photography and topographic data with other maps representing patterns of geology, climate, soil or settlements (e.g. Neef, 1967; Haase, 1989).

However, once landscapes other than clearly bounded fields are examined, the challenges of defining boundaries of multi-functional landscape units became clear. Indeed, some practitioners within the European school concede that definitions of landscape units are socially constructed, heuristic devices, designed to aid description and analysis that can offer only partial views of the total 'geocomplex' (Haase, 1964).

2.3.5 Critique

Criticisms of the European school are centred on two related issues. Firstly, landscape units are far from self-evident, involving many subjective decisions for their delineation. As more and more data sets and finer and finer resolution satellite data become available, the number of ways in which landscapes can potentially be observed has dramatically increased. This highlights the fact that choices need to be made and that landscape units are far from self-evident. As we learn from the American school, different patch mosaics can be seen at different scales of observation (Levin, 1992), by using different combinations of variables or by constructing classes according to different rules (Buyantuyev & Wu, 2007). Different scales,

variables and class definitions are suited to different purposes or the study of different organisms (e.g. Wiens, 1989).

Secondly, the European school infers that all similarities and differences in form signal similarities and differences in process. As Moss (2000) puts it:

> *"The underlying weakness of the geoecological theme is the assumption that superimposition of individual land-component data generates functional landscape units. In fact, to understand function requires a knowledge of process, and the study of processes, in complete land-unit systems, requires a functional integration, not merely the combining or superimposition of a range of pedagogical, geomorphic, lithospheric and atmospheric process information." (Moss, 2000 p. 176)*

If the landscape classification is to be used to inform spatial and temporal extrapolations, then it is essential that the described pattern is credibly linked to formative processes. The literature of the European school is replete with examples of attempts to describe process relationships between system components. Unfortunately, no conceptual model is agreed upon, and most descriptions consist of spaghetti-like diagrams that do little more than emphasise the tangled web of interactions that characterise complex systems (see, for example the diagram of ecosystem processes in Zonneveld, 1995).

Furthermore, it is highly unlikely that a single conceptualisation of spatial units can describe structural-functional landscape units that are relevant to all possible end users. Although planners may desire multifunctional landscape units that simultaneously bound functions ranging from economics to aesthetics, including diverse uses such as residence, recreation, transport, agriculture and industry and the provision of natural resources such as water and fertile land (e.g. Ling *et al.*, 2007; Kareiva *et al.*, 2007; Tockner *et al.*, 2011), there is no ecological reason why these functional boundaries should coincide. Indeed, functional boundaries would only coincide if all the functions considered formed part of a single closed system, which is clearly not the case. All components of the system interact with other components that fall outside any proposed boundary, such that tracing all connections could potentially extend the boundary to the edges of the universe (Currie, 2011).

Complexity, dynamics and heterogeneity are extensively discussed in many texts (e.g. Naveh, 2000; Bastian & Steinhart, 2002). However, these concepts are not operationalised, in that no tools are offered to address the challenges of complexity, contingency, heterogeneity and dynamics that are posed by the new ecological paradigms. Instead, the tools that are suggested for landscape analysis are either those developed by the American school or consist of simple overlay of available spatial data sets. All of these techniques suffer from issues associated with categorical representation, in that patches are defined and represented as discrete and internally homogenous entities that can be adequately described in terms of average values.

Thus, whilst a holistic conceptualisation of the world promises an integrating perspective on landscapes, the detection and delineation of ecological 'wholes' is problematic. Indeed, Wu

and Hobbs (2007) rather cruelly described European landscape ecological studies as ranging from:

> *"Tedious technical mapping of heavily populated areas and systematic land evaluation to philosophical (and sometimes enigmatic) discourses on the wholeness of landscapes" (Wu & Hobbs, 2007 p. 275).*

The desire to provide a holistic perspective on landscapes also leads into the temptation of including so much in the description of the whole that the system is no longer separated from its environment and all explanatory power is lost:

> *"(this) totality is never anything more than a plastic bag enveloping whatever it found any way it could, and enveloping it too well: the more the totality becomes full, the emptier it becomes." (Morin, 2008 p. 33).*

In summary, the detection of the holistic landscape units described by the European school of landscape ecology is highly subjective and contestable, involving tacit assumptions and expert opinion. Such methods are generally poorly documented and hard to replicate in different circumstances or with different groups of experts. It is therefore unsurprising that no consistent way of operationalising holistic theories of landscape structure and processes has yet been developed.

2.4 Ecoregion mapping

2.4.1 Overview: Meeting the demand for integrated 'ecosystem' approaches to management

The demand for holistic, integrated approaches to landscape analysis from land use planners and managers is still as strong today as it was at the time of the emergence of European landscape ecology. All over the world, ecoregion maps have been produced to meet this demand.

Ecoregion maps depict simplified conceptualizations of regions that are characterized by similar environmental conditions that contain similar biotic communities, similar natural resources and that are likely to respond to changes or stressors in similar ways (e.g. Bailey, 1983; Omernik, 1987; Loveland & Merchant, 2004; McMahon *et al.*, 2004; Sayre *et al.*, 2009; Olson *et al.*, 2012). Such regionalisation helps to organise the study, management and plans for large, diverse areas. Indeed, ecoregion maps are very widely used at global, continental, national, regional and local levels, with applications ranging from natural resource allocation, conservation and land use planning to food security and compliance with local and international standards and laws (MacMillan *et al.*, 2003).

The 'ecosystem approach' to natural resource management

The rise of ecosystem mapping in the 1980s and 1990s was largely associated with the 'ecosystem approach' to natural resource management that came to dominate natural resource management and planning in the United States during the 1990s and was enshrined in the 1992 United Nations Convention on Biodiversity (United Nations Environmental Program, 1992; Interagency Ecosystem Management Task Force, 1995; Waltner-Toews *et al.*, 2008).

Such an approach offers a holistic perspective that unites aquatic, terrestrial, biotic and abiotic system components, with ecoregion maps providing a common spatial framework, not only for the integration of knowledge across different disciplines, but also for the integration of policies, management interventions, research, monitoring and assessment between agencies responsible for managing different resources (e.g. forestry, water, wildlife and recreation) (Omernik & Bailey, 1997).

Ecoregion maps were originally conceived as the spatial expression of ecosystems:

> *"Ecological land classification is a process of delineating and classifying ecologically distinctive areas of the earth's surface. Each area can be viewed as a discrete system which has resulted from the mesh and interplay of the geologic, landform, soil, vegetative, climatic, wildlife, water, and human factors which may be present." (Wiken, 1986 p. 4)*

Areas within the same ecoregion are assumed to be part of the same ecosystem or as containing ecosystems that are subject to similar sets of dominant processes and are therefore likely to offer similar 'aggregates of environmental resources' available for human exploitation (Omernik & Bailey, 1997 p. 939). These 'process domains' (*sensu* Montgomery, 1999) are also assumed to be likely to respond in similar ways to natural disturbances, environmental changes or management interventions (Bailey, 1987; Omernik & Bailey, 1997). Similarly, environmental scientists, managers, planners and policymakers all assume that sites belonging to the same class or ecoregion are ecologically equivalent (Bailey, 2002), resulting from similar sets of processes and having similar ecological functions, such as biomass productivity and water quantity and quality (Omernik & Bailey, 1997 p. 939). This ecological equivalence justifies the selection of individual sites for assessment, monitoring, experimentation and/or measurement and the subsequent extrapolation of results to all areas within the same ecoregion (e.g. MacMillan *et al.*, 2003).

Ecoregion mapping and systematic conservation planning

Ecoregion mapping is also widely used in systematic conservation planning. These endeavours typically aim to optimise the assignment of land that is to be protected from future development that may threaten the overall levels of biodiversity in a nation or region and/or the habitats of rare or threatened species (Margules & Pressey, 2000). Systematic conservation planning relies heavily on maps that describe and classify areas containing different types of biota and/or ecosystems. These resources are used to provide an inventory of each type and to ensure adequate representation of each type in plans for conservation (Driver *et al.*, 2005). Resulting maps are drawn at different scales and use different attributes, depending on expert opinions on the relative importance of different measurements of biodiversity. For example, the South African National Spatial Biodiversity Assessment (NSBA) for terrestrial landscapes are mapped at a resolution of a quarter degree square and are based on spatial overlays that include vegetation types, wetlands, distributions of some rare and threatened species, as well as data selected as spatial surrogates for ecological and evolutionary processes, such as high run off, biogeographical nodes (more than four vegetation types within 500m), high carbon sequestration potential (certain vegetation types), resilience to climate change (no change in

biome predicted under three different climate change scenarios), barriers to species migration (the Great Escarpment) and classes of climate and upland-downland gradients (Driver *et al.*, 2005). By contrast, the equivalent NSBA for aquatic systems are mapped at a scale of 1:500 000 (equivalent to a resolution of approx. 6km^2, assuming a minimum mapping unit of 0.5cm). Spatial overlays of datasets include ecoregions (derived from data relating to relief, climate, geology, soils and potential vegetation (Kleynhans *et al.*, 2005)), flow variability, morphological zones, distribution of endemic fish species and land cover (Nel *et al.*, 2009). Both NSBA maps can be called 'ecoregion' maps, since they are all founded on the assumption that the classification captures distinct ecosystems and process domains, with members of each class being 'ecologically equivalent' and equally able to represent the whole class.

2.4.2 Critique

The purpose, techniques and underlying assumptions of ecoregion mapping are very similar to those of the European school of landscape ecology. Both approaches stem from a policy-led demand to assess land potential in terms of the availability of natural resources for human use. Both rely heavily on map overlays to identify areas that are relatively homogeneous with respect to a suite of environmental attributes. Both are underpinned by the notion that landscapes can be partitioned into areas that are dominated by distinct ecosystems that each function in particular ways to deliver characteristic packages of natural resources. And both approaches are subject to similar criticisms, centring on the lack of an objective way of defining or verifying either the regions or the ecosystems that these maps aim to represent.

For ecosystems to be delineated, the spatial boundaries of different systems need to be identified in some way. Acknowledging that ecosystems are open systems, so that complete separation between systems can never be achieved, most ecoregion mappers seek merely to reproduce the spatial clusters of co-varying environmental attributes that have traditionally been described by biogeographers and naturalists. However, although landscapes are often highly spatially organised and such clusters undoubtedly exist (Kay & Schneider, 1994; Mitchell, 2009), the attributes that are clustered, their rate of change and the degree of variation between clusters varies from place to place (Comer *et al.*, 2003). It is therefore far from evident which data sets best describe these clusters at which scales:

> *".. in most cases there are no unambiguous boundaries between plant communities or ecological systems in nature, and species assemblages or ecosystem processes are not entirely predictable. Any method of dividing the continuously varying and somewhat unpredictable phenomenon of community types and systems must be somewhat arbitrary with multiple acceptable solutions." (Comer et al., 2003 p. 8).*

It is not therefore surprising that disagreement as to the nature of the spatial entities mapped was one of the main stumbling blocks to the development of a standardised approach to ecoregional mapping by a US inter-agency task force (McMahon *et al.*, 2004; Omernik, 2004). Without agreement on the nature of the mapped entities, the delineation of ecoregions depends entirely upon the results of statistical associations and GIS overlays. However, although such procedures have a veneer of objectivity, they actually involve many subjective decisions.

There are two main approaches to the definition of spatial units in ecoregion mapping. The first approach, adopted by Bailey and his followers (e.g. Sayre *et al.*, 2009), use the conceptualisation of a scaled hierarchy of controlling factors to justify the order in which data sets are overlaid at various scales. Landscapes are first divided into regions according to climatic differences. These regions are then subdivided using geological data and then divided again using topographic and vegetation data (Klijn & Haes, 1994; Bailey, 2009a). However, I suspect that the correlation of vegetation patterns with climate at coarse scales, with geology and soils at intermediate scales and with topography at fine scales is very likely to be related to the scales at which each data set is collected and made available. Furthermore, it is likely that *all* of these factors act as controls on vegetation at *all* scales, at different rates at different times and in different places. Conversely, the presence of vegetation is itself likely to modify many environmental factors, since relationships are reciprocal and co-dependent. It is therefore more realistic to think of the totality of intertwined abiotic and biotic processes that co-evolve and self-organise at all scales, rather than attempt to separate out particular factors associated with particular scale domains (Levin, 2005; Corenblit *et al.*, 2008, 2011).

The second approach recognises that landscape patterns result from a complex and ultimately indescribable interplay between all factors at all scales. Scales and data sets are determined by a panel of experts who sketch the boundaries of each region in a qualitative manner, guided by their gestalt perceptions of ecoregions, based on expert judgement and local knowledge in a manner reminiscent of the methods adopted by the European school of landscape ecology (Omernik, 1987). Different data sets are used in different locations, reflecting the fact that different factors and processes generate the patterns observed in different climatic and geological settings (Omernik, 2004). This approach is highly subjective, so that unless all agree on the selection of scales of observation and the variables used to delineate and classify regions, different panels of experts produce different results (Figure 2.3).

Both approaches are highly pragmatic, with little or no explicit theoretical justification for the choice of scales of observation or the data sets used, l*et al*one the multitude of technical decisions needed to reconcile the differences in generality, accuracy, and particular classifications of the different maps that are overlaid (Cushman *et al.*, 2010b). If regions are produced merely as overlaid GIS layers, the observed patterns and regions are merely the representation of statistical associations, lacking a theoretical underpinning that can justify either regional identity or/and extrapolations across space and time (Moss, 2005).

Even if agreement is reached on the definition of ecoregions, several studies have questioned their utility. For example, researchers have shown that these regions account for only a small part of the variability of fish assemblages, wildlife communities, particular hydrologic characteristics, and macroinvertebrate distributions (e.g. Lyons, 1989; Poff & Ward, 1989; Poff & Allan, 1995; Snelder *et al.*, 2004). In each case, other variables were found to be more strongly correlated with the spatial distributions of the target species, assemblage or physical characteristic than were ecoregions. Omernik and Bailey (1997) countered these criticisms by reminding us that ecoregions are designed to describe the overall character and resources of each area and may therefore not provide the best description of any single resource. However,

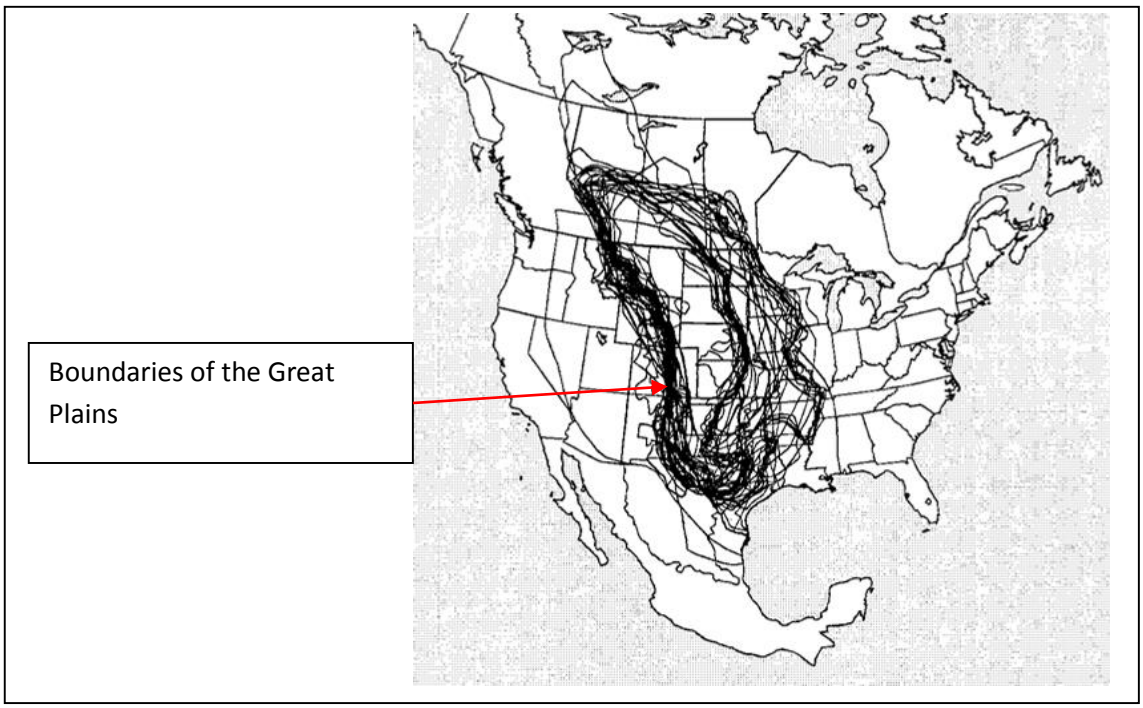


Figure 2.3: Fifty versions of the Great Plains.

Fifty experts/groups of experts with different perspectives and from different disciplines produce fifty different maps of the same ecoregion, demonstrating the subjectivity of ecoregional boundaries when there is no agreement on appropriate scales of observation and defining variables (from Rossum & Lavin, 2000 p. 546).

This riposte does not fully answer the challenge, but merely raises the vexed question of how the validity of ecoregions might be verified. Given that there are many valid ways of partitioning the earth's surface, the validity of ecoregions cannot be evaluated or ground truthed as more or less correct. Instead, an ecoregion map has to be justified to end-users in terms of its credibility and relevance to their needs (see Section 1.6).

The controversy surrounding the correlation (or lack of correlation) between ecoregions and the distribution of various communities of flora and fauna also highlights the importance of multi-scale representations of landscape patterns. Although correlations between biotic communities and (mainly) physically-defined landscape units may be poor across coarse regional scales, correlations increase at finer scales of analysis, such as catchment level and below (Townsend *et al.*, 2003).

Another assumption underlying ecosystem mapping is that areas within the same ecosystem have similar ecological resources and are likely to respond to human use or intervention in similar ways. It is further assumed that if better and more complete knowledge were available, the outcomes of proposed interventions would be predictable. These assumptions are seriously challenged by the new paradigms of complexity and heterogeneity, which suggest that factors such as local differences, multiple pathways, thresholds and lags may mean that outcomes are inherently uncertain and unpredictable and ecological surprises are common (e.g. Kay & Schneider, 1994; Scheffer *et al.*, 2001; Wu & Hobbs, 2002).

Ecoregion mapping also suffers from the drawbacks associated with all categorical mapping, in that discrete polygons are poor representations of dynamic, heterogeneous landscapes with indistinct boundaries. Information is lost as differences within each polygon are averaged out and all boundaries are represented as abrupt.

In summary, ecoregion mapping lacks sound theoretical foundations, relying heavily on subjective expert opinion to perceive and delineate landscape units. Furthermore, the approach does not address the challenges posed by complexity, heterogeneity and ecosystem dynamics. In spite of these difficulties, however, ecoregion mapping is very widely used, demonstrating the demand and the range of applications for integrated maps of ecological entities.

Hierarchy theory, landscape ecology and ecoregion mapping provide examples of approaches to the conceptualisation, classification and mapping of landscape units that aim to transcend disciplinary boundaries. In transcending these boundaries, they offer useful tools and techniques for describing and mapping landscapes, but fail to deliver integrated conceptual models that link pattern to process. I now review approaches to landscape conceptualisations that have emerged from disciplinary perspectives, focusing on the factors most frequently considered as creating differences between ecological systems: vegetation, soil, topography (landforms) and water.

2.5 Vegetation mapping

2.5.1 Overview: Potential natural vegetation

Whereas the mapping of land cover merely records existing land use, maps of plant communities aspire to delineate the geographical niches, described in terms of combinations of abiotic environmental attributes, that are either occupied or potentially could be occupied by various assemblages of plants. It is often claimed that such maps describe 'habitats' or 'habitat types' (e.g. Ferree & Anderson, 2013), although what species or range of species are supposed to occupy these habitats (apart from the plants) is rarely specified. Maps of plant communities are often used in conjunction with ecoregion maps, representing a finer scale view of ecological patterns and biodiversity that can inform regional and local conservation management and planning (e.g. Comer *et al.*, 2003; Ferrar & Lötter, 2007; Ferree & Anderson, 2013). Vegetation maps produced at coarser scales are also used as inputs to either ecoregion maps or national/regional biodiversity assessments (e.g. the use of Mucina and Rutherford's (2006) vegetation map of South Africa is used as an input to the National Spatial Biodiversity Assessment (Driver *et al.*, 2005)).

Approaches to vegetation mapping include niche modelling (also termed 'species distribution modelling') (Franklin, 1995; Guisan & Zimmermann, 2000; Austin, 2002; Elith & Leathwick, 2009), phytosociology (Braun-Blanquet, 1928) and potential natural vegetation (Tüxen, 1956; Küchler 1964; Westhoff & van der Maarel, 1978). Niche modelling entails the identification of representative samples of vegetation (or species presence/ absence data), analysis to reveal environmental attributes associated with these samples and extrapolation to other locations

that share the same attributes. Phytosociology is based on identifying associations of plants that commonly grow together, based on field surveys of selected plots (relevés). The two approaches are combined in maps of potential natural vegetation (PNV), which is conceived as the climax stage of vegetation that would develop if human influence on the site and its surroundings were to stop (Westhoff & van der Maarel, 1978). PNV maps are typically constructed by identifying environmental attributes associated with remnant areas of vegetation believed to be natural or near-natural and then classifying all environmentally similar locations as potentially supporting that class of vegetation (e.g. Mucina, 2010).

2.5.2 Critique

In recent years, PNV mapping has come under severe criticism on both conceptual and methodological grounds (e.g. Carrión, 2010; Chiarucci *et al.*, 2010). Conceptual criticisms challenge the notion of a stable end-point to vegetation succession when equilibrium is established between plants communities and their environment. Whilst steady state conditions may persist for long periods of time, bioclimatic conditions are constantly changing, such that a stable end-point is never reached. Perceptions of equilibrium and climax states are therefore dependent on the temporal scale considered (Perry, 2002; Chiarucci *et al.*, 2010). Furthermore, successional dynamics may be irreversibly changed by human interventions (Perry, 2002; Chiarucci *et al.*, 2010) or by spatial differences in disturbance dynamics or animal populations, such as variations in the fire regime or the numbers of elephants (Dublin *et al.*, 1990), all of which are capable of creating alternative stable states for the same patch of land, under the same geological and climatic conditions (Beisner *et al.*, 2003). These criticisms have been countered by a move towards defining potential vegetation as the vegetation that could flourish in a particular location, given current conditions, based on a description of extant plant communities:

> *"Mapping PNV has a descriptive aim and offers the possibility of depicting not only a 'natural' scenario according to the extant vegetation types and current environmental factors, but also an ecological description of the territory. It is not a commitment to build any ideal stage of nature but it can contribute to better management by providing targets for restoration and improving naturalness, ecosystem conservation and biodiversity preservation" (Loidi & Fernández-González, 2012 p. 596)*

This description brings the maps of PNV very close to ecoregion maps, and their associated critiques around the selection of mapping scales and defining attributes and the failure to address challenges posed by local heterogeneity, system complexity and dynamics (Section 2.4). The main difference between the two approaches is that while ecoregions are usually defined through the overlay of selected GIS layers, PNV maps are based upon *a priori* definitions of vegetation communities.

The selection and definition of these *a priori* communities is strongly criticised as being overly subjective (e.g. Carrión, 2010; Chiarucci *et al.*, 2010). Communities are usually defined by a field description of a patch considered to be representative of a certain class. However, both the taxonomy of classes and the selection of representative patches are inherently subjective

and are therefore not guaranteed to be repeatable. Furthermore, it is not clear how communities consisting of invasive plants or human plantings should be treated. Should they be included to provide a thorough description of existing habitats, even though such inclusions may compromise the use of the map for determining conservation targets? Lastly, the extrapolation of field results to produce a PNV map involves many more subjective decisions and assumptions that are rarely articulated (Chiarucci *et al.*, 2010; Loidi & Fernández-González, 2012).

Like ecoregion mapping, vegetation mapping lacks a strong theoretical basis, which affects the credibility and utility of these maps and classifications in several ways. Firstly, it leaves the selection of examples and the creation of a taxonomy to expert judgement, rather than being transparently and contestably justified in terms of reasons why certain similarities and differences are considered to be more important than others. Secondly, niches are defined solely in terms of statistical associations between the exemplar plant communities and environmental attributes, with few attempts to describe these links in terms of generative processes. This means that it is difficult to justify decisions relating to the scale of analysis or the selection of environmental attributes, even if agreement is reached on the taxonomy of classes to be mapped. Lastly, spatial extrapolations of these niches involve many questionable assumptions. The lack of theory explaining why observed communities persist in places characterised by particular suites of environmental attributes also means that it is not possible to hypothesise possible future trajectories once the (somewhat dubious) state of climax vegetation is reached.

2.6 Digital soil and landform mapping

2.6.1 Overview: The soil-landscape model

In contrast to vegetation mapping, digital soil mapping (DSM) is grounded in theory and conceptual models. DSM aims to map soil distributions by translating the mental soil-landscape models tacitly used by soil surveyors into explicit, transparent rule sets (Scull *et al.*, 2003; Lagacherie & McBratney, 2006; Deng, 2007). Soil-landscape models are underpinned by Jenny's (1941) theory that identifies soil forming factors as climate, relief, organic matter, parent material and time (Huggett, 1975). Assuming that climate and parent material and time are constant, the model posits relationships between soil distributions and hillslope morphology (Gerrard, 1992; Paton *et al.*, 1995), with changes in dominant soil formations signalled by changes in vegetation composition or structure. These relationships have been informally applied for years in field-based soil surveys carried out by practitioners who are expert in mentally adapting the soil landscape model to local circumstances, to interpret the geomorphic and vegetation clues that signal soil patterns. DSM formalises these mental models to create rules that link sampled soils to variations in hillslope morphology and vegetation response that can be observed in stereo photographs and gridded Digital Terrain Models (DTMs) (McBratney & Odeh, 1997; Bui, 2004).

Soil-landscape models are well grounded in theory, being based on well-established systematic relationships between topography and soils at the scale of individual hillslopes, known as

'catenas' or 'toposequences' (Milne, 1935; Huggett, 1975). Many of the ways in which hillslope morphology affects the development of soils, hydrological flows and vegetation are well understood as feedback mechanisms, whereby soils, water fluxes and vegetation affect the erosional and depositional processes that shape hillslope morphology itself (Moore *et al.*, 1991; Monger & Bestelmeyer, 2006). Indeed, DSM practitioners are warned that correlations between GIS layers are likely to be spurious or misleading if they cannot be justified in terms of the principles of soil genesis, as applied to the location to be mapped (McKenzie & Gallant, 2007).

Soil-landscape models have been extended to include many other geomorphic processes besides the downslope transport of water and solutes (Wysocki *et al.*, 2000). For example, the 'nine-unit' model (Conacher & Dalrymple, 1977) links topographic and soil differences between hillslope and channel units to formative geomorphic processes such as soil creep, landslides and fluvial erosion (Figure 2.4).

DSM and geomorphometry

DSM is closely associated with geomorphometry, a discipline concerned with the derivation of geomorphological features (landforms) from DEMs (see MacMillan & Shary, 2009). Landforms provide a vehicle to integrate a potentially vast number of highly interdependent and correlated terrain variables into a single unit. Furthermore, the use of landforms to predict soil distributions delivers more accurate results, more efficiently than is achieved by correlating individual soil attributes (such as depth, texture and colour) with individual terrain attributes such as gradient, curvature and elevation (Florinsky *et al.*, 2002). In addition, geomorphological understandings of landform processes can be used to frame linkages between soil properties and topographical variables, informing the selection of appropriate scales and variables for soil mapping. Indeed, early practitioners such as Ruhe (1956, 1960, 1975) and Hammond (1964) developed conceptual models that still underpin current DSM procedures. Procedures have been developed for using gradients and curvatures derived from DTMs to automatically delineate landforms such as pits, peaks, channels, ridges (or divides), passes and intervening midslope areas (Peuker & Douglas, 1975; Pennock *et al.*, 1987; Dikau, 1989; Shary *et al.*, 2002).

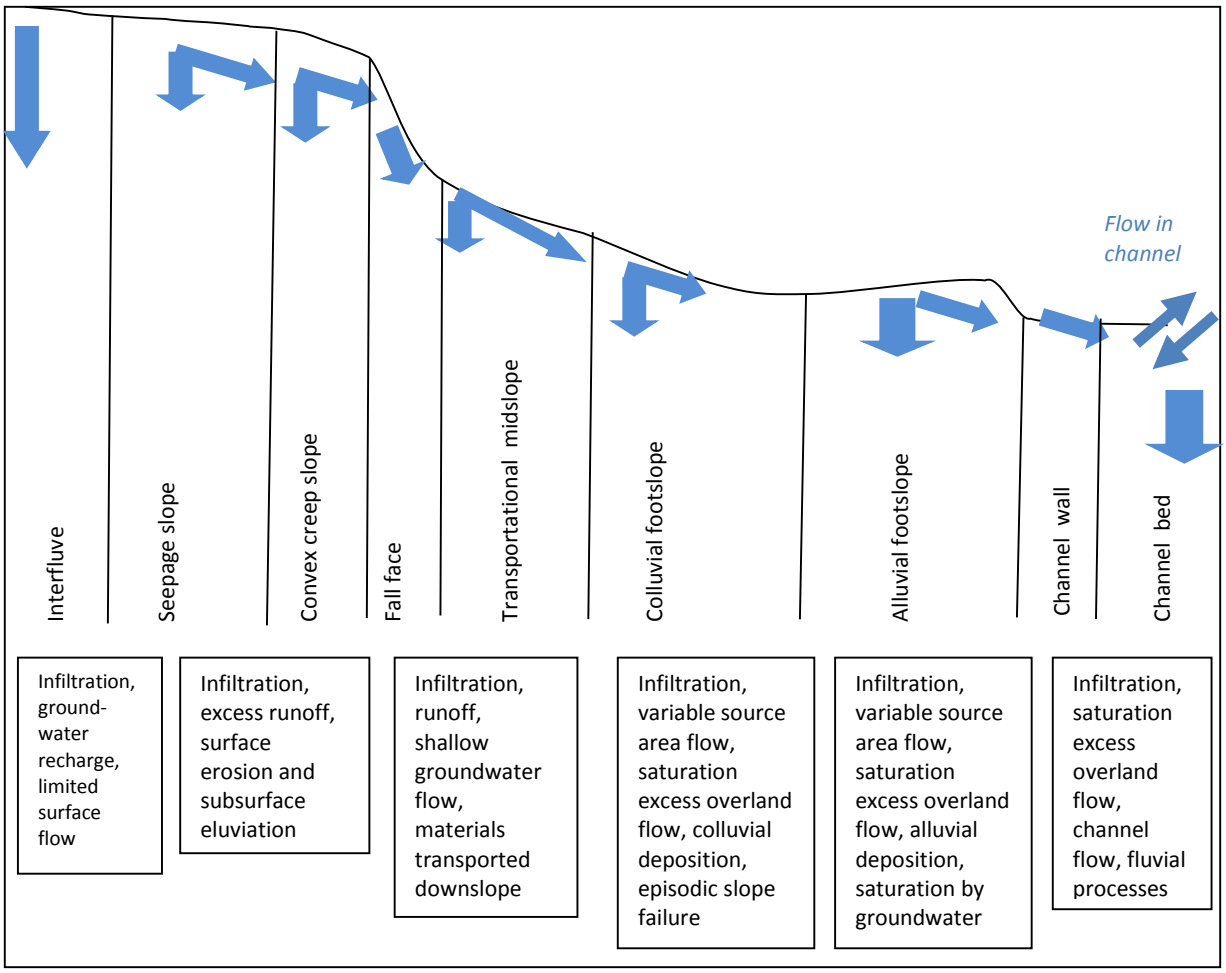


Figure 2.4: The 'Nine-Unit' hillslope model.

The nine slope units are not necessarily present in all instances. Blue arrows show the predominant directions of water movement in each unit. Each unit has a distinct morphology and is dominated by different hydrological and geomorphic processes. In a given climatic and geological setting, each unit is characterised by a particular water budget, soils and vegetation. (after Conacher & Dalrymple, 1977; Park & Burt, 2002).

Heterogeneity

The characteristics of soils often vary considerably over short time periods, influenced by factors such as the degree of saturation. However, in DSM, it is assumed that these changes occur within a range of variability characteristic of each soil type. Hence, the taxonomic definition of soil types includes all the various states of that soil at different levels of saturation. Soil characteristics are also prone to vary considerably over very small distances that usually fall below the resolution captured in soil surveys (Lagacherie *et al.*, 2007). As such, it is not surprising that soil scientists have developed various ways of dealing with this heterogeneity and the consequent uncertainty of spatial extrapolations. For example, fuzzy classification methods are a powerful tool for dealing with the imprecision in both the class and positional boundaries of landforms and associated soils. In fuzzy classifications, the degree of membership to each class is calculated separately for each image object (i.e. a pixel or group of pixels). Classes are neither mutually exclusive nor exhaustive, so it is possible for a single

spatial object to fit equally well (or badly) into two or more overlapping classes (Burrough, 1989).

Scale

Issues of scale and the search for objective ways of defining units and classes of units have been recurring themes in the DSM and geomorphometry literature. The delineation of peaks, for example, is dependent both on DTM resolution and the window size used for calculating curvatures. Indeed, many locations can be simultaneously and correctly described as on the midslope at coarse scales and on a crest or a divide when viewed at fine scales (Schmidt & Dikau, 1999; Evans, 2003; Zhu *et al.*, 2008). Furthermore, as pixel size increases, microtopography is smoothed and fewer features are seen (e.g. Arrell *et al.*, 2007). Even basic metrics derived from a DTM are highly dependent on both image resolution and the window size used. For example, at coarser resolutions, gradients become gentler on steep slopes and steeper on flatter slopes, curvatures decrease and areas contributing to flow at a certain point are overestimated in upper hillslope positions and underestimated in lower hillslope positions (Wolock & McCabe, 2000; Thompson *et al.*, 2001; Wu *et al.*, 2008). Vertical resolution also affects the measurement of gradient and curvature, in that decreasing vertical precision tends to exaggerate differences, producing both more flatter areas and more steep and highly curved areas (Thompson *et al.*, 2001). Metrics such as gradient and curvature produce quite different results and convey different information when measured over different distances (Fisher *et al.*, 2004; Schmidt & Andrew, 2005). When measured over relatively short distances, gradient and curvature convey information about local topography, such as terraces and banks associated with a stream. However, the same measures calculated over longer distances convey quite different information about valley shape and geometry.

Furthermore, the scales appropriate to the observation of landforms vary between landscapes with different stream densities. Differences in the horizontal spacing of major ridges and valleys ('topographic grain' (Wood & Snell, 1960; Pike, 1988; Pike *et al.*, 1989)) mean that hillslopes in different areas vary in length, with consequent variation in landform size. For example, in finely dissected landscapes with high stream density and relatively short hillslopes (e.g. the southern granites of KNP), a much smaller support distance is needed to capture hillslope morphology and landforms than in landscapes with low stream density, large catchments and long hillslopes (e.g. the southern basalts of KNP).

Attribute selection

Once a scale of observation that is suited both to landscape and purpose has been decided upon, the next challenge is to define landforms and boundaries between them. This is no easy task, since a multitude of morphometric measures can be used to describe topography (Gallant & Dowling, 2003) and different landforms may be observed, depending on the selection and weighting of the metrics used to define them (Deng & Wilson, 2006; Richards & Clifford, 2011). Thus the delineation of landforms is not merely a matter of detecting boundaries, but of conceptualising the entities to which the boundaries relate. Even if such entities appear at first to be self-evident and well described by language, the definition of landforms and /or soil units is fraught with challenges. For example Fisher *et al.* (2004) and Smith & Mark (2003) highlight

the vagueness and imprecision associated with the transition from an entity conceptualised as a mountain to one conceptualised as a valley.

Incorporating local variability

The quest for a standard set of procedures for defining landforms is confounded by variation in both the dimensions of different landscapes and the relative importance of different land- and soil- forming factors, processes and histories (e.g. Moller *et al.*, 2008). This variability means that different combinations of topographical variables, thresholds and scales of observation are needed to describe similar landforms in different landscapes, so that methods are not easily transferable between locations (Behrens *et al.*, 2010). Instead, new procedures need to be developed for each new location, designed to suit both the landscape being described and the purpose of the classification.

Semantic import models

DSM and geomorphometry both provide excellent examples of semantic import models (Burrough, 1989), in which concepts embedded in the language and tacit mental models of experts are translated into rules that can be encoded in a computerised mapping procedure (e.g. Bui, 2004; Walter *et al.*, 2006). This process has highlighted the need to justify the way landscape units and classes are defined, as well as the selection of scales of observation.

Regional conceptualisations of soil-landform models

When used to inform DSM, the soil-landscape model is usually applied at scales associated with individual hillslopes. However, the model has also been applied at regional scales to inform inventories of agricultural potential and development opportunities. Christian (Christian & Stewart, 1953; Christian, 1958) mapped large parts of (then) relatively unknown territories in Australia and New Guinea to inform development policy and planning. He not only identified 'land units' at hillslope scales, but also introduced the concept of 'land systems', which consist of recurring sequences and patterns of land units that are related to each other and result from the same geomorphic processes and history. These concepts have been widely used in South Africa, notably by MacVicar *et al.* (1974), who pioneered the development of 1:250 000 'Land Type' maps for the entire country. These maps continue to be used to this day to describe agricultural potential (see http://www.agis.agric.za/agisweb/landtypes.html). However, although repeating patterns of morphology, soils and vegetation have been noted as characteristic of many different areas, no standard way of automatically delineating, describing or analysing these patterns has yet been developed (MacMillan *et al.*, 2004; MacMillan & Shary, 2009).

Convergence with other disciplines

The rise of DSM has spawned a vast research effort and associated literature that addresses many of the issues central to this thesis, including approaches to the description and analysis of landscape patterns as well as the selection of appropriate variables and scales of observation. The emphasis is slowly shifting from the mapping, classification and inventory of traditional soil classes towards efforts to map soil functional types that can inform planning for food security, water resources or provide inputs for climate change models (Sanchez & Ahamed, 2009). The growth of DSM has also prompted a new emphasis on quantification and modelling in soil

science, stimulating research that aims to understand the interdependence of processes that are strongly influenced by soil properties, such as water movements and nutrient cycling (Wilding & Lin, 2006). Emerging approaches to integration such as hydropedology (Bouma, 2006) and ecohydrology (Rodriguez-Iturbe, 2000) cross conventional disciplinary boundaries, providing integrated conceptualisations of landscapes. Conceptualising hillslope units as areas containing not only distinct morphology and soils, but also distinct hydrology, biota and biogeomorphological processes (ranging from nutrient cycling to soil erosion) comes close to the concept of landscape units as containing distinct ecosystems, as developed within the European school of landscape ecology and as represented in ecoregion mapping.

2.6.2 Critique

The application of the soil-landscape model to DSM and the development of landform mapping has involved remarkable self-reflection, with a vast literature tackling issues such as the integration of different forms of knowledge (e.g. Gobin *et al.*, 2000; Zhu *et al.*, 2001; Walter *et al.*, 2006; Shi *et al.*, 2009), fuzzy classification (Burrough, 1989; Qi *et al.*, 2006), the effects of various scale and attribute choices (e.g. Wood, 1996; Fisher *et al.*, 2004; Schmidt & Andrew, 2005; Deng & Wilson, 2006; Zhu *et al.*, 2008) and the advantages and disadvantages of different mapping methods (e.g. Park & Burt, 2002; Bryan, 2006; Deng, 2007). It is evident that DSM and landform mappers are intensely aware of the slippery issues of scale, heterogeneity, attribute selection and other methodological choices that can dramatically affect mapping results.

There is acute awareness within the DSM and morphometry communities that hillslope scales and soil-forming factors vary in different landscape settings. Techniques such as Fourier analysis, wavelets or semivariograms (e.g. Lark, 2006; Perron *et al.*, 2008; Dragut *et al.*, 2009) are being investigated to detect characteristic scales associated with landform and soil variability in different landscapes. Whether soil-landscape models are described in terms of statistical correlations or in terms of expert knowledge, they are open to challenge on the basis of the idealised nature of the conceptualisation. The model contains numerous assumptions that often do not hold in real landscapes (Grayson *et al.*, 2002). For example, general assumptions of the soil- landscape model are that:

- Characteristic hillslope units and landforms exist as distinct entities that are discrete and identifiable at various scales (Smith & Mark, 2003; Fisher *et al.*, 2004).
- Hydrological and soil-forming processes are governed mostly by surface relief. Although relief controls surface runoff in all circumstances, for terrain to affect soil moisture patterns in the vegetation rooting zone, subsurface lateral downslope flow must occur. This means that precipitation must exceed evapotranspiration at least for long enough to saturate the soil sufficiently to initiate flow, and some restrictive layer must exist over which lateral sub-surface flow occurs. Thus topographic control on patterns of soil moisture in the rooting zone is often restricted to particular times and places (Grayson *et al.*, 2002).

- Subsurface controls result in the same patterns as surface controls, which may not be the case if large aquifers are present (McDonnell *et al.*, 1996).
- The processes controlling water budgets, vegetation and soils are tightly coupled, so that the distributions of soils, vegetation and water are more or less spatially aligned. In semi-arid climates, where water availability is limited, the coupling is likely to be tighter than in other climates where water is plentiful and other factors also limit the distribution of plants, animals and soils (Porporato *et al.*, 2002).

There are therefore many places in which the model does not hold. Furthermore, even in areas where the model is generally applicable, there are many reasons why it will not apply in certain locations or at certain times. For example, local differences in gradient, substrate and vegetation cover, as well as the presence of stones, soil crusts, termite mounds or exceptionally large trees will all disrupt flows, resulting in preferential flow paths and different sized threads of water moving at different speeds across and through even a single soil-landscape unit. Below the surface, the rate and direction of flows is often determined more by the presence of a few macropores than by the average soil texture and the flow in these macropores is also often restricted or blocked by air bubbles that change position over time (Baird, 2004). In other words, local spatial heterogeneity can undermine the general principles described in the model.

Although every place is potentially unique, this does not mean that general principles and conceptual models are not useful. Such principles and models serve as a starting point for the construction of local understanding, providing a basis to assess when and where local differences alter the basic model. In traditional soil surveys, local understandings are rarely made explicit and remain hidden in the soil-landscape models formed tacitly in the minds of soil surveyors. However, encoding these models in DSM means that such understanding needs to be made explicit, demanding rules that determine when, where and how local differences are likely to matter.

2.7 Mapping the spatial distribution of water

The spatial distribution of water is arguably the most important factor affecting temporal and spatial ecological patterns in semi-arid, savanna systems. A multitude of ecological processes are limited by water, resulting in clusters of environmental features and processes that are coupled to the spatial distribution of water (Noy-Meir, 1973; Porporato *et al.*, 2002; Rodríguez-Iturbe & Porporato, 2004). Besides acting as a precondition or catalyst for may biogeochemical processes, water also provides resources and shelter for biota, transports all manner of organisms, materials and energy across and through landscapes, is an agent of disturbance through flooding and erosion and creates landforms, shaping the earth's surface over multiple scales in time and space (Sponseller *et al.*, 2013).

Given the multiple functions and great importance of water to all life forms (including humans), it is hardly surprising that hydrological flows and resources are studied and managed from many perspectives. In this review, I focus on the two principle ways that landscapes are

classified from a hydrological point of view: in terms of Hydrologically Similar Surfaces (HYSS) and in terms of river classifications.

2.7.1 Hydrologically based landscape classifications

The decade of Predictions in Ungauged Basins (PUB)
Prompted by perceptions of changes in water-related flows and their impacts on human wellbeing (e.g. increased flooding, droughts, water quality issues and responses to climate change), the PUB decade (2002-2012) involved a huge, concerted effort to improve hydrological Predictions in Unguaged Basins (McDonnell & Woods, 2004; Wagener *et al.*, 2007; McDonnell *et al.*, 2007; Ali *et al.*, 2012; Hrachowitz *et al.*, 2013). The decade involved many projects constructed around the central aims of better understanding the 'ensemble of processes underlying hydrological system response, and the catchment-scale feedbacks between these processes', the 'multiscale spatio-temporal heterogeneity of processes across different landscapes and climates' and to improve 'regionalisation techniques to transfer understanding of hydrological response patterns from gauged to ungauged environments' (Hrachowitz *et al.*, 2013 p. 1200).

Efforts were focused around the idea that regional similarities between catchment morphology would act as indicators of hydrological properties such as flood frequency, stream flow variability and subsurface and base flow responses to rainfall events, providing key inputs for models to predict flows in ungauged catchments (Blöschl *et al.*, 2013). Many of the new models build upon the concepts of Hydrologically Similar Surfaces (HYSS), Hydrological Response Units (HRU) and Hydrologic Landscape Regions (HLR) (e.g. Flugel, 1995; Cammeraat, 2002; Bull *et al.*, 2003; Wolock *et al.*, 2004; Tague & Band, 2004; Wagener *et al.*, 2007). HYSS, HRU and HLR are spatial entities that have a common climate, land use and underlying pedological, topographical and geological associations that control their hydrological dynamics, resulting in different suites of dominant processes that characterise the area (e.g. Flugel 1995; Grayson & Bloschl 2000; Sivakumar 2004).

Several findings are pertinent to this thesis:

- No single set of catchment characteristics were identified that consistently predicted flows. Instead, many studies across different sets of catchments demonstrated that different landscape types generate different processes that demand different model structures to describe them (e.g. Hellebrand *et al.*, 2011). This finding echoes the experience of DSM and ecoregion mapping, confirming that different variables and mental models are required to describe many ecological functions in different landscapes.
- Different thresholds operate at different scales to control overall catchment hydrological responses. For example, both run-off and water storage capacities were shown to be related to non-linear responses at very local (individual macropores and small aquifers), soil unit and entire hillslopes (e.g. Andréassian *et al.*, 2004; Troch *et al.*,

2009). This confirms that hierarchical separation of different scale domains is essential to understanding and modelling hillslope hydrological processes.

- Models have been used as learning tools, both in terms of the interplay between local empirical observations and broad conceptual models and in terms of the construction of virtual realities that simulate system responses to climatic forcing and other changes to boundary conditions (e.g. Dunn *et al.*, 2008; Beven & Alcock, 2012).
- It was widely acknowledged that stronger links need to be built between hydrology, climate, vegetation, soils, topography and humans all of which co-evolve, adapting to and at the same time shaping the hydrological system (Hrachowitz *et al.*, 2013; Blöschl *et al.*, 2013). As in DSM, the recognition of the interdependence of so many factors has given renewed impetus to the emerging cross-disciplinary fields of ecohydrology and hydropedology.

Compared to soil scientists, hydrologists are relatively new to the world of spatial extrapolations from areas with known data to areas of unknown data, so it is not surprising that discussions of scale and attribute choice are far less advanced. Nevertheless, the parallels are exciting and lend weight to the potential utility of an integrated approach.

2.7.2 The classification of river systems

Overview: The spatial organisation of river systems

Like hillslopes, river systems are highly organised in space, with many patterns being repeated from system to system. These patterns are often fractal, in that the same pattern can be observed over a range of scales (Mandelbrot, 1982; Rodriguez-Iturbe & Rinaldo, 1997). For example, relationships between the area drained, the number of streams (and hence stream density), stream length and hillslope gradient have been observed in many river systems and are expressed in Hack and Horton's laws (Horton, 1945; Hack, 1957). Schumm (1977) described a general downstream transition from a zone of sediment production in the headwater region, through a zone dominated by sediment transport to an accumulation zone along the lower river reaches. The biological implications of this physical gradient have also been articulated, notably by Vannote *et al*. (1980) in their 'River Continuum Concept'.

These clinal patterns are produced by downhill fluxes of water, transporting sediment, nutrients and organic material, all of which can be involved in multiple, overlapping series of cascading interactions. These patterns, and the processes that generate them, are conceptualised by Petts and Amoros (1996) as the 'fluvial hydrosystem', which operates in all four dimensions and at many scales (see also Ward, 1989):

- *Longitudinal* gradients occur along the course of a river: Schumm (1977) described how river character and behaviour differ between headwater zones that are dominated by erosional processes and *sediment production*, *transfer* zones where sediment is temporarily stored before being transported downstream and *accumulation* zones, where depositional processes dominate. Longitudinal patterns are also described in the River Continuum Concept (Vannote *et al.*, 1980), where gradients in physical

changes in stream morphology and hydraulics are related to differences in habitat and nutrient availability.

- *Lateral* gradients include relationships between hillslopes, floodplains and channels, where systematic differences in morphology, soils and vegetation have been repeatedly documented.
- *Vertical* gradients result from interactions between the channel and groundwater through the hyporheic zone (Stanford & Ward, 1988). Plant species and assemblages change according to elevation above the stream and consequent inundation frequency (e.g. Hupp & Osterkamp, 1996; Bendix & Hupp, 2000), and also in relation to height above the water table (Renno *et al.*, 2008).
- *Temporal* changes are associated with the magnitude, frequency and timing of water and sediment movement (e.g. Junk *et al.*, 1989; Poff *et al.*, 1997), disturbance regimes and succession patterns following disturbance (e.g. Parsons *et al.*, 2006).

Gradients, networks and patches

The spatial organisation of rivers can not only be described in terms of gradients, as in the fluvial hydrosystem, but also in terms of networks of channels (or corridors that include riparian areas and floodplains), or as a series of interconnected patches (Pringle *et al.*, 1988; Ward *et al.*, 2002; Poole *et al.*, 2004). These different ways of viewing river systems tend to be associated with different disciplines and with different applications. For example, the network perspective is useful when considering water flows, informing management on issues such as pollution, floods or environmental flows (Omernik & Bailey, 1997). Although the gradient perspective is useful in theoretical descriptions and explanations, it is of less use in practical management applications, where the delineation of patches allows for classification, the construction of inventories and the use of sample or reference sites (Benz *et al.*, 2004). Indeed, river classifications are now routinely used for a wide range of management applications, including the assessment and monitoring of water quality, biodiversity and ecological integrity (Melles *et al.*, 2012; Olden *et al.*, 2012; Buffington & Montgomery, 2013).

The gradient, network and patch perspectives on rivers have also been combined. For example, Poole (2002; 2004) has built upon the patch mosaic concept from the American school of landscape ecology, describing river systems in terms of patches that are connected by surface and subsurface downslope flow paths that carry water, energy and materials (Figure 2.5).

The conceptualisation of river systems as a series of interconnected patches is inherently dynamic, since flows are ever-changing and the strength and frequency of connections between landscape elements vary through time. The degree of connectivity between patches not only varies with climatic conditions and antecedent conditions, it also depends on factors such as the distance between objects, the permeability of boundaries and buffer zones and the presence of vegetation (Cova & Goodchild, 2002; Strayer *et al.*, 2003; Lesschen *et al.*, 2009). Fluxes of water through a series of interconnected patches can be described in terms of the flood regime of a system (Poff, 1997). Although floods are notoriously unpredictable, their

magnitude, frequency and intensity are constrained at various scales by the climatic and geological setting, valley morphology and vegetation cover. The flood regime forms an important part of the physical template of a river system at all scales, with significant biophysical consequences. For example, the Flood Pulse Concept theorises that various characteristics of the flood regime act as the principal driving force behind the existence, productivity and interaction of diverse biota at different positions within catchments (Junk *et al.*, 1989).

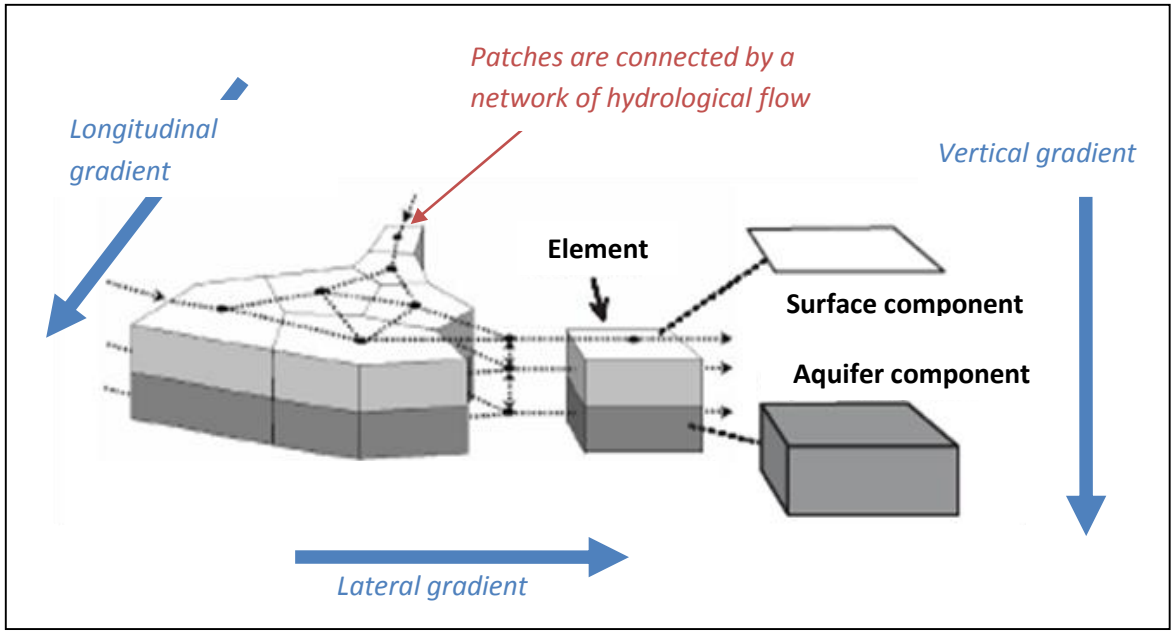


Figure 2.5: Gradients, networks and patches in a river system.

Diagram describing river systems as a dynamic patch mosaic in which patches are configured in accordance with the gradients described in the fluvial hydrosystem and connected by temporally variable fluxes of water that can also carry materials and energy that merges the gradient, network and patch perspectives. (after Poole et al.*, 2004).*

Hydological connectivity is not only important for flows of water, but also for the transport of sediment, nutrients, organisms and other materials such as seeds (Pringle, 2003; Reiners & Driese, 2004). Indeed, it is increasingly recognised that patterns of hydrological connectivity are critical to ecosystem integrity and therefore must be explicitly considered in rehabililitation projects (Kondolf *et al.*, 2006). However, as yet there is no consensus about how to define and measure hydrological connectivity, either on hillslopes or in fluvial systems (Bracken *et al.*, 2013).

The variability of gradients, networks and patches can be described and classified at different scales by invoking a hierarchy.

River hierarchies provide the basis for classifications

Most river classifications delineate spatial riverine units at scales associated with various organisational levels within a nested hierarchy. These units are then grouped into classes based upon observable characteristics that are indicators of particular processes (e.g. Frissell *et al.*, 1986; Rosgen, 1994; Bohn & Kershner, 2002; Rogers & O'Keefe, 2003; Brierley & Fryirs,

2005; Thorp *et al.*, 2010). All these classifications are based on the idea of identifying process domains (*sensu* Montgomery, 1999), identifying the past and likely future trajectories at various scales to inform management and planning decisions. All show remarkable agreement, both in how best to decompose river systems vertically into different levels of organisation and in the processes and controls that are hypothesised to operate at each level (Cullum *et al.*, 2008) (Table 2.1).

Table 2.1: Features and processes associated with hierarchical organisational levels of a river system. (after Schumm, 1977; Frissell et al*., 1986; Montgomery, 1999; Brierley & Fryirs, 2005; Buffington & Montgomery, 2013).*

Level of organisation	***Typical Features***	***Typical Processes***	***Typical drivers and controls (excluding humans)***
Region	Ridge-valley spacing Drainage density Network patterns Gradient and relief of major ridges/ slopes	Tectonics Fluvial erosion over long timescales (centuries)	Geology Climate
Zone/ Segment	Valley and channel geometry	Sediment production, transport and deposition	Valley width Stream gradient Drainage area
Reach	Bank and channel materials and geometry Riparian trees Floodplain Assemblages of geomorphic units	Local sediment storage, production or deposition Periodic flooding and flushing Riparian vegetation buffers lateral inputs of water and sediment	Sediment load Stream power Flood regime Vegetation Animals
Geomorphic unit	Levees, bars, pool-riffle sequences, runs	Local eddies and currents shaping erosional or depositional units	Sediment size Substrate shear stress Local currents Vegetation Animals
Hydraulic units	Fast/ slow flowing patches, eddies, temperature differences	Movement of individual grains and packets of water	Grain size Local currents Vegetation Animals

Although many descriptions of river hierarchies describe the scale domains associated with each organisational level in terms of absolute spatial and temporal values, I believe this is a fundamental mistake. The features and processes described in the hierarchy can occur over very wide ranges of distance and time periods. For example, reaches of the Amazon may extend over kilometres, whilst those in a small stream may only extend over a few metres. The

size of the scale domains associated with a particular river system varies with stream density, so that scale domains associated with the organisational levels of streams in finely dissected landscapes can be orders of magnitude smaller than those associated with streams in low-density systems where there are large distances between streams.

Critique

Critics of descriptions of the organisation of river systems (such as the fluvial hydrosystem and the River Continuum concept) have drawn attention to the many instances in which reality defies such descriptions, claiming that local controls on the composition and spatial configuration of system elements are more important than position in the network (Junk *et al.*, 1989; Montgomery, 1999; Poole, 2002; Thorp *et al.*, 2006). Others draw attention to disruption in longitudinal patterns associated with tributary junctions (Benda *et al.*, 2004; Ferguson *et al.*, 2006). Many deviations from the idealised patterns of river organisation are associated with regional or local variations in climate and/or geology (e.g. Minshall *et al.*, 1983). For example, intrusive rocks which are less easily eroded than the surrounding substrate are often associated with knickpoints where there is an abrupt change in channel gradient (see Poole, 2002). The change in potential energy available to erode and transport sediment as well as the change in substrate then results in an abrupt change in river character and behaviour (Schumm, 2005). Other commonly observed deviations from the idealised patterns are associated with human interventions that disrupt flow and disturbance regimes such as dams, channelisation, changes to land cover or fire suppression (e.g. Ward, 1998).

Such critiques are similar to those addressed to DSM and to all attempts at generalisation, which inevitably obscure local differences that may turn out to be important. Such observations highlight the underlying tensions between the need to generalise, to be able to transfer knowledge and experience, and the need to ensure that important local differences are not lost. Automated approaches to classification and mapping lag behind those developed in DSM, but there have been significant recent developments in the automated delineation of river reaches, valley width, and other key attributes (e.g. Gallant & Dowling, 2003; Parker *et al.*, 2012; Beechie & Imaki, 2014).

However, whilst geomorphological approaches to the description and analysis of the spatial organisation of river systems offer many useful insights and tools, they maintain and reinforce the disciplinary divide between terrestrial and aquatic systems. Focussing on processes involving fluxes of sediment and water and/or on physical habitats for aquatic species, the important influences of vegetation and animals on these processes (e.g. Murray *et al.*, 2008; Corenblit *et al.*, 2011; Gurnell, 2014) is generally overlooked in river classifications, particularly at higher levels of organisation.

2.8 Summary

A conceptualisation of landscapes that could provide a platform for integrated ecological science, management and policy making needs to meet certain criteria to avoid the pitfalls associated with current approaches. It must:

- Integrate many system components and processes, so that the conceptualisation is relevant to a wide range of applications, integrating the perspectives of different agencies and disciplines to avoid fragmented approaches to ecological science, management and policy making.
- Be adaptable, so that spatial units can be tailored to accommodate the various scales and attributes characteristic of individual landscapes.
- Be grounded in accepted theory that identifies key system components and interactions and links pattern to process. Most applications require extrapolations in time and/or space, which need to be justified in terms of widely-accepted theory and conceptual models rather than on potentially spurious statistical relationships.
- Acknowledge the inherent uncertainties associated with dynamic, complex, locally heterogeneous ecosystems, to avoid (or at least be prepared for) ecological surprises.
- Be repeatable, with transparent methods that are contestable and open to further refinement and development rather than relying on tacit, subjective expert judgements.

Although no single approach unequivocally fulfils all of these requirements, each of the approaches reviewed in this chapter has something valuable to contribute to a new, synthetic conceptualisation (Table 2.2). Whilst hierarchy theory offers a useful heuristic framework for horizontal and vertical relationships between spatial entities and formative processes, it does not attempt to specify what those entities might be or how landscapes might be decomposed to construct them. Whilst the American school of landscape ecology offers a very useful conceptualisation of landscapes as patch mosaics at various scales, together with tools for describing and analysing patterns in the mosaic, no attempt is made to specify the spatial entities that make up the mosaic. Indeed, we are warned that landscape mosaics are scale- and purpose- dependent, and that ecological systems are open, with indeterminable boundaries that exist only in the minds of observers. Furthermore, we are shown that heterogeneity is central to ecological diversity and functioning, such that disguising that heterogeneity in generalised conceptualisations can run counter to conservation objectives. Ultimately, the American school of landscape ecology takes up a very relativist position, suggesting that all perspectives on landscape are subjective and partial, justifiable only in terms of a particular organism or process of interest.

By contrast, the European school of landscape ecology promises a holistic perspective, integrating all system components, including humans, into a tangled web. This web is claimed to be decomposable by virtue of clusters of spatially aligned features and processes, allowing vertical and horizontal decomposition into a spatial hierarchy. However, the identification and delineation of these clusters is problematic, relying on supposedly self-evident gestalt perceptions. Whilst the placement of boundaries may be unproblematic in heavily modified agricultural and urban landscapes in central Europe, where this approach was developed, (particularly when the boundaries are specified by centralised land planners invoking incontestable institutional authority during the 1950s and 1960s), clusters are far from self-evident in the savanna landscapes that are the subject of this thesis.

Ecoregion mapping also promises integrated landscape conceptualisations that are prompted by demands of land planners and policy makers. However, as for European landscape ecologists, the conceptual foundations of these maps do not clearly inform the selection of scales and attributes.

Somewhat counter-intuitively, it emerges that the disciplinary perspectives offer more useful approaches to the specification of integrated spatial entities than do the cross-disciplinary perspectives discussed above. Rather than producing maps and classifications based on statistical correlations among a dealers choice of environmental attributes and scales, soil maps, hydrological catchment classifications and geomorphological river classifications are all grounded in conceptual models that link observed features and/or gradients to generative processes. All offer valuable insights into strategies and techniques that facilitate interplay between empirical field observations and general principles and theory, allowing place based understandings to be constructed by careful adaptation of idealised mental models. Furthermore, techniques are being developed to translate these mental models into rules that can be codified in at least semi-automated digital maps.

Table 2.2: Evaluation of existing approaches to landscape conceptualisation.

The reviewed approaches are evaluated in terms of their ability to support the integrated description and mapping of landscape patterns and processes, using criteria developed in Section 1.6 to meet the challenges posed by the new paradigms of ecological system complexity and heterogeneity.

Criteria / Approaches	**Integrates many system components?**	**Defines spatial units that guide the selection of scales and variables?**	**Grounded in accepted theory?**	**Acknowledges uncertainties associated with dynamic, complex and heterogenous ecosystems?**	**Is repeatable, with transparent methods?**
Hierarchy theory	Potentially yes, but depends on the nature of the spatial entities defined. It is only a heuristic device/ framework, with no 'content'.	Yes: if objects with intrinsic scale are defined in a hierarchy, choices of scale and defining attributes are at least narrowed, if not entirely resolved.	Potentially yes, but depends how the hierarchy is constructed and the credibility of any underpinning theory.	Yes: hierarchy theory reconciles reductionist and complexity paradigms.	Yes: assuming the hierarchy is clearly defined.
American landscape ecology	No: not truly integrated: Different combinations of environmental attributes are considered for each organism/process of interest.	Yes/No: spatial units are defined using scales and variables relevant to the organism/process of interest.	Yes/No: usually an overlay or statistical correlation of data seen as relevant to the particular organism/process of interest, with only broad reference to the theories underlying these choices.	Yes: dynamics, complexity and heterogeneity are central components of landscape conceptualisations.	Yes: generally well documented. Useful tools to quantify patch diversity and connectivity.

Criteria / Approaches	Integrates many system components?	Defines spatial units that guide the selection of scales and variables?	Grounded in accepted theory?	Acknowledges uncertainties associated with dynamic, complex and heterogenous ecosystems?	Is repeatable, with transparent methods?
European landscape ecology	Yes: abiotic components, biota and humans are considered as integrated, interdependent components of a system that is to be studied and managed in its entirety.	No: landscape units are conceived either as self-evident entities that do not require definition, or as contestable mental constructs.	Yes/No: founded upon systems theory and hierarchy theory. Numerous attempts describe relationships between components, but most are tangled webs.	Yes/No: complexity, dynamics and heterogeneity are extensively discussed, but rarely operationalised.	No: usually involve many tacit assumptions that rely on expert judgement, so methods can be hard to replicate in different circumstances or with different groups of experts.
Ecoregion mapping	Yes: aims to delineate distinct ecosystems that integrate biotic, abiotic and human components.	No: spatial units are not defined a priori, but result from data overlay and/or spatial clustering.	No: usually an overlay of available data. The web of interactions is usually deemed too complex to admit description.	No: the mapped ecosystems are conceived as stable entities with behaviour that is potentially predictable. Local heterogeneity is disregarded as a complication.	No: many decisions are based on tacit assumptions and the final outputs are usually subject to expert assessment.
Vegetation mapping	Yes: vegetation patterns integrate many landscape components, since distributions are dependent upon geology, climate, soil, relief and history.	No: spatial entities are only defined in relation to class examples.	No: relies on spatial correlations.	No: vegetation communities are assumed to be stable.	Yes: although the analyst is faced with many subjective decisions, these can be documented.

Criteria / Approaches	Integrates many system components?	Defines spatial units that guide the selection of scales and variables?	Grounded in accepted theory?	Acknowledges uncertainties associated with dynamic, complex and heterogenous ecosystems?	Is repeatable, with transparent methods?
Digital soil mapping	Yes: soil patterns integrate many landscape components, since soil distribution is dependent upon geology, climate, biota, relief and history.	Yes/no: units at hillslope scale often correspond to landforms - but the scales and variables used to define landforms are highly contestable.	Yes: aims to articulate tacit mental models used by soil surveyors that describe and explain systematic relationships between soils, topography and vegetation at hillslope scales that result from the downslope movement of water and sediment.	No: assume that soil distributions are stable over decadal time scales relevant to management. System complexity is acknowledged but not operationalised. Fuzzy mapping techniques are used to describe spatial heterogeneity.	Yes: generally well documented, with discussion around the choice of scales and variables. But methods are not easily transferable between locations, since the relative importance of different land- and soil-forming factors and processes varies between different locations.
Hydrological classifications	Yes: HYSS are defined in terms of a wide range of biotic and abiotic attributes.	Yes/No: catchments are defined entities, but scale is not specified and sub-catchment entities are often recognised as important.	Yes: is largely based on models /equations that describe universal laws and principles.	Yes: hydrological flows are inherently heterogenous, complex and dynamic.	Yes: modelling approaches are generally very well documented, although results are not easily transferred between locations.

Criteria / Approaches	Integrates many system components?	Defines spatial units that guide the selection of scales and variables?	Grounded in accepted theory?	Acknowledges uncertainties associated with dynamic, complex and heterogenous ecosystems?	Is repeatable, with transparent methods?
River classification	Yes/no: focus on aquatic species and fluvial processes. Although catchment influences on fluvial processes are widely recognised, terrestrial and aquatic systems are usually studied and managed separately. Connectivity between system components is emphasised.	Yes: many river classifications are based on similar conceptualisations of structural-functional units at different organisational levels within a hierarchy.	Yes: much attention is paid to form-process links, with future behaviour foresighted on the basis of geomorphological theories.	Yes: since flows are ever-changing and are sensitive to local conditions, conceptualisations are inherently dynamic and address heterogeneity and complexity.	No: most river classifications are heavily reliant on expert judgement. Standardised approaches are open to strong criticism, given the potential for local variability.

This process of translating expert knowledge and interpretation is invaluable, since it ensures that the assumptions underlying conceptualisations are fully articulated, allowing debate and criticism as well as development and refinement. The possibility of such debate is critical to the development of consensus around conceptualisations that are to be shared by a community: since all conceptualisations are ultimately contestable, it is imperative that each competing conceptualisation (or refinement to conceptualisations that have already been adopted) is supporting by narratives demonstrating its credibility and relevance to the purpose(s) in hand (see Cash *et al.*, 2003).

Vegetation, soil and HYSS mapping all use classification techniques that involve the identification of representative class samples together with environmental features or gradients that are strongly correlated with that sample to inform spatial extrapolations that estimate the distribution of each class. These techniques have been particularly well developed in DSM, where techniques of fuzzy classification have been successfully applied to describe the gradual transitions and overlapping classes that often characterise real landscapes. In fuzzy classification it is recognised that not all instances of a class are equally good exemplars of the entire class, which has led to the idea of developing *a priori* class prototypes that are used to define classification rules. This is potentially a very powerful way of reconciling the need for generalisation with the desire to retain information about local heterogeneity. This issue is considered in more detail in the following chapter of this thesis.

Of all the approaches reviewed, those that seek to describe and classify distributions of water are those that deal best with notions of heterogeneity, complexity and system dynamics. This is hardly surprising since hydrological flows are inherently dynamic, complex and sensitive to local differences. Geomorphologists tend to approach these issues by focusing on the development of place-based understandings, in which general principles are adjusted to accommodate local idiosyncrasies and differences, forming new mental models that describe and explain particular local features and processes (e.g. Brierley *et al.*, 2013). This approach is very similar to soil surveyors' adaptations of the soil-landscape model in the light of field observations (Section 2.6.1), reflecting the strong emphasis on fieldwork and empirical observations and interpretation in both disciplines. However, in geomorphological river classifications there is an even stronger emphasis on local interpretations, with classification being used mainly to establish an initial link between particular places and general principles to inform place-based and river-specific rehabilitation or management efforts, rather than to compare and group different areas for planning and management purposes. Compared to DSM, the strategies that are used to build place-based understandings are conceptually more developed in river classifications, with wide consensus around a hierarchy that defines spatial entities and connectivities between them. Each entity is inherently dynamic, being characterised by a flow regime as well as by connectivity with neighbouring units. Furthermore, many mental models are documented that link generative processes to the observable characteristics of these entities.

At present, HYSS classification is still a relatively new field that is far less developed compared to river classification, so has not gone far beyond the stage of flagging the issues raised by

complexity and heterogeneity. It will be very interesting to see how the field develops, particularly given the emphasis on modelling rather than on the expert interpretation of field-based observations and measurements that characterises geomorphological approaches to river classification.

The disciplinary based perspectives reviewed in this chapter all seem to be converging around a desire to identify geographical complexes of interwoven, co-evolved ecological attributes that are both cause and consequence of the spatial organisation of landscapes (see Buffington & Montgomery, 2013). The jury may be out as to why and how environmental attributes tend to cluster together in space, but there seems to be general agreement that spatial clusters of abiotic and biotic environmental attributes exist. These clusters are the same spatial objects that are the focus of European landscape ecology. Indeed, the disciplinary-based approaches to the description and mapping of soils, vegetation, landforms and hydrological classes are equivalent to the partial views of the total geocomplex (Haase, 1964) that forms the basis of the European approach to landscape ecology (Section 2.3.4). From a slightly different perspective, the same complexes are seen as the spatial expression of ecosystems by ecoregion mappers (Bailey, 2009a) (Section 2.4) or as clusters of attributes described as 'lumps' by Holling (1992) and 'grains' by Ulanowicz (1999) (Sections 1.4 and 3.4).

The description and mapping of these complexes, or 'landscape units' is clearly considered useful by a wide range of people, for a wide range of purposes. Not only do these units signal the distribution of individual attributes emphasised in disciplinary foci, but they also provide a geographical basis for land management and planning. Moreover, it is increasingly recognised that partial descriptions of these units is unsatisfactory for both ecological science and management. It is not possible to manage land separately for each species or process, so integrated management and policy approaches are essential. Integration is needed in science too, both to make progress in individual disciplines and to inform integrated management and policy (Tress *et al.*, 2005). It is now widely recognised that integrated science and management relies upon shared conceptualisations and language (Pickett *et al.*, 2007; Stirzaker *et al.*, 2011). Shared maps depicting landscape units based upon this conceptualisation are the logical next step.

In the following chapter, I synthesise the lessons learnt and techniques gleaned from this review to develop a new, integrated conceptualisation of savanna landscapes. In later chapters, I will apply this conceptualisation to the development of a classification of KNP landscapes, to assess correspondence with reality and the potential utility of the conceptualisation.

CHAPTER 3: TOWARDS A NEW CONCEPTUALISATION OF SAVANNA LANDSCAPES

The purpose of the conceptualisation is to present a view of reality that can inform the integrated study and management of savanna systems, describing and mapping spatial clusters of biophysical attributes in terms of a biophysical template that constrains a wide range of ecological processes. Pattern is linked to process by invoking theory from geomorphology and soil science. Aquatic and terrestrial perspectives are integrated by recognising that the spatial distribution of toposequences of associated soils, vegetation and hydrology is structured by the drainage network. A landscape hierarchy describes entities at three levels of organisation: catenal elements, associated with individual hillslopes, catchments, which contain toposequences of catenal elements and physiographic zones, which contain catchments that vary systematically in their morphology and toposequences according to their position in the drainage network. Applying this hierarchy to the classification and mapping of landscape entities at each organisational level involves an interplay between the general abstract concepts of the hierarchy and observations of features in particular landscapes. Archetypes are used to mediate between general, abstract concept and particular instances, with varying degrees of precision. The conceptual vagueness of archetypes and fuzzy classification methods help to address the challenges of dealing with the vagueness inherent in geographical concepts and the reality they represent.

3.1 Introduction

3.1.1 Reality, conceptualisations and representations

In philosophy 'ontology' is the study of the constituents of reality, of 'being' and of 'what exists'. Most science is founded on a realist ontology, following the classical Greek tradition in which reality is conceived as existing independently of any observer. Isolated parts of reality are conceived as 'particulars' or instances of 'universals' that fall neatly into 'natural kinds'. However, the 'natural kinds' and 'universals' that make up reality are only dimly and partially perceived by human observers. In this classical tradition, the task of science is seen as describing, classifying and explaining the true nature of this reality, thus revealing the ontology of the world. For example, species taxonomies are seen as describing how nature is 'carved at its joints' (Plato: Phaedrus 265e), such that increasingly precise taxonomies draw us closer to true knowledge of the natural world. However, more recent relativist and constructionist views claim that reality is at least partially constructed through a particular way of knowing. Kuhn, for example, has shown us how science mediates our perception of reality through the use of paradigms that contain conceptualisations, theories, models and methods that not only determine how questions can be answered but also the questions that it makes sense to ask (Kuhn, 1962). Even in biological taxonomy, the concept of species has been recognised as a human construct rather than as an incontestable way of partitioning organisms (De Queiroz, 2007). Furthermore, it is now also recognised that scientific framings can be influenced by institutional and political circumstances (Sarewitz, 2004; Tadaki *et al.*, 2014)

Whilst a realist ontology implies that there is only one ideal, correct or optimum way of viewing landscape objects, a constructivist perspective suggests that the same landscape can be decomposed in many different ways, each of which is valid for a particular purpose. An extreme constructivist position would be that reality does not exist outside of human perception, cognition or language.

Like Raper and Livingstone (2001) and others, I adopt a weak realist view of landscapes (Figure 3.1), in which the world exists independently of human perception and cognition, but can be partitioned in many different ways. Under this perspective, both mind and matter play a part in constructing landscape units, with the dominant role shifting between the two as conceptualisations are modified by experience and observation (Raper & Livingstone, 1995, 2001). From this point of view, conceptualisations are heuristic devices that are used to simplify descriptions of the world and to organise knowledge. Conceptualisations are mental constructs that include abstract, generalised concepts and relationships between these concepts and can carry connotations and values.

Conceptualisations provide a framework within which representations of reality can be constructed in various ways, including language, models, theories and maps. Representations allow us to reproduce, share, refine and preserve concepts that would otherwise remain inside the mind of an individual. These representations articulate the concepts and relationships that form a conceptualisation, so allowing communication about the world and hence the sharing of knowledge and experience (see Agarwal, 2005; Guarino *et al.*, 2009). Many different representations of the same conceptualisation are possible.

The relationship between reality, conceptualisations and representations mirrors the semiotic triangle (Ogden & Richards, 1923) in which signs and symbols (representations) stand for thoughts (conceptualisations) about referents (reality). Ogden and Richards explained how words and symbols had no meaning in themselves, but act as conventionally adopted signs that represent thoughts and concepts that are formed by an individual's perceptions and experiences of the world. Although representations can sometimes be used to consider the adequacy with which a conceptualisation describes or explains a real-world phenomenon, there is no direct relationship between signs/representations and their referent.

In recent decades, cartography has moved away from realist perspectives that evaluate maps according to their ability to correctly and efficiently represent and communicate external realities towards constructionist perspectives in which map-makers are seen as creating realities for map-users. The advent of GIS and map distribution over the internet has opened new possibilities for map-users to be involved in this process, selecting their own layers and thereby becoming involved in the map-making process (Crampton 2010).

3.1.2 Representations involve a trade-off between precision, generality and reality

Different conceptualisations are useful for different purposes and each conceptualisation can be represented in many different ways and include more or less detail. Levins (1966) explained that models are always partial representations, omitting some details to simplify reality and

make it more manageable. The selection of what to include and what to leave out involves choices between generalisation, precision and realism:

- Generality may be sacrificed to realism and precision, as in empirical models that are parameterised so that they fit one location or circumstance well, but are not easily applied elsewhere.
- Alternatively, realism may be sacrificed to generality and precision, as in Newtonian physics where general laws and equations make assumptions that rarely apply in the real world.
- Lastly, precision may be sacrificed to realism and generality, as in qualitative models, Bayesian statistics or fuzzy logic (e.g. Zadeh, 1996) that are easily applied in many circumstances, but which cannot deliver precise results.

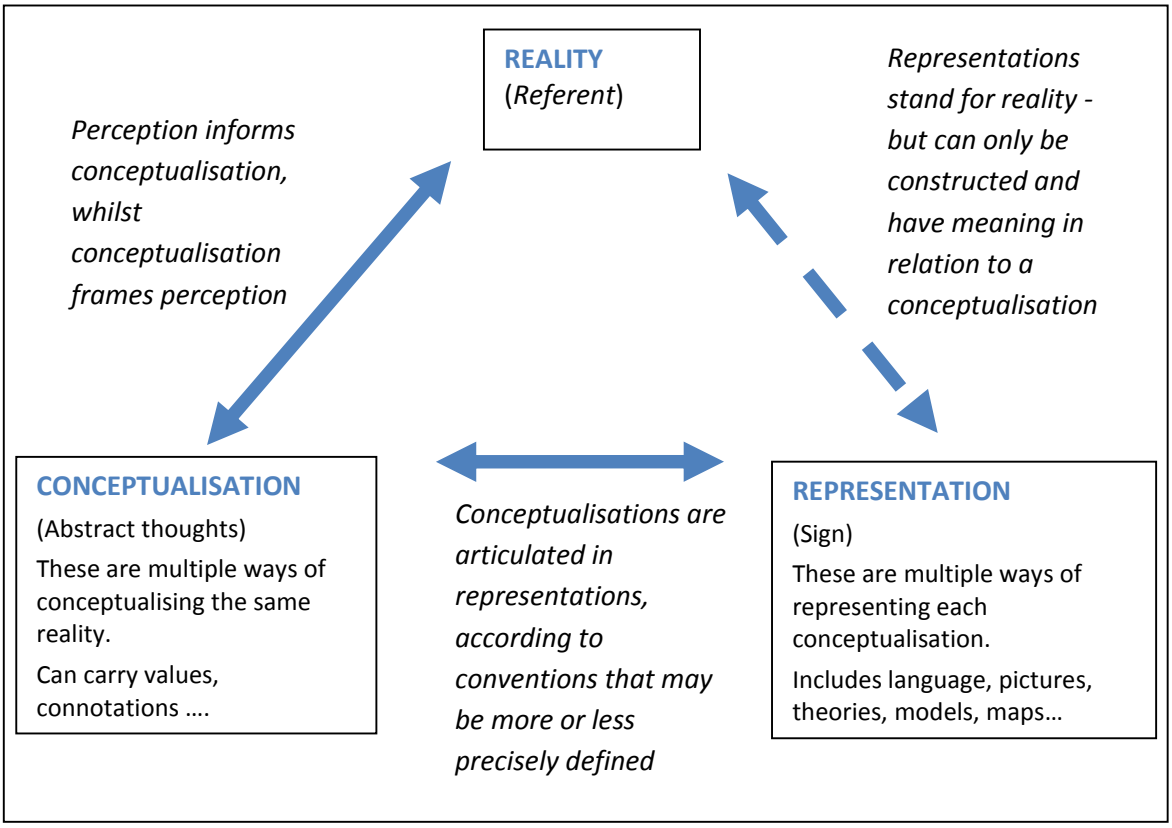


Figure 3.1: Relationships between reality, conceptualisations and representations.

Conceptualisations of reality can be articulated and shared in many representations, including language, art, science, models and maps. Relationships between reality, conceptualisations and representations mirror the semiotic triangle in which signs and symbols (representations) stand for thoughts (conceptualisations) about referents (reality (Ogden & Richards, 1923).

Both conceptualisations and representations can be more or less precise, more general or more particular and more or less grounded in reality. Several models can be used to build up a more complete conceptualisation of the same reality, each emphasising different aspects of that reality and/or making different choices between realism, precision and generalisation.

3.1.3 Shared conceptualisations

Because many different conceptualisations of the same reality are possible, we are able to describe landscapes in a multitude of different ways, with different types of knowledge forming a rich tapestry of understanding that loosely coalesces in a concept of 'place' (Relph, 1976; Tuan, 2001). However, the many possible perspectives also create challenges for integrated trans-disciplinary and trans-institutional research and management, since it becomes difficult to prevent misunderstandings arising from different terms, scales of observation and the relative importance placed on each system component (Dollar *et al.*, 2007; Pickett *et al.*, 2007; Stirzaker *et al.*, 2011).

Given the importance of shared conceptualisations to successful transdisciplinary projects, huge efforts are underway to develop definitive vocabularies, taxonomies and concepts that can be used to facilitate data and knowledge transfer between different domains (see Fonseca *et al.*, 2002; Madin *et al.*, 2008 for reviews of progress in environmental and ecological science). Within information science, these information systems are (rather confusingly) called 'ontologies' (e.g. Guarino *et al.*, 2009). In this sense of the word, an 'ontology' is a formal, codeable description of entities, classes, properties and functions that form a particular view of the world. Such ontologies are artefacts that are purposively designed and engineered to facilitate the exchange of knowledge, data and programs and are adopted by convention and agreement (Guarino, 1998).

Like other forms of representation, these efforts are always based on a particular conceptualisation, either implicitly or explicitly. Indeed, ontologies are frequently described as formal specifications of conceptualisations (Gruber, 1993), aiming to codify the way a particular group of people conceptualise and bound a domain of knowledge rather than aiming to describe the ultimate constituents of reality (Smith & Mark, 1998).

In the world of information science it is recognised that conceptualisations are contestable, such that the adoption of a particular ontology involves an 'ontological commitment' to a particular way of viewing the world (Gruber, 1993; Guarino, 1998). It has become clear that consensus around a shared conceptualisation needs to be won rather than taken as self-evident.

In this thesis, I develop a conceptualisation of savanna landscapes that offers a view of reality that I believe will be useful and relevant to a wide range of scientists, environmental managers and planners, offering a platform for the integration of different types of knowledge and action. The body of the thesis consists of an articulation and justification for this conceptualisation, striving to demonstrate its credibility and utility for a wide range of purposes in order to gain 'ontological commitment' among potential users. The credibility of the conceptualisation is demonstrated by its foundations in existing theory and practice, its internal coherence and completeness and from its ability to adequately describe examples of savanna landscapes in ways that are potentially relevant and useful for a wide range of purposes.

In this chapter, I develop and articulate my conceptualisation of savanna landscapes, situating it within widely accepted theories drawn from ecology, soil science, hydrology and

geomorphology. To ensure internal coherence and completeness, the conceptualisation is framed within a 'meta-ontology' of geographic objects borrowed from geographic information science (Couclelis, 2010). After describing this meta-ontology, the conceptualisation is developed, building up to the presentation of a heuristic hierarchy of landscape entities. Next, I consider how this abstract, skeletal hierarchy is used to inform a landscape classification that describes and maps particular instances of these entities. In later chapters, the approach is used to develop various classifications of savanna landscapes in KNP, demonstrating how the conceptualisation describes these landscapes in ways that can potentially integrate knowledge and experience across a wide range of communities and interests.

3.2 A meta-ontology of geographic objects

In geographical information science, conceptualisations describe the world in terms of spatial objects and relationships. The composition, structure and properties of these spatial objects can be formally described in terms of geographic ontologies (Fonseca *et al.*, 2002; Couclelis, 2010). Geographic ontologies, as described by Couclelis (2010) do not describe the structure of reality, but rather the structure of a representation of the world. Couclelis (2010) has devised a 'meta-ontology' that can be used in the design and construction of geographic ontologies, ensuring that each part of the ontology fits with the whole and is appropriately justified in terms of its overall purpose. It starts from the premise that geographic information is not a direct representation of reality, but that various representations of reality are possible, each framed to emphasise features and relationships that are relevant for a particular purpose:

> *"Geographic information science is about designing good geographic information tools to serve specific purposes, not about discovering how things are in the world, and is thus much closer to engineering than to traditional empirical science." (Couclelis, 2010)*

Couclelis describes a hierarchy of different levels of geographic information that each provide different representations of the same empirical referent (Table 3.1). Moving down each level in the hierarchy, options are progressively limited by the contextual constraints of higher levels. Semantic content is progressively removed, leaving behind information objects that are 'still meaningful, though increasingly semantically impoverished' (Couclelis, 2010). As the hierarchy is descended, less intelligent processes are needed to process the information. Since less cognitive input is required to process lower levels of information, these levels are less contested and are more easily agreed upon than is information at higher levels.

This meta-ontology shows how coherent sets of geographic objects can be constructed by starting with a clearly defined purpose and then focusing on more detailed levels in descending order of complexity (Table 3.1). Higher levels in the ontology are theoretical, setting out the general principles of a conceptualisation, whilst lower levels describe the application of these generalities to a particular landscape, creating a geographic representation of the conceptualisation.

3.3 Overview of the Couclelis meta-ontology

The four highest levels of the Couclelis ontology follow an Aristotelian description of four dimensions of meaning associated with objects. In descending order, these are:

> Level 7: The *telic* dimension refers to the ultimate purpose of things or the reason why things happen. Different purposes require different windows on the world, such that once the purpose is defined, then choices at lower levels of the ontology are drastically narrowed as only attributes, processes and entities relevant to that purpose need to be considered.
>
> Level 6: The *agentive* dimension concerns functions and generative processes (how an object comes to be, how it affects other objects and its function as a means to some end (*instrumentality).*
>
> Level 5: The *constitutive* dimension of *composite objects* considers the various parts that an object is composed of and their relation to the whole. These *associations* include both spatial relationships (e.g. containment, contiguity and non-spatial relationships such as similarity, membership, authority and inheritance. At this level, objects and patterns are stripped of their meaning in terms of purpose or process.
>
> Level 4: The *formal* dimension concerns *simple objects* and the properties that distinguish between different *categories* of objects.

Table 3.1: A meta-ontology of geographic information.

Ontological levels are described in the first column (after Couclelis 2010), whilst the next column shows how this framework is applied in the development of a new conceptualisation of savanna landscapes.

Ontological level	***Questions addressed in developing a new conceptualisation of savanna landscapes***	***How implemented in the new conceptualisation***
7. Purpose (highest level - Maximum semantic content.) *Intentionality* – why something happens Frames the domain of discourse, bridging science, mapping and management/planning applications. Allows all ways of talking about the object (describing, analysing, explaining, specifying, designing, querying, etc.).	Aim: A spatial framework for the description, analysis and mapping of biophysical patterns to inform the integrated study and management of savanna systems. Perspective - determining what functions/ patterns are to be considered.	Clusters of environmental attributes constrain a wide range of ecological processes. These clusters form a biophysical template that is conceived as a patch mosaic, connected by hydrological fluxes. Patches and connections between patches are dynamic, ever changing in response to seasons and disturbances such as fire and flood.
6. Function *Agentive* – the means to the end purpose. *Instrumentality* – understanding generative processes and other processes where the entity is a driver or control.	Theories linking patterns to generative and sustaining processes.	Toposequences (soil science/ geomorphology) structured by river network (river science).
5. Conceptual entities and relationships *Constitutive* – the definition of composite objects in terms of parts and wholes. *Association* – relationships of inheritance, emergence, types of interaction and connectivity.	How define and represent abstract landscape units: structural-functional spatial objects. Relationships between wholes and parts, and between neighbours.	Landscape hierarchy that defines spatial entities (archetypes) and how they relate to each other - a) in a schematic/ abstract form and b) in a particular landscape.
4. Spatial objects *Formal* – defining attributes of an object *Categorisation* – supervised allocation to groups.	Defining attributes of each object.	Archetypes describing objects and object classes in a particular landscape. Combining relevant variables to map archetypes.
3. Similarities *Measureable* gradients (fields) *Classification* - Clusters/ groups of measures.	Measureable gradients (fields) Classification – clusters/ groups of measures (e.g. class intervals).	Define relevant and measurable candidate variables and explore statistical relationships between them.

Ontological level	***Questions addressed in developing a new conceptualisation of savanna landscapes***	***How implemented in the new conceptualisation***
2. Observables *Perception*.	Qualitative assessment – no measurement.	Observe environmental attributes that cluster in ways suggested by the archetype.
1. Granules (lowest level -least semantic content) *Awareness* Discrete granules of time and space.	Atomistic, discrete granules of time and space.	Spatial and temporal scales that reveal patterns suggested by the archetypes.

At lower levels of the hierarchy, it is no longer possible to distinguish objects and the perspective changes to a 'field' view of continuous attributes:

> Level 3: Attributes are measurable, so it is still possible to discern *similarities* and to identify patterns and group attributes with similar values. However, such classification lacks intention or purpose (as in unsupervised image classification).
>
> Level 2: Attributes can be perceived (*observables)*, but are not measurable. Qualitative assessments of pattern are possible and notions of distance, shape, orientation and neighbourhood relations inherited from higher levels can be discerned.
>
> Level 1: The simplest geographic construct carries no meaning, allowing only awareness of *granule*s of space and time.

Couclelis does not identify a transition from abstract mental concepts to the construction of a material representation of those concepts in terms of a map or a classification of imagery and data. However, I see this transition occurring at Level 4. Above this level, entities are abstract concepts that do not necessarily relate to specific instances of these concepts in particular landscapes. However, at Levels 1-3, imagery or other data are used to delineate particular examples of the geographic objects defined in levels 4 and 5.

My conceptualisation therefore deviates slightly from Couclelis's at this point. Rather than separating levels 4 and 5 on the basis of parts and wholes, I would prefer to include both parts and wholes at level 5, recognising that the same object may appear as a whole at one scale of observation, with its constituent parts becoming evident at other, finer scales. It is at this level of parts AND wholes that a conceptual hierarchy is defined, guiding the identification of specific entities at lower ontological levels. It is only at my interpretation of Level 4 that objects occupy a specific space and time, demanding the selection of variables and scales of observation that allow these objects to be identified in available imagery and data.

In the following sections of this chapter, I go through each ontological level in turn, applying the meta-ontology to inform the development of the conceptualisation that is the subject of this thesis.

3.4 Couclelis Level 7: Purpose (highest level)

The highest level of the meta-ontology frames the domain of discourse, defining the 'intentionality' of the conceptualisation in terms of the purposes, intentions, motivations, needs, beliefs and values of a user of the system. The review of existing conceptualisations of landscapes in the previous chapter revealed that land managers, policymakers and scientists are all demanding integrated perspectives on landscapes that can unite disciplinary approaches and bridge gaps between different institutions and agencies. All are searching for a process-based conceptualisation that links observable features to generative processes, allowing comparisons, classification, and spatio-temporal extrapolations of the character and behaviour of ecological systems in different locations. However, the very possibility of an integrated

approach is seemingly denied by some landscape ecologists who have tended to adopt increasingly relativist positions and fragmented perspectives in the face of the challenges posed by issues of scale, complexity, heterogeneity and dynamics of ecological systems (see Section 2.3.3).

The purpose of the new conceptualisation of savanna landscapes developed in this thesis is to provide a platform for the integrated study and management of savanna systems in a way that begins to address these challenges. The new conceptualisation needs to describe structural-functional units that integrate components of ecological systems that are seen as relevant to a wide range of applications in environmental science, management and policy development. The conceptualisation must offer a way of simplifying and abstracting components and interactions in ecological systems so that comparisons can be made and learning can be transferred between locations. However, it must also deal with the challenges that the new insights into system complexity, heterogeneity and dynamics present to the classical, reductionist ways of thinking about landscapes. The conceptualisation cannot only be abstract, but must also provide a framework that can be used as a basis for landscape classification and mapping, providing a way of partitioning satellite imagery and GIS data in ways that are likely to be relevant to many different applications, defining ecological regions so that it can fulfil the same purposes as ecoregion mapping (Section 2.4).

In one sense, defining ecological regions is easy: ecoregions are the spatial expression of ecosystems, containing clusters of relatively homogeneous sets of interacting biotic and abiotic features and attributes that are distinct from those found in neighbouring ecoregions (e.g. McMahon *et al.*, 2004). These clusters have been recognised and described at many scales for centuries, so that they are embedded in our language. In everyday language we comfortably distinguish between wetlands, forests and grasslands, between narrow, steep, turbulent, mountain streams and wide, slow, meandering rivers, between sandy beaches and rocky shores. However, drawing lines around these clusters is not so easy, since:

- Different clusters can be observed at different scales, and these clusters are not necessarily nested (Levin, 1992). Indeed, clusters may not exist at all in some landscapes. Because ecological systems are inherently complex and open (Kay & Schneider, 1994; Mitchell, 2009), with interactions that occur across scales (Currie, 2011), there is no reason why all interactions and all system components should cluster in the same way or at the same scale.
- The scales at which clusters occur, and the attributes that cluster vary between landscapes (e.g. Schmidt & Dikau, 1999; Omernik, 2004)
- Since landscapes are dynamic and ever-changing, the determination of enduring characteristics that define patch identity is challenging. The insight that patch identity depends on the time-scale at which the landscape is viewed (Hobbs *et al.*, 2006, 2013) has challenged notions of landscape stability and equilibrium (see e.g. Perry, 2002).

- Environmental attributes usually form gradients, such that clusters often have blurred edges and large transition areas may exist, challenging the placement of exact boundaries (e.g. Burrough, 1989; Burrough & Frank, 1996).
- Humans have modified clusters or created new clusters in innumerable ways (Hobbs *et al.*, 2006, 2013)

Each of these issues is now addressed in turn, developing the broad basis of the conceptualisation and so defining its domain of discourse.

Spatial clusters of biotic and abiotic landscape attributes

It is now well understood that observed patterns of biotic and abiotic attributes depend on the scale at which they are observed (Levin, 1992). Furthermore, because the web of interactions between the various components of ecological systems is not bounded, there is no reason why spatial patterns in the distribution of these components need to be neatly aligned with each other. As Currie explains:

> *''Plant populations interact with one another through shading and competition for nutrients, but each population is likely to reproduce over a different spatial range dictated by the movements of its pollen and seeds. Animal populations interact ecologically with plant populations (e.g. through herbivory) and with one another (as in predator–prey interactions) but do not necessarily share the same spatial ranges as either plant or other animal populations. …… Investigators often define a boundary around an area to delimit a locale in which to study an ecosystem. …. Plant populations extend through these areas, while animal populations might forage in this locale but reproduce somewhere else, or vice versa. If we believe that flows of energy (e.g. in herbivory and predation) are key for organism growth and survival, that reproduction is key in regulating populations, and that ecological interactions among populations are key, then in the vast majority of cases it would be extremely difficult to study, or even to define, a complete ecosystem." (Currie, 2011 pp. 23–24)*

A shift of emphasis helps to clarify and resolve this dilemma. Ecoregions need not aim to delineate complete ecosystems, nor need they define areas occupied by particular species, populations or communities of plants and animals. Rather than focussing on populations and population dynamics, we can choose instead to focus on biophysical constraints on the distribution of populations, considering ecoregion clusters as a web of system components that form a template upon which ecological processes are played out.

The habitat template concept (Southwood, 1977; Townsend, 1989; Townsend & Hildrew, 1994) was originally developed as a framework for relating the characteristics of species and communities to the spatial and temporal variability of environmental attributes. The theory is closely related to the concept of environmental filters (Poff, 1997), which suggests that the species found in a particular place are filtered from a pool of potential colonists on the basis of traits that enable the species to survive and reproduce in that space.

The main criticism of this conceptualisation centres on the concept of 'habitat', which suggests a suite of resources that can support a particular species, whilst failing to specify the scales or species we are talking about (Hall *et al.*, 1997). Since every species has different and

overlapping resource requirements, often using different resources at different scales, the concept of habitat is empty and meaningless unless applied to a specific species and at a specific scale (Whittaker *et al.*, 1975; Mayor *et al.*, 2009). Moreover, animals are mobile, with many moving large distances, using different parts of the template for different purposes or at different times (e.g. Fonseca *et al.*, 2002).

However, rather than conceiving the template in terms of habitat for a particular species, I use the concept to describe clusters of abiotic and abiotic variables that can be observed at multiple scales. Such a notional template does not determine the species or population of plants and animals that use the resources it provides, but it does limit the possibilities by providing contextual constraints at many scales, in the way described by hierarchy theory (see, for example Phillips (2004) and Section 2.2.3).

Conceiving ecological clusters in terms of a template that constrains ecological processes and the organisms that can be supported by the resources present in a particular location is an inherently *geographical* conceptualisation of ecosystems. As such, it focuses on the characteristics of a particular *space*, rather than on the organisms that use that space. From a functional geographical perspective, the particular species that influences the template is not of primary importance. For example, the presence of grass affects the water balance, soil formation, forage available to animals and susceptibility to erosion, but the same functional role can be played by a wide variety of grass species.

A geographical conceptualisation is essential for management applications, since it is generally impractical to manage the same tract of land separately for different species or ecosystem processes. Apart from in agricultural contexts, where land is managed to maximise the productivity of a particular crop, both urban and rural landscapes are generally multi-functional (e.g. Ryan *et al.*, 2007). This means that landscapes ideally needs to be managed in a manner that integrates many different perspectives, prompting initiatives such integrated catchment management (e.g. Jakeman & Letcher, 2003).

The functional geographical view of ecological systems can be contrasted with aspatial functional perspectives that describe relationships between pooled aggregates or abstract concepts of system components (e.g. Odum, 1953). In a geographical, spatially explicit conceptualisation of an ecosystem, locations remain static over time, even though the ecosystems that occur there may change (e.g. in response to climate change or human actions). History is important, since the resources available at a particular location depend not only on contemporary interactions, but also on the history of previous interactions (e.g. Cadenasso *et al.*, 2006; Jenerette *et al.*, 2012). Thus both the history and the geography of a location combine to shape the spatial distribution of resources that forms a template that provides contextual constraints within which contemporary processes are played out.

Focusing on the contextual constraints on ecosystem processes rather than on the specific organisms or communities supported by the template does not mean that the influence of these organisms on the template is not acknowledged. Biotic communities shape the biophysical template as well as being shaped by it (e.g. O'Neill *et al.*, 1986; Monger &

Bestelmeyer, 2006; Corenblit *et al.*, 2011), often physically engineering their environment in many different ways (Jones *et al.*, 1994). Beaver dams, for example, may dramatically alter flow/sediment regimes, as do caddis fly nets on a much smaller scale (Cardinale *et al.*, 2004; Westbrook *et al.*, 2006). Fish affect character and dynamics of gravel beds of rivers (Statzner *et al.*, 2003), whilst termites change the character of soil, with knock-on effects on vegetation and animal communities (Debruyn & Conacher, 1990; Asawalam *et al.*, 1999; Holdo & McDowell, 2004). More than any other biotic community, humans both shape and are shaped by the template. Indeed, humans play such a significant role in shaping ecosystem character and dynamics that many now refer to 'socio-ecological systems', claiming that it is unhelpful to see humans as separate, exogenous influences impacting a separate biophysical system (e.g. Folke *et al.*, 2005).

I conceive the biophysical template as a conceptual mantle that is draped over the earth's surface, following the topography of the land. The mantle contains clusters or complexes of biophysical attributes including vegetation, water budget (rainfall inputs as well as the use, storage and transmission of water) and substrate (bedrock and its weathered products, including soils). This template is not seen as a static overlay of environmental attributes (as in 'field of dreams' restoration (Hilderbrand *et al.*, 2005), but rather as a dynamic web of interactions between abiotic and biotic (including human/social) components. Clusters link together to form a dynamic patch mosaic, *sensu* Wu and Loucks (1995) that can be viewed at many different scales or from many different perspectives. 'Ecoregions' can then be seen as the spatial clusters of co-varying vegetation, hydrology, substrate and topography that exist at various scales.

This 'biophysical template' is similar to the 'soil-geomorphic' template conceived by Monger and Bestelmeyer (2006), which combines the influences of soil, topography, and parent material and which is then used to explain vegetation patterns and dynamics observed in arid and semi-arid environments. However, rather than using the soil-geomorphic template to explain vegetation patterns, I prefer to incorporate these patterns (and the hydrological regimes associated with them) into the template, recognising the myriad of linkages and feedback loops that exist between vegetation, hydrology, substrate and topography (Figure 3.2). The conceptualisation is not designed to explain one system component in terms of another, but rather to describe key components of the system itself from an integrated perspective.

For example, in water-limited savanna landscapes, the combination of soil, vegetation and water inputs in a particular time and place controls soil moisture, which in turn controls plant species distributions through adaptations to local levels and timing of water availability (Rodriguez-Iturbe, 2000; Rodríguez-Iturbe & Porporato, 2004). At small scales, the degree of infiltration and storage of rainfall is controlled by soil texture and the nature and extent of vegetative cover (e.g. Bergkamp, 1998; Wilcox *et al.*, 2003). Soil water content affects chemical and microbial processes within the soil as well as the type and biomass of vegetation (Skopp & Jawson, 1990). In turn, vegetation affects soil texture through organic inputs, root systems and the actions of fauna (micro and macro) that are associated with the plant community (e.g.

Jenny, 1941; O'Connell *et al.*, 2000; Caylor *et al.*, 2006). At large scales, rainfall (the water component) and geology (parent material producing the soil component) interact to produce weathering and erosion regimes that are largely responsible for the topography that controls the distribution of water through the drainage network (e.g. Howard, 1967; Bull & Kirkby, 2002).

Although disturbance regimes, bio-engineering and human activities are also important components of the template, the focus here is on biophysical elements, particularly soil, water, topography and vegetation, which are the key components of soil-landscape models upon which this conceptualisation is largely based (Section 2.6).

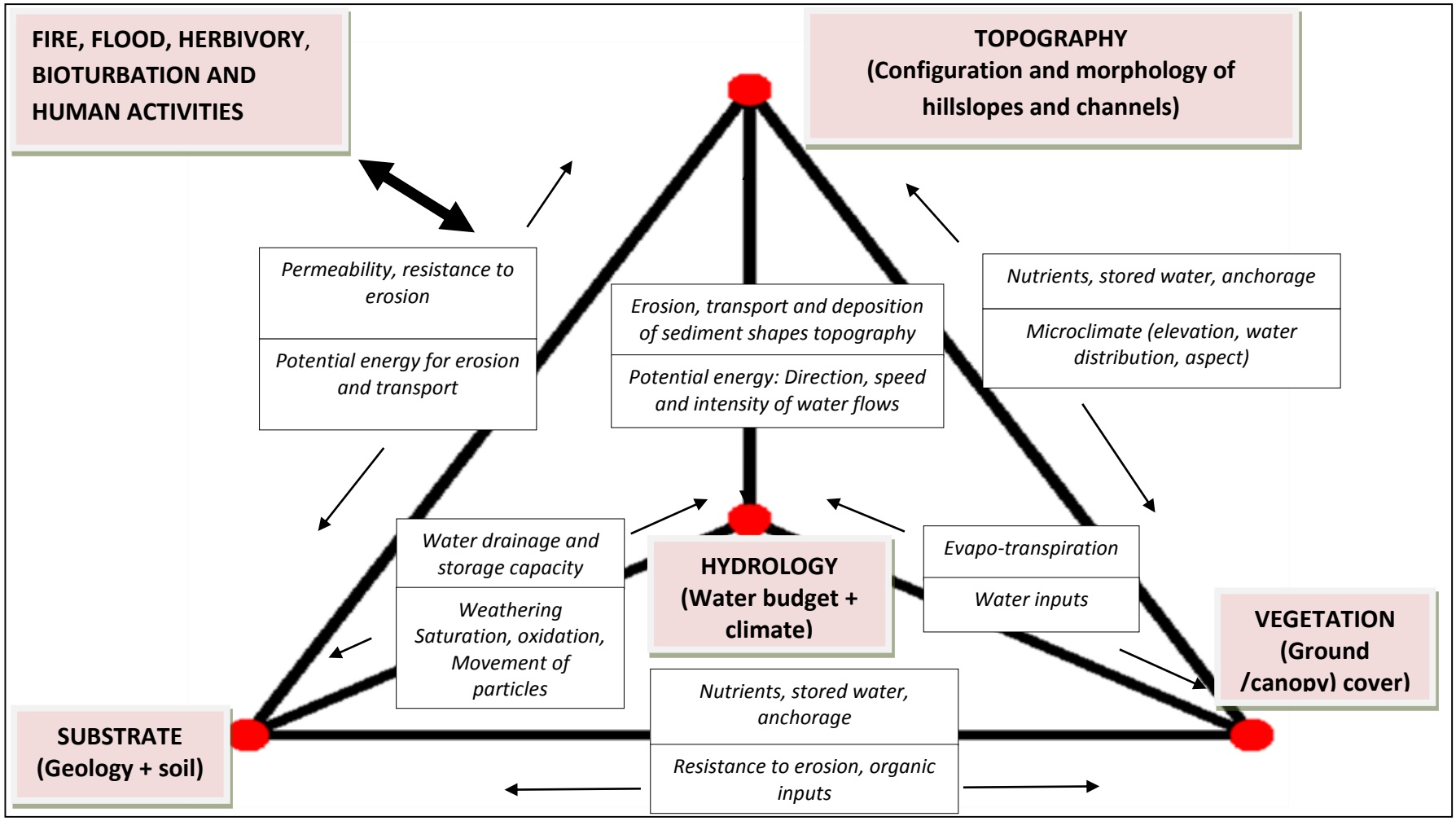


Figure 3.2: Linkages and feedbacks between components of the biophysical template of water-limited savanna ecosystems.

The template is conceives as a conceptual mantle draped over the earth's surface, continually changing and evolving, creating a history that constrains present and future interactions. Although disturbance regimes, bio-engineering and human activities are also important components of the template, the focus here is on biophysical elements, particularly soil, water, topography and vegetation.
(Moore et al*., 1991; Rodríguez-Iturbe & Porporato, 2004; Monger & Bestelmeyer, 2006; Khomo, 2008)*

The criticism that ecoregion boundaries are inherently unmappable because ecosystems are open systems with indeterminable boundaries does not necessarily apply to this biophysical template. There are many systems in which soil, vegetation, hydrology and topography do cluster at various scales. However, there is no reason why this should always be the case or why these attributes should always cluster to the same extent. If it is the case that the distributions of vegetation, hydrology, substrate and topography do indeed align in a particular location at a particular scale, then the ecoregion exists somewhat independently of observers and can be mapped. However, if these distributions do not align, then the criticism holds, since the ecoregion boundaries will vary depending on the attribute(s) used to define the region and a single, integrated view will not be possible.

In some systems, soil, vegetation, hydrology and topography do cluster spatially, as a result of tight coupling between the processes that generate and sustain these components. This coupling is often due to many processes being limited by the same environmental control. For example, in semi-arid savannas, many ecological processes are limited by the scarcity of water, such that many processes are tightly coupled to water availability in time and space and hence to each other (Scholes & Walker, 1993; Rodríguez-Iturbe & Porporato, 2004; Caylor *et al.*, 2005a). This results in distinct patterns of soils and vegetation associated with the varying amounts of water available in different hillslope positions (as in the catenas described by Milne, 1935). Strong spatial coupling is also seen between vegetation and soil in complexes associated with the temperature and moisture regimes found at different altitudes, generating banded vegetation patterns up mountainsides, often with abrupt boundaries such as tree lines (Körner, 2003).

In other systems the coupling between vegetation, soils, hydrology and topography may be much looser, introducing more variability at each hillslope position. For example, the distribution of soil/vegetation patterns in New Zealand kauri forests is largely dependent on the distribution of kauri trees, which is in turn determined by patterns of windfall (Ogden & Stewart, 1995). Although windfall is most common on ridgelines, such that there is an elevation control on upland forest patterns, aspect and the direction of prevailing winds also affect the likelihood of windfalls. Thus the direct relationship between hillslope position and the biophysical template is weakened as other factors come into play. Spatial coupling between the various system components is loosened when each of these other factors can vary independently, such that patterns can overlap, rather than align.

However, in many clusters in the biophysical template clearly do exist at many scales. Indeed it is these clusters that provide the inferential basis for soil surveyors to use topography and vegetation as indicators of soil distributions (see Section 2.6), for vegetation mappers to use topography, geology and climate to support hypotheses about the spatial distribution of plant communities (Section 2.5) and for hydrologists to suggest that flow regimes might be predictable from catchment characteristics (Section 2.7). Furthermore, it is likely that the convergence between disciplinary approaches is prompted by the presence of such clusters (Section 2.6.1).

3.4.1 Variables and scales appropriate for the observation of biophysical clusters vary between landscapes

If we accept the existence of spatial clusters in the biophysical template and see that they are routinely used by soil scientists and others, why are they so controversial and difficult to map? One of the main reasons why no standardised classifications and methods have emerged for any of the disciplinary approaches to the description of these clusters is that different drivers, controls and boundary conditions operate in different systems and at different scales (e.g. Schmidt & Dikau, 1999; Omernik, 2004; Moller *et al.*, 2008; Behrens *et al.*, 2010). It is not therefore surprising that the selection of defining variables and scales of observation emerge as central issues in all the approaches reviewed in Chapter 2. It is not the case that each discipline uses a different suite of scales and variables to describe landscapes. On the contrary, all the disciplinary approaches reviewed used similar suites of variables at similar scales. Furthermore, all recognise that more easily observed variables (e.g. topography and vegetation) could indicate the distribution of other, more difficult to observe variables such as water or soil. However, in each approach, no standardised set of variables or scales has been determined. I would suggest that no such standard is possible, since each landscape demands its own set of variables and techniques to describe the ecological clusters it contains. However, a systematic approach, such as that developed in this thesis, can guide efforts to map the clusters that can be observed in most savanna systems.

Geomorphologists routinely decompose landscapes into entities, or 'landforms' that are closely associated with variations in the biophysical template. Landforms are identified at various scales and are linked to theories that explain their formation and likely future behaviour. However, the same landforms can vary enormously in size (Schmidt & Dikau, 1999; Evans, 2003). As the Red Queen says to Alice:

> *" '… I thought I'd try and find my way to the top of that hill…' 'When you say 'hill',' the Queen interrupted, 'I could show you hills, in comparison with which you'd call that a valley'." (Carroll, 1871 Ch. 2)*

The classic example is an alluvial fan, which is formed by the same processes, whether it is a few centimetres or several kilometres wide (Blair & McPherson, 1994). Furthermore, the material composition and vegetation covering the fan will vary between geological and climatic settings, such that different sets of variables would be needed to identify fans in remotely sensed imagery in different locations. Thus the scales and variables needed to observe them would differ from place to place, such that a single, standard classification is unlikely to succeed in all contexts.

The challenges of indeterminate scales and defining variables have been articulated within geography as the Modifiable Areal Unit Problem (MAUP) (Openshaw, 1984). One way of avoiding the MAUP is to identify spatial entities or objects that are to be mapped. For example, if the focus is on individual trees, then a suitable mapping scale can be determined based on the dimensions of the trees and the required boundary precision. Basic units (e.g. pixels) can be aggregated so as to identify individual trees, producing a map that corresponds to a shared perception of reality which can be verified by ground truthing. When there is agreement as to

the nature and meaning of the entities to be mapped, then the selection of the data needed to delineate the entities and the choice of mapping scales is clarified. Hierarchy theory also aims to avoid (or at least reduce) the MAUP by imposing a framework that guides the decomposition of an object of study (e.g. a landscape) into units that are separated from each other in both horizontal and vertical dimensions. Applying hierarchy theory to the definition of ecoregions implies that landscapes can be decomposed into spatially distinct clusters (horizontal decomposition) within distinct scale domains (vertical decomposition).

For issues of scale and variable selection to be resolved through the use of hierarchy, there must also be agreement on the nature and utility of the entities into which landscapes are decomposed. Later in this chapter (Section 3.6.2) I will present a landscape hierarchy around which such agreement might be reached, but first the foundations for such a hierarchy need to be established.

Persistence and variability

Unlike continuous fields, spatial objects (entities) have discrete identities. They persist through time, even though properties may change through time and different people may describe the object in different ways. (Couclelis, 1992) Identities evolve and change, creating a history that can be the subject of a scientific explanation or carry cultural significance (Couclelis, 1992). Since landscapes are constantly adjusting, part of the identity of a landscape unit involves defining the boundaries of changes that can occur before the unit is deemed to belong to a different class, or to be sustained by different processes or even to have ceased to exist as a separate entity.

In the classical view of the world (Section 1.1), patch identity was not an issue, since ecosystem dynamics were envisioned in terms of progression towards a climax state, which was then held in place by the balance of nature (Watt, 1947). Even when the idea developed into a conceptualisation of landscapes as shifting patch mosaics (Bormann & Likens, 1979), patch identity remained unproblematic, since patch boundaries were conceived as stationary, even though changes associated with disturbance and succession occur. Viewed over a long enough period, this conceptualisation assumes that internal patch differences average out, so that patches can be treated as if they are internally homogenous. However, few studies have identified stable mosaics, even over large areas with relatively small and frequent disturbances (Turner *et al.*, 1993).

Complexity paradigms offer a different way of conceptualising landscape dynamics. Moving away from notions of equilibrium and steady states, ecological systems are instead conceived as open systems that are held in states far from equilibrium by interactions, feedbacks, disturbances and hierarchical constraints (e.g. DeAngelis & Waterhouse, 1987; O'Neill *et al.*, 1989). The illusion of equilibrium is fragile, depending on the time periods over which the system is viewed. A small change in the system can result in sudden, catastrophic and unpredictable change if an ecological threshold is crossed (Scheffer *et al.*, 2001). Furthermore, the boundaries that constrain the system are also liable to change over time, such that the whole system can be considered to be on a trajectory towards some future, different state (e.g. Holling, 2001; Gunderson & Holling, 2002). However, the course of this trajectory is always

subject to disruption, usually by large, infrequent disturbances that reset the system or even send it on a new trajectory (Turner *et al.*, 1998). It is because these disturbances have such profound impacts that system history can be thought of in terms of a series of contingent, episodic events, which often leave legacies that affect the course of future dynamics (Parker & Pickett, 1998).

Under the new paradigm, stability is conceived in terms of the tendency of a system to remain within defined boundaries, whilst change is ubiquitous, unpredictable and scale dependent. Different landscapes have different abilities to resist or accommodate disturbance, so that some, more resilient landscapes can buffer disturbances that would tip other, less resilient landscapes into catastrophic, maybe even irreversible change (Holling, 1973; Gunderson, 2000).

In the conceptualisation presented in this thesis, landscape entities are conceived as in perpetual flux, continually at risk of catastrophic change that threatens their identity. However, it is assumed that for the decadal timescales and spatial scales of 1-100km^2 that are most relevant to managers and planners, patch identities persist within a range of variability that is constrained by their horizontal and vertical neighbours in a landscape hierarchy (Section 2.2).

Boundaries

Although patterns in vegetation, water and soils may be strongly linked to each other and to topography, patch boundaries are often far from clear. Large transition areas often exist, raising questions around the most appropriate scale at which to devise class boundaries and about whether or not it is helpful to represent a gradual change as a series of categorical classes in the first place. An approach to classification is needed that deals with approximations rather than hard and fast rules, focussing on central tendencies rather than thresholds and boundary conditions that are difficult, if not impossible, to determine precisely. Fuzzy classification techniques show great promise in this respect, since they admit many grades of class membership (Section 2.6.1).

Secondly, even though strong associations may exist, there are often many exceptions to the rules. Local contingencies can either upset an otherwise regular pattern, or can be responsible for ecological surprises in an area that has been classified as homogenous (Phillips, 2004). In other words, although landscapes may be highly organised, they are not precisely organised. Again, fuzzy approaches offer new opportunities to use classifications to reveal dissimilarities within classes. Rather than just focus on similarities, fuzzy classifications offer the possibility of using graded class membership to identify locations that do not fit the class archetype, identifying those locations where transferred knowledge about class characteristics and behaviour may not be apply and ecological surprises are likely.

Human modifications

The vast extent of human modifications to landscapes is well documented (e.g. Vitousek *et al.*, 1997; Crutzen & Stoermer, 2000; Millenium Ecosystem Assessment, 2005). Indeed, in most circumstances it is impossible to disentangle natural systems from human systems. However, this thesis focuses on biophysical patterns, marginalising both humans and animals as system

components, drivers and controls. This focus was adopted partly to facilitate the adoption of the soil-landscape model (Section 2. 6) and partly to avoid the complications associated with moving organisms that interact with the biophysical template in many different ways in different locations and times.

3.4.2 Network, patch and gradient perspectives of landscapes

Thus far, this chapter has framed the new conceptualisation of savanna landscapes presented in this thesis in terms of seeking to describe clusters of biophysical attributes that result from the dependence of many ecological processes on the availability of water in semi-arid systems. It has been suggested that these clusters can be conceptualised as a biophysical template upon which other ecological processes (such as the use of resources by animals or the spread of fire and flood) are played out. However, there are many ways of conceptualising and representing this template: it can be considered in terms of a mosaic, of discrete patches, as an overlay of graduated fields representing various environmental attributes or as a network of hydrological or other flows.

The *patch mosaic* conceptualisation, as developed within the American school of landscape ecology (Section 2.3.2) offers a useful way of treating landscape as a series of spatial objects. The object perspective has the advantage of defining discrete entities that each have a particular character and history. Unlike gradients, landscape patches can be counted, compared, classified and aggregated to create inventories or set management priorities (Couclelis, 1992). Patterns can be quantified using metrics that describe size, shape and neighbourhood relationships (e.g. Li & Wu, 2004). However, often the mosaic concept is not very realistic, since many landscapes show ecotones, or blurred transitions between one patch and the next. Furthermore, conceptualising landscapes as a mosaic of internally homogenous patches entails simplification, ignoring local differences that sometimes turn out to be very important for some processes (Phillips, 2004). Although the importance of connectivity and the nature of boundaries is theoretically recognised in both the hierarchical patch dynamics paradigm and the patch-corridor-matrix model (see Section 2.3.2), patches are generally visualised in two-dimensional categorical maps that fail to communicate connectivity or boundary characteristics (McGarigal & Cushman, 2005; Cushman *et al.*, 2010a).

Gradient, or field, perspectives are used to represent gradations in a single field, such as elevation or vegetation cover. The advantage of this conceptualisation is that local differences can be preserved and contentious boundary issues are completely avoided. Although statistical correlations between overlaid maps of different fields can reveal geographical clusters, multidimensional feature space is hard to visualise. Furthermore, such clusters need to be interpreted within a conceptual model or framework before they can be given ecological significance or meaning (e.g. Aldrich, 1995; McIntire & Fajardo, 2009).

Whilst terrestrial landscapes are usually described in terms of gradients or patch mosaics, rivers are usually portrayed as linear *networks.* In network perspectives, connectivity is emphasised, rather than areal cover or neighbourhood relationships. The description of flow patterns is essential to understanding the distribution of aquatic species and hence to aquatic

conservation planning and management (e.g. Abell *et al.*, 2012). Furthermore, the effects of pollution are propagated both downstream and upstream, such that connectivity is an important consideration when planning to mitigate or prevent negative effects on water quality or sediment load networks (e.g. Omernik & Bailey, 1997).

One of the challenges in uniting aquatic and terrestrial landscape perspectives is to marry a network perspective of streams, in which the focus lies on the connectivity along linear pathways, with a terrestrial patch perspective in which the focus is on a mosaic of areal units. This marriage involves realising that network, patch and gradient perspectives are not mutually exclusive. It is possible both to construct hybrid perspectives and to move between different perspectives on the same piece of land to take advantage of the benefits of each conceptualisation.

Patch and network perspectives have been married by many authors who conceive stream systems in terms of patches that are connected by hydrological flows (e.g. Pringle *et al.*, 1988; Ward *et al.*, 2002; Poole *et al.*, 2004; Section 2.7.2). Similarly, the conceptualisation underlying many models of hillslope hydrology is that preferential surface and subsurface hydrological flow paths connect terrestrial patches (e.g. Beven & Freer, 2001; Tague & Band, 2004).

Network and gradient perspectives are combined in Petts and Amoros (1996) fluvial hydrosystem, in which hydrological flows are responsible for the clinal patterns observable in four dimensions. Indeed, discontinuities in these gradients are often associated with breaks in network connectivity, where the flow/sediment regime is altered by changes in the geological substrate (e.g. forming a knickpoint), land cover, dams or channelisation (Minshall *et al.*, 1983; Ward, 1998; Poole, 2002).

Gradient and patch perspectives blur when fuzzy classification methods are used to define membership to spatial objects (Couclelis, 1992). In fuzzy classification, class membership is graded, as opposed to binary yes/no membership used in crisp classifications. Fuzzy membership values for a particular class can therefore be mapped both as a gradient, using a field to contain the various values and a raster representation as a patch, where a threshold value defines patch boundaries. Alternatively, a feature map can be produced, in which pixels are assigned to the class for which they have the highest membership value, generating a patch mosaic.

3.4.3 Integrating hillslopes and channels

Combining the network, patch and gradient perspectives allows the development of a conceptualisation that describes both hillslopes and channels, merging perspectives from terrestrial and aquatic ecology. The key is to stop viewing channels as separate entities from the hillslopes that drain into them. As Davis reminded us, rivers and hillslopes are part of the same system: although rivers might appear to be like the veins of a leaf, broadly viewed, rivers and hillslopes together make up the entire leaf (Davis, 1899 p. 495).

In fluvially incised landscapes, the spatial configuration and morphology of hillslopes and hillslope units is largely determined by the structure of the drainage network. Thus, when

drainage basins are viewed as 'entire leaves', hillslopes are placed in the context of place within the drainage network. As Huggett (1975 p. 7) noted, the soil-landscape model is 'a systematic expansion of the proposition that the valley basin … is the basic organizational unit of soil systems' (Rowe, 1996 p. 16) had the same insight, but related it to the spatial organisation of entire ecosystems, rather than just the soil component of the system:

> *''two of the enduring or slowly changing terrain features that are visible at the earth's surface – landforms and the drainage patterns that help to reveal them – are also among the most important for understanding ecosystems and their sites'' (Rowe, 1996 p. 16)*

Furthermore, it is no longer necessary to distinguish sharply between hillslope flow paths and stream channels, between colluvial and alluvial processes or to decide whether to treat ephemeral streams as part of a terrestrial or an aquatic system (see also Willgoose *et al.* 1991). As Conacher and Dalrymple pointed out:

> *"Drainage basins, seen as 3 dimensional landscape entities, comprise a continuum rather than a sharp distinction between 'slope' and 'stream' processes." (Conacher & Dalrymple, 1977 p. 128)*

Despite these insights, drainage basins or catchments are rarely used as basic spatial entities for digital soil mapping or the classification of landform types, and the conceptualisation remains undeveloped (Dehn *et al.*, 2001). Schmidt *et al.* (1998) recognised the congruence between hydrological and geomorphological classifications, identifying catchments and landforms as hydrological objects that could be described and classified. Band (1989, 2005) and Wood (1996) both described how to define a framework of individual hillslopes by intersecting channels and ridges. However, neither of these authors proposed that these hillslopes could be characterised as landform units for either geomorphological or hydrological classifications (MacMillan & Shary, 2009).

However, once hillslopes and channels are integrated, the conceptualisations and tools developed to describe and analyse the spatial organisation of river systems become relevant to the description of terrestrial systems, and indeed, entire landscapes. For example, stream ordering systems provide a convenient way of describing network position and of contrasting streams of similar sizes and stream power (Horton, 1945; Strahler, 1957). Extending such a system to include the hillslopes that drain into a particular order stream allows such descriptions to cover the whole landscape. The hillslopes draining into each stream segment can be delineated within subcatchments or CASSs (Contributing Areas to Stream Segments). CASSs are similar to the concept of 'hillslopes' used in the RHESSys model of hydrological and ecological fluxes (Band, 1989; Tague & Band, 2004), except that CASSs extend over both sides of the stream and specifically include the channel area.

Each CASS can be described in terms of the order of the stream segment it drains into (Figure 3.3). Thus the patterns of soil, vegetation and morphology associated with first order streams and the hillslopes in their associated catchment areas can be examined and compared, as can

patterns associated with second, third, fourth and higher-order streams and catchments (Huggett, 1975; Gerrard, 2000; Khomo, 2008, Rogers, K., pers.comm.).

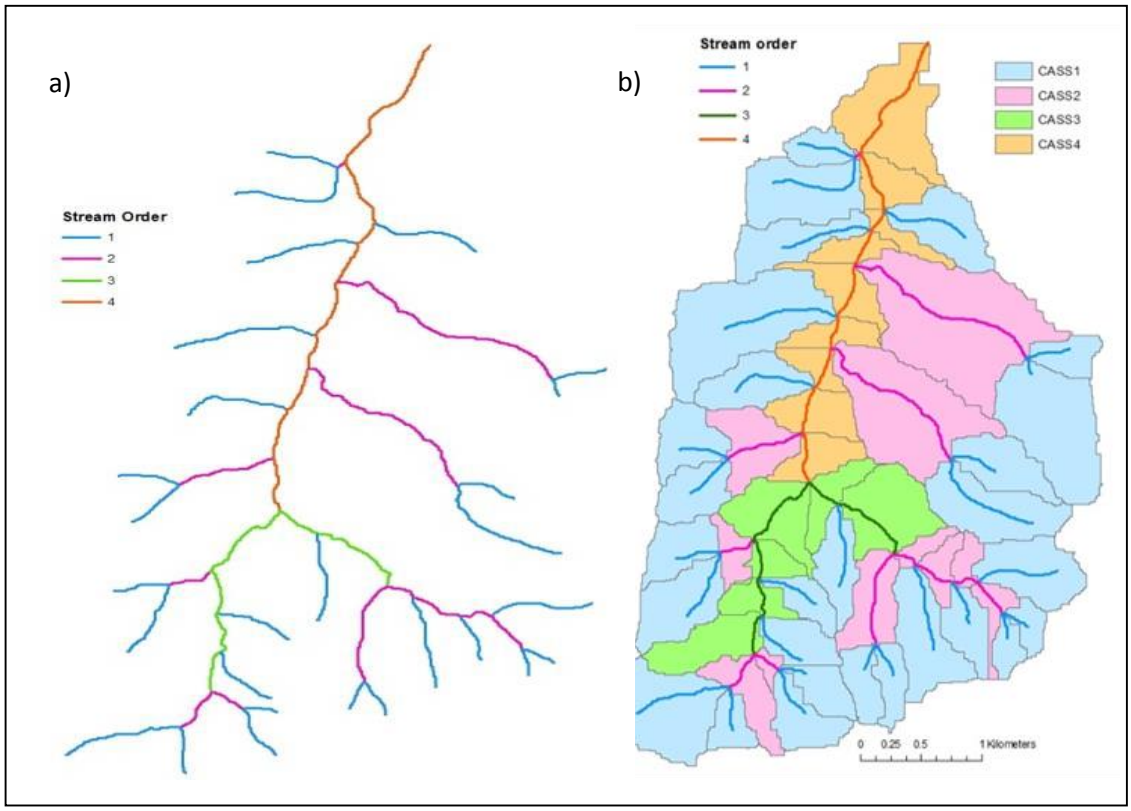


Figure 3.3: Horton-Strahler stream order.

a) Source streams are defined as 'first order'. When two streams of the same order join, stream order increases by one, such that when two first order streams join, a 'second order' stream is formed, when two second order streams join a 'third order' stream is formed and so on (Horton, 1945; Strahler, 1957). b) Extending the stream order concept to hillslopes, CASSs (Contributing Area to Stream segments) can be labelled with the stream order of the stream segment that they drain into.

Once hillslopes are conceived as being organised by the structure of the drainage network, an integrated landscape conceptualisation begins to emerge. Terrestrial and aquatic perspectives are combined in this framing of a dynamic landscape in which a terrestrial patch mosaic is connected by a network of water fluxes in space and time, forming a highly organised template for a wide variety of ecological processes. Patterns of channels and hillslopes associated with network position have been described and explained within both fluvial geomorphology and ecology (Schumm, 1977; Cullum *et al.*, 2008). Furthermore, these patterns underpin widely-used river classifications (e.g. Frissell *et al.*, 1986; Rosgen, 1994; Bohn & Kershner, 2002; Rogers & O'Keefe, 2003; Brierley & Fryirs, 2005; Thorp *et al.*, 2010). It is but a short step to synthesise these conceptualisations and to include soil-landscape models (Section 2.6), to lay the foundations for an integrated conceptualisation of savanna landscapes.

3.4.4 Bounding the domain of discourse

In this Section, I have bounded the scope of the conceptualisation that will be further developed below. The purpose of the conceptualisation is to describe clusters of coupled

biophysical attributes that result from the dependence of many ecological processes on the availability of water in semi-arid systems. These clusters are conceived as a biophysical template that provides contextual constraints on a wide range of other ecological processes, such as the use of resources by animals or the spread of fire and flood. The template is conceived as a dynamic patch mosaic that is connected by fluxes of water and sediment across and through both hillslopes and channels. The mosaic is highly organised, since the spatial organisation of hillslopes is structured by the river network. Although disturbance regimes, bio-engineering and human activities are also important components of the template, the focus here is the key components of soil-landscape models upon which this conceptualisation is largely based: soil, water, topography and vegetation.

3.5 Couclelis Level 6. Function: Linking pattern to process

At this level of the ontology, theory is invoked to link pattern and process. A purely empirical description of pattern does not carry any ecological meaning, since no mechanism or process is implied to account for the existence of the pattern or to guide inferences about its history and possible future states (e.g. Aldrich, 1995; McIntire & Fajardo, 2009). If the conceptualisation is to be used to make inferences across time and space, or to foresight responses to various scenarios (as in Bohn & Kershner, 2002; Gaines *et al.*, 2013, for example), then observed patterns need to be linked to the processes that generate and sustain these patterns (Aldrich, 1995; McIntire & Fajardo, 2009). Therefore an appreciation of these processes guides the choice of relevant variables and linkages at lower levels of the ontology.

To provide a conceptualisation that is relevant to a wide range of applications, the description of pattern must be relevant to a wide range of ecological processes. Ultimately, all ecological processes are controlled by the availability of a few basic resources and the factors that control the rates at which these resources are processed. These resources include water, sediment, energy, nutrients and shelter, with rates of processing mediated by factors such as temperature, pH, relief (controlling the potential energy available for gravitationally-induced flows) and the frequency and intensity of disturbances such as fire and flood (e.g. Austin, 1985; Guisan & Thuiller, 2005).

Even though system complexity and local contingencies deny us the possibility of building detailed models that are able to predict precise outcomes in every location, many of the processes responsible for the distribution of basic ecological resources are generally understood, at least in terms of broad principles. For example:

- The factors influencing soil formation are known (Jenny, 1941; Paton *et al.*, 1995), even though the relative importance of each factor may vary in different locations. Processes of soil formation are indicated by attributes such as soil colour or mottling, which provide evidence for different degrees of oxidation or saturation (Wysocki *et al.*, 2000).
- The energy available to transport sediment in a stream is well described by the concept of stream power, which relates to the area drained and the gradient of a stream

(Bagnold, 1966). The amount of stream power available varies systematically within a stream network and is both cause and consequence of channel and valley geometry and a wide range of fluvial features (Schumm, 1977). Mental models based on the concept of stream power can therefore be used to link observed features with formative processes (Section 2.7.2).

Since the emphasis in this thesis is on the detection and description of pattern, rather than on detailed explanations of the processes responsible for these patterns, descriptions of broad principles suffice to inform the selection of variables and scales appropriate to the identification of process domains.

3.6 Couclelis Level 5: Conceptual entities and relationships: A hierarchy for the description, analysis and mapping of ecological landscape units in savannas

Construction of the next ontological level of the conceptualisation involves specifying the spatial entities that are to be mapped. Identifying patch mosaics in the biophysical template requires that the MAUP is solved, defining the scales at which it is appropriate to describe e and map spatial clusters of environmental attributes. The most straightforward way of solving the MAUP is to we define *a priori* the types of entity that we seek to observe (Section 3.4.1).

Agreement on the nature and utility of the entities into which landscapes are decomposed is key to the acceptance of the conceptualisation as a platform for shared perspectives and understanding. Indeed, the lack of agreement on the definition of an ecoregion was one of the main stumbling blocks for the NITT (National Interagency Technical Team) set up in 1996 to develop a standardised spatial framework that could be shared between all the US environmental agencies:

> *"The task faced by the NITT was difficult, largely because of the lack of agreement over the definition of ecoregions and how they should be mapped. This problem and its ramifications were noticed by an ecologist who was invited to attend one of the early NITT meetings and who, after observing a day of discussion, was asked for his comments. He responded that it was like watching a group of people packing for a trip without first agreeing on where they were going and learning what the place was like. Instead, he said, they appeared to be throwing things into suitcases without knowing if they would be needed." (Omernik, 2004 p. S28)*

Omernik (2004) describes the way in which the NITT circumvented this issue, not wanting to directly contrast or evaluate the frameworks used by the participating agencies for fear of causing conflict between entrenched views or challenging frameworks in which much money and effort had been invested. Consideration of the politics of spatial frameworks, falls outside the scope of this thesis (Tadaki *et al.*, 2014), which is devoted to the theoretical basis and practical implementation of such frameworks. Ultimately, the NITT process failed to create a hierarchy of spatial objects that represent ecoregions.

Without agreement on the spatial entities to be mapped, it is impossible to solve the MAUP (Section 3.4.1). However, the construction of hierarchy of spatial entities that represent patches in the biophysical template described above (Section 3.4) is no trivial task. The first hurdle is to ensure that the fundamental assumptions of hierarchy theory hold in this context.

A hierarchical perspective of the landscape (see Section 2.2) involves viewing patches of land as components of a system:

- That can be *decomposed* into spatial entities that are internally homogenous and exhibit a stable range of variability, both
    - Vertically, where the entities are separated into different levels of organisation, each of which has a characteristic scale domain, so that units at higher levels are larger in area and change more slowly over time than units at lower levels and
    - Horizontally, where differences between entities are greater than differences within entities
- That is *nested* both in terms of function (i.e. systems that contain subsystems that contain subsystems, etc.) and in terms of geography, in that lower-level units occur at locations within higher-level units. The character of units at a particular hierarchical level is largely determined by processes that occur at lower hierarchical levels, within a range of variability that is contextually constrained by higher level units.

Each of these assumptions is now considered in turn.

3.6.1 Decomposing landscapes into spatial entities

Water has multiple roles within landscapes. Not only is it a vital resource, essential to the survival of all plants and animals, but it also provides shelter and habitat for many organisms, and it acts as a vector transporting materials and energy and as an agent of geomorphic change (Sponseller *et al.*, 2013). Water is also essential for many biochemical processes, including photosynthesis, seed germination, nutrient mineralization, soil weathering and the microbial breakdown of organic matter to name but a few (Rodríguez-Iturbe & Porporato, 2004). A lack of water therefore places severe constraints on ecosystem composition, structure and dynamics. Hence, in places where water is limited, many geomorphological and ecological processes are tightly coupled to the spatial and temporal distribution of water, at various scales (Section 3.4 and Figure 3.2). This coupling results in strong spatial associations between many environmental attributes. For example, the distributions of soils and vegetation are both strongly linked to the distribution of water in semi - arid settings. Since water generally flows downhill, topography is an important control on the distribution of water in a landscape, with water tending to drain off crests into valley bottoms. These flows often generate toposequences of patches with strong soil-vegetation associations that recur at certain hillslope positions, as described in soil-landscape models (Section 2.6). Each patch in the toposequence can be characterised by a water budget that is both cause and consequence of a particular combinations of soils, vegetation and topography.

The patch mosaic formed by these toposequences provides the starting point for my conceptualisation of savanna landscapes. The mosaic is conceived as a biophysical template that sets environmental limits for a vast range of ecological processes and features, controlling the availability of basic resources such as water, nutrients and the plant cover that provides food, shade and concealment for a vast range of biota (Section 3.4.1).

Toposequences tend to recur repeatedly on the hillslopes in a particular setting, where landforms, soils and vegetation have co-evolved with biota, creating a landscape that is characteristic of a particular geological and climatic setting (e.g. Salthe, 1985; Salthe & Matsuno, 1995; Jenerette *et al.*, 2012; Pelletier *et al.*, 2013). Particular advantages are gained by appraising these relationships in river systems, as they are highly organised, such that the hillslopes and channels within a particular setting tend to have characteristic hillslope lengths, gradients, morphology and topographic grain (e.g. Pike *et al*., 2008; Partridge *et al*., 2010). Channel geometry, landforms and water fluxes also tend to change systematically within a stream network, so that the channels and associated landforms found at a particular position in the stream network tend to be similar in both character and behaviour (Section 2.7.2). Situating hillslope toposequences within the structure of the stream network allows us to describe the structure of the entire landscape, integrating aquatic perspectives of river systems with terrestrial perspectives of hillslope soils, vegetation and hydrology (Section 3.4.3). This not only means that knowledge linking form and process within soil science and terrestrial ecology can be linked with similar knowledge from fluvial geomorphology, but also that experience in soil classification and mapping at hillslope scales can be married with experience in river classification at coarser scales. Both classification approaches can be brought together in an integrated landscape hierarchy, within which distinct spatial entities can be identified.

3.6.2 A nested hierarchy of terrestrial and aquatic landscape units

Building upon the various premises and constructs outlined earlier in this chapter, the integrated landscape hierarchy developed in this thesis focuses on three nested organisational levels, each of which can be decomposed into distinct spatial entities (Figure 3.4):

- **Catenal elements** are parts of a hillslope that have distinct water budgets that are both cause and consequence of a particular combination of plant cover, soil, hillslope characteristics and hillslope position. Channels are also conceived as catenal elements, such that toposequences of catenal elements fill an entire catchment or subcatchments, from the watershed right down to the channel.
- **Catchments and CASSs** are areas of land that drain to a particular point (catchments) or to a particular stream segment (Contributing Area to a Stream segment: CASS, see Section 3.4.3). Catchments and CASSs contain toposequences (assemblages) of catenal elements that are connected by fluxes of water that flow across and through hillslopes to the network of channels.
- **Physiographic zones** are areas with distinct patterns of channels and hillslopes that are both cause and consequence of catchment hydrology, soils and vegetation. Within a physiographic zone, catchments in a particular network position tend to have similar

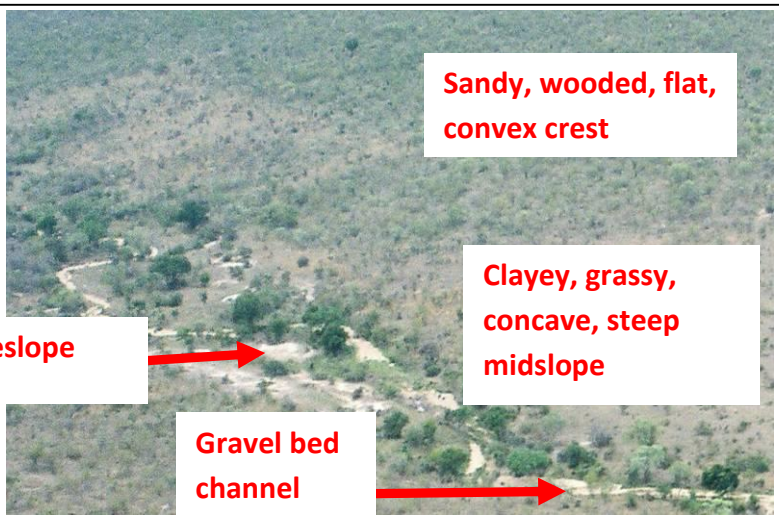
relief and geometry, with catchments and CASSs containing recurring assemblages of catenal elements that are configured in sequences that typify the zone.

The possible character and behaviour of units at each organisational level are constrained by their position within the hierarchy, which are described in relation to the context in which they occur (see Section 2.2). For example, the character and behaviour of catenal elements are determined by their hillslope position within a catchment and by the position of the catchment (and/or CASS) within the stream network. Similarly, the character and behaviour of catchments and CASSs are limited within a range of possibilities imposed by the climate and geology of the physiographic zones in which they occur. In addition to these 'vertical' constraints', horizontal constraints are imposed through neighbourhood relationships and connectivities. For example, upslope catenal elements may (or may not) deliver water to downslope elements and the amount of rainfall in headwater catchments affects the erosive capability of streams further downstream.

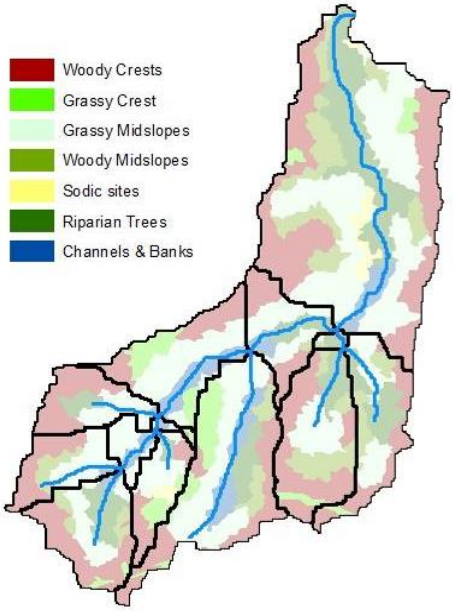
Network position has profound influence on biotic and abiotic system components both at the level of catenal elements and at the level of catchments and CASSs. Morphological differences in hillslopes and channels vary systematically with stream order (Horton, 1945; Hack, 1957; Gregory & Walling, 1973) and biological differences accompany these changes (Vannote *et al.*, 1980; Benda *et al.*, 2004; Bellmore & Baxter, 2014), even though patterns may be disrupted by geological features, large tributary junctions or human interventions (e.g. Ward & Stanford, 1983; Benda *et al.*, 2004; Thorp *et al.*, 2006; Ferguson *et al.*, 2006; and see Section 2.7.2)

Each level of the landscape hierarchy is now considered in more detail.

CATENAL ELEMENTS are areas that have distinct water budgets, plant cover, soil, slope characteristics and slope position.



CATCHMENTS and CASSs contain sequences of catenal elements



PHYSIOGRAPHIC ZONES each have distinct topographic signatures, characterised by different stream densities, landforms and morphologies

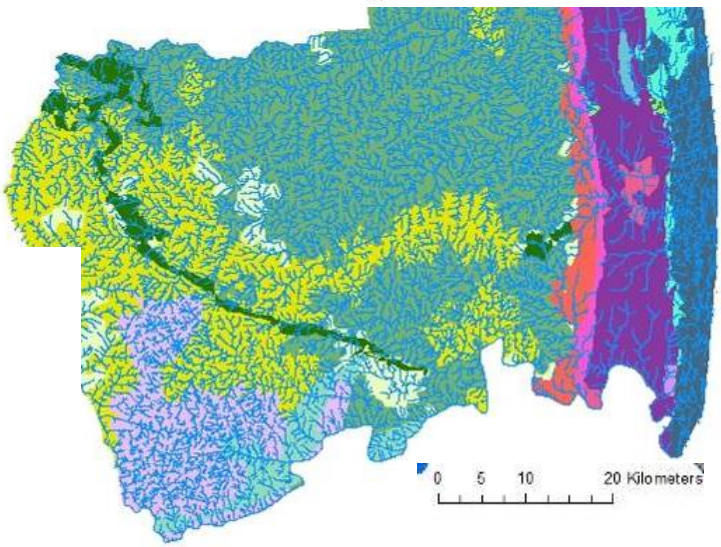


Figure 3.4: A hierarchy of structural-functional units in savanna landscapes. Rivers and hillslopes are integrated at each hierarchical level.

3.6.3 Catenal elements

Definition of catenal elements

Catenal elements are hillslope components that have distinct water budgets that are both cause and consequence of a particular combination of plant cover, soil, hillslope characteristics (e.g. gradient, curvature and aspect) and hillslope position. Catenal elements are equivalent to the hillslope-scale Hydrologically Similar Surfaces (HYSS) that have been described and modelled by hydrologists (e.g. Flugel, 1995; Bull *et al.*, 2003; Tague & Band, 2004; Wagener *et al.*, 2007). These framings are commonly used to describe flow regimes in ungauged basins (Sivapalan, 2006; Hrachowitz *et al.*, 2013). HYSS (also called Hydrological Response Units, amongst other names) are spatial entities that have a common climate, land use and underlying pedological, topographical and geological associations that control their hydrological dynamics, producing dominant processes that are characteristic of the area(e.g. Flugel 1995; Grayson & Bloschl 2000; Sivakumar 2004). Catenal elements can also be considered as three-dimensional equivalents of the soil-vegetation units described in the toposequences of the catena model and Conacher and Dalrymple's (1977) 'nine unit' model (see Section 2.6.1). However, unlike these conceptual models, river reaches are also considered to be catenal elements, so that the entire landscape can be partitioned into catenal elements.

Catenal elements are all connected by surface and subsurface hydrological flow paths along which water transports solutes and sediment across and through the catchment. Thus the water budget associated with a particular catenal element depends not only on the combination of vegetation and soils occurring within the unit, but also on the position of the element within the catchment and the nature of its boundaries with neighbouring units. For example, downslope units may receive water from upslope units, providing that the boundary between the units is permeable. Thus the overall capacity of a catchment or CASS to store, transmit or receive water depends both on the composition of an assemblage of catenal elements and on its structure (i.e. how catenal elements are arranged within the CASS or catchment).

Most catchments contain a channel (bed and banks of a stream), and a riparian zone (riparian area and floodplain) in the valley bottom. The middle zone between the valley bottom and the crest may be subdivided into footslopes, midslopes, and /or shoulders. Crests straddle catchment boundaries across a watershed. Not all of these components are necessarily present in all settings and in some settings important hydrological differences may also occur between divergent and convergent hillslopes, and/or between hillslopes with different aspects. In some circumstances, features such as scarps, large rocky outcrops, terraces, local depressions and alluvial fans may be of a size and frequency to merit a separate class.

Microfeatures are produced by local interactions between water, soils and vegetation at scales finer than those associated with catenal elements. However microfeatures are not constitutive parts of catenal elements in the same way that catenal elements are constitutive parts of catchments or CASSs. Microfeatures are not systematically arranged within catenal elements, nor can entire catenal elements be decomposed into microfeatures. However, particular types

of microfeatures are often closely associated with certain catenal elements within a given setting. Not only do catenal elements provide contextual constraints on the types of microfeatures they can contain, but the microfeatures also feed back to shape the character and behaviour of catenal elements. For example, termite mounds are strongly associated with sandy crests in the southern granites of KNP (Levick *et al.*, 2010), and are likely to have a large influence on the water budget of crests in this area. Similarly, step pool sequences are commonly found in the gravel beds of ephemeral streams in this area, providing temporary water storage that supports plants and animals alike.

Spatial and temporal domains characteristic of catenal elements

In my conceptualisation of savanna landscapes, the persistence of systems in a certain state is conceived as a range of variability that is bounded by contextual constraints, either imposed by neighbours on the same organisational level, or by higher organisational levels in a landscape hierarchy (Sections 2.2 and 3.6.2). This range of variability is scale-dependent, in that variability generally decreases as temporal and spatial scales become coarser (Openshaw, 1984; Turner *et al.*, 1989). To define the likely range of variation that can be observed at the spatial scales associated with units in each organisation level in the landscape hierarchy, it is therefore necessary to specify the time scales over which these are to be observed.

Periods of 10-30 years and spatial scales of 1-100km^2 are appropriate to the land management and planning applications that the conceptualisation developed in this thesis aims to inform (Section 1.1). Thus seasonal changes and changes associated with relatively small and frequent disturbances (e.g. fires and floods with a 10-20 year return period) are all considered to be part of the range of variability of catenal elements. The intra- and inter-annual variability associated with these changes therefore needs to be accommodated within descriptions of catenal elements.

In theory, catenal elements can occur on the hillslopes of catchments of any steam order. Indeed, nested patterns of catenal elements can potentially exist, in which soil-vegetation patterns associated with catchments of different stream orders are superimposed upon each other. In practice, catenal elements will most usefully be delineated in CASSs where the lowest stream order considered is bounded by hillslopes that have vegetation and soil toposequences that can be clearly observed in the field and/or in available imagery. In the savannas of KNP, this means that small gullies with slopes that are either grassy or bare (due to earth movement) are not partitioned into catenal elements. The size of the smallest catenal units considered will therefore vary between landscapes, depending on hillslope length and the degree of variability of vegetation and soils.

3.6.4 Catchments and CASSs

Catchments are defined as areas that drain to some given point in the landscape. However, in practice, catchments are normally delineated either in relation to the ultimate outlet of a stream (such as the point where a river meets the sea), or in relation to tributary junctions.

In this thesis, catchments are defined in two ways. Firstly, catchments are defined as areas drained by the whole of a stream of a particular stream order, using the Horton-Strahler

method of stream ordering (Horton, 1945; later modified by Strahler, 1957) (Figure 3.3). Secondly, CASSs are areas that drain into a stream segment located between two tributaries, between the source and the first tributary junction or between a tributary junction and an outlet such as a lake, or the sea (Section 3.4.3). CASSs may be described in terms of the order of the stream that they drain into (Figure 3.5). Catchments associated with each stream order do not cover the entire landscape, but are separated by 'interior' or 'adjoint' catchments. Therefore, CASSs are used when it is necessary to partition the entire landscape (Figures 3.6 and 3.7).

CASSs are useful descriptors of the position of a stream within the drainage network, with implications for the amount of water received from upstream, channel and hillslope morphology and the stream power available to transport sediment and shape landforms, as described in theories of fluvial geomorphology (Schumm, 1977; Cullum *et al.*, 2008). For example, first order CASSs draining into 2nd order CASSs are situated high in the headwaters. They tend to have relatively steep slopes and narrow channels. In semi-arid settings, high order streams are often ephemeral, rarely holding surface water, but with flashy hydrographs, flowing rapidly soon after rainfall. Higher order CASSs occur progressively further downstream and usually contain gentler slopes, wider channels and are more likely to hold seasonal or permanent water.

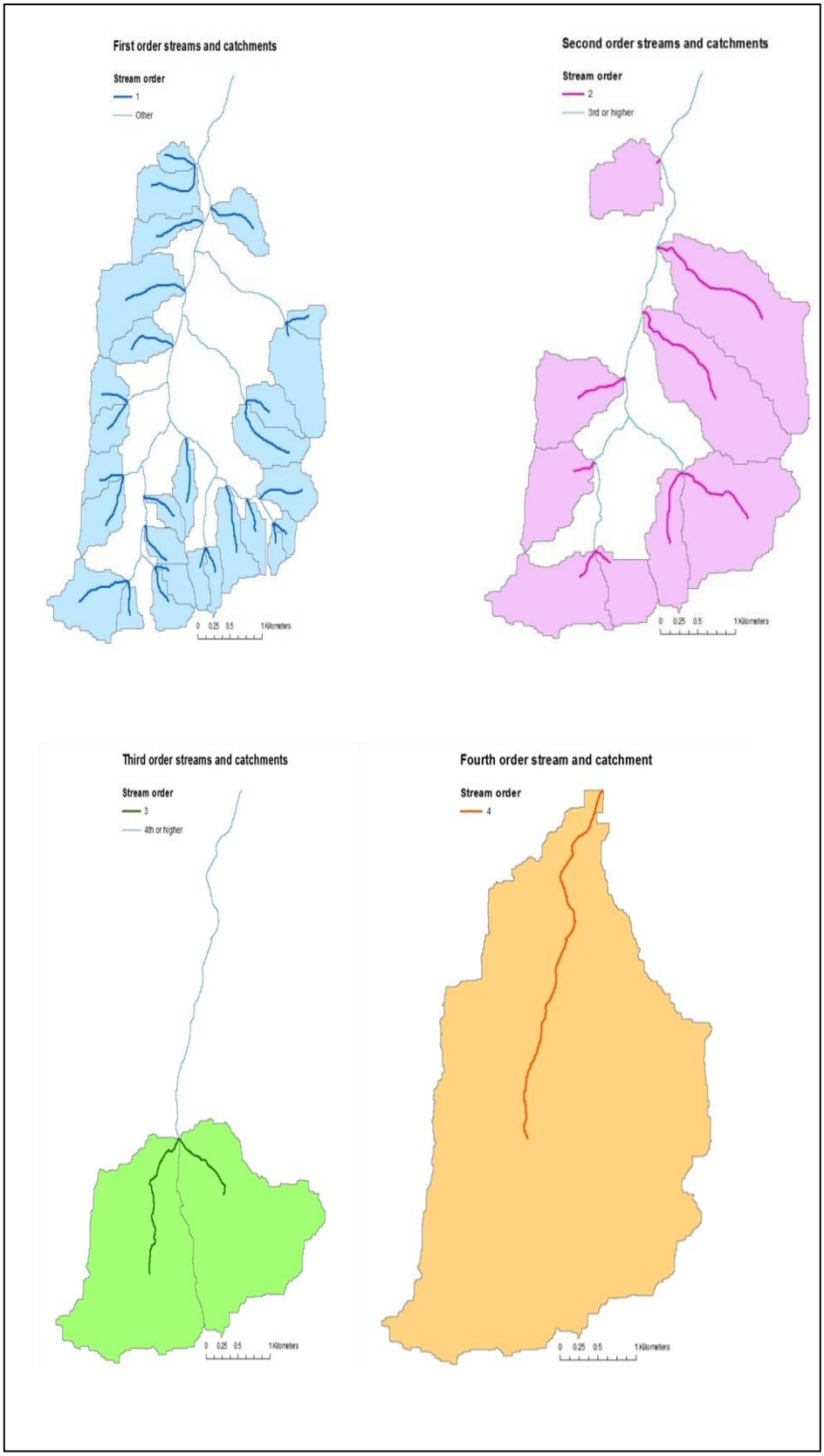


Figure 3.5: Catchments of different stream orders.

Catchments defined in relation to streams of different orders nest within each other, potentially forming several sub-levels of the hierarchy.

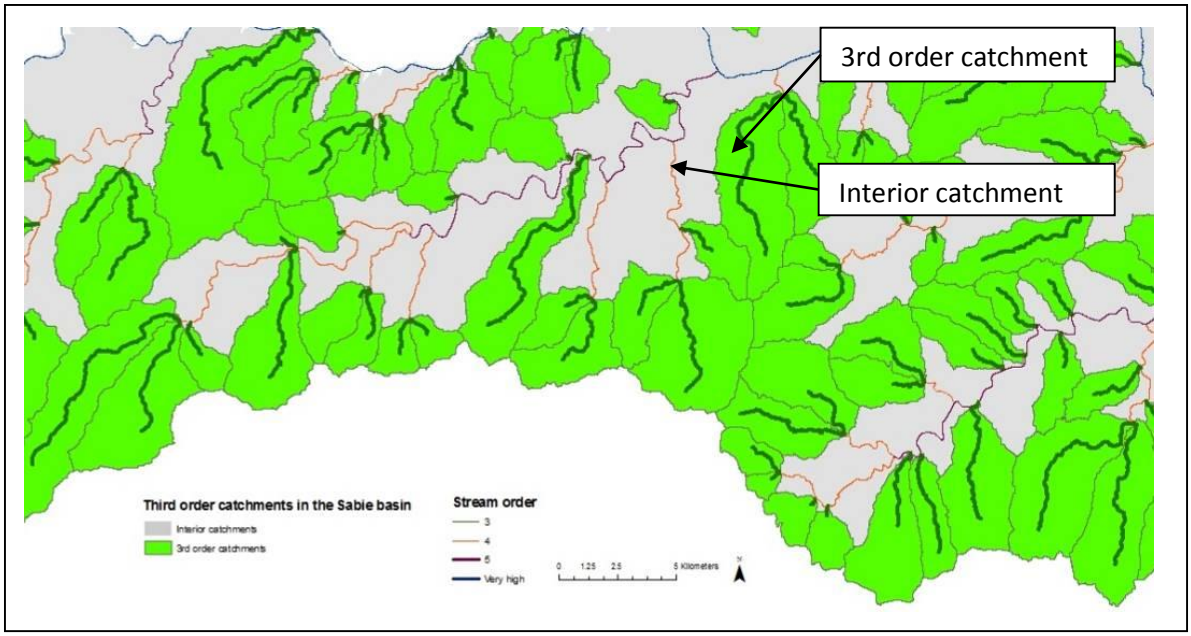


Figure 3.6: Third order catchments in the Sabie River basin.

Catchments associated with each stream order do not cover the entire landscape, but are separated by 'interior' or 'adjoint' catchments.

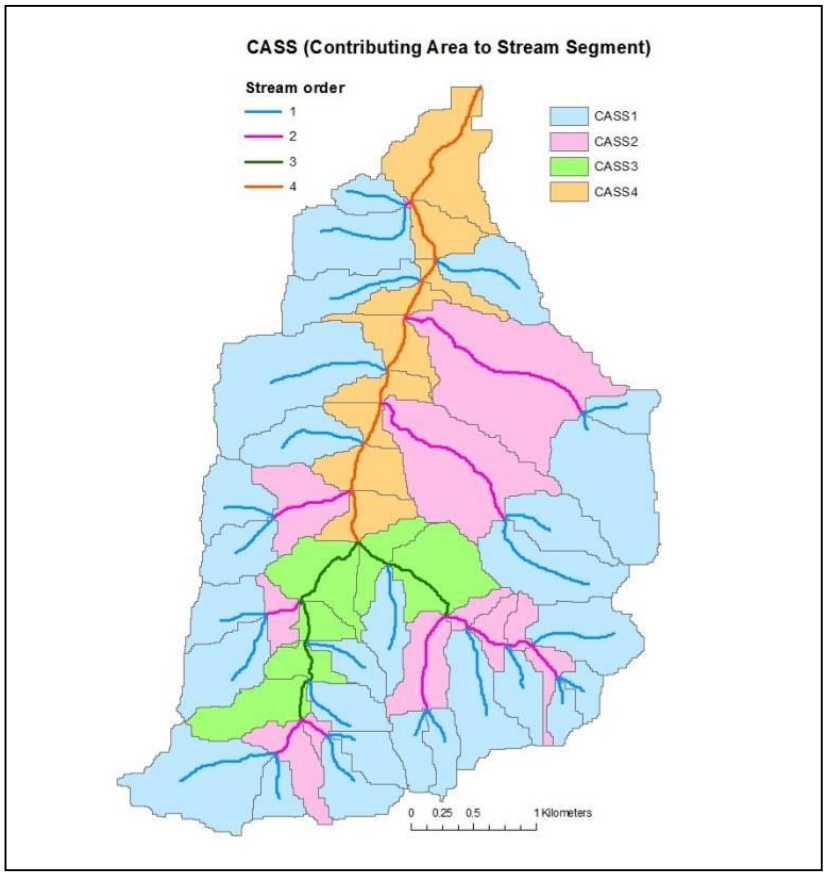


Figure 3.7: CASSs of different stream orders.

Contributing areas are numbered according to the order of the stream segment they drain into, which provides an indication of the position of a CASS within the drainage network.

However, although the Strahler-Horton system of stream order is convenient and easy to apply, it has several shortcomings (e.g. Gregory & Walling, 1973; Hughes & Omernik, 1981; Hughes *et al.*, 2010).

- The system is very scale sensitive, particularly for low stream orders. At fine scales, many more channels are mapped than at coarser scales, so that the same stream segment can be classified as first order at one scale, but as a much higher order when mapped at a fine scale.
- If maps have been prepared inconsistently, stream order will not be comparable across regions. This is an issue of great concern in the U.S., where there are inconsistencies arising from the amalgamation of maps with differences in scale, procedures for including (or omitting) ephemeral or very small streams, and the season or year of mapping (Hughes & Omernik, 1981; Hughes *et al.*, 2010).
- In some areas streams are very difficult to map and have indeterminable positions. For example, many streams are ephemeral, intermittent or not distinctly channelized and slopes do not always drain to streams (e.g. in arid regions, karst geology).

These are all essentially mapping challenges that have been resolved in the 1 50 000 topographical maps of the KNP area that are used for this study. These maps have all been prepared to the same scale and in a consistent manner, using topographical and vegetation cues to determine the course of ephemeral streams (see Section 5.2.2 below for more detail).

- Stream ordering systems are confounded by deltas and side channels.

This is not an issue in KNP, where these network patterns are not present.

- A large number of tributaries can enter a channel, greatly increasing the size and power of a stream, but without altering the stream order. Conversely, the entry of a small stream can raise the stream order of the trunk channel.
- Streams emerging from lakes, wetlands, springs, and glaciers may have higher stream power than suggested by their stream order.
- Altered flows (dams, channelisation, etc.) can distort the relationship between stream order and stream power.

These criticisms have led to the use of alternative stream numbering systems (e.g. Shreve, 1967) or measures such as catchment area or mean annual discharge as better indices of stream relative stream power than Strahler-Horton stream orders. However, I do not use stream order as a proxy for stream power, but merely as an indication of network position.

- Stream orders reflect processes of channel initiation. In some geo-climatic settings, headwaters are characterised by many short ‘fingertip’ streams, which join to form higher order streams over short distances, whilst in other areas, headwaters may consist of a large waterlogged area from which a single stream emerges. This means

that streams of the same order in different geo-climatic settings may be associated with different stages of development of the stream.

This criticism means that care needs to be taken when comparing the character and behaviour of streams of the same order in different physiographic zones. However, it can also be turned to advantage, as such comparisons reveal differences associated with a change in process, signalling a possible physiographic zone boundary.

- In some circumstances, stream order is a poor indicator of network position. First/low order streams draining into a main stem of a much higher order are likely to differ in character and behaviour to first/low order streams in the headwater region of a river. For example, the geomorphic effect of a tributary junction changes according to the difference in stream order between the stem and the tributary joining the stem. The junctions of small, low-order streams and high-order stems are associated with far smaller geomorphic impacts than occur when the stem and the tributaries are of a similar order (Statzner *et al.*, 2003).

This is a valid criticism. It is highly unlikely that first order streams and CASSs joining second order streams are similar in character and behaviour to first order streams joining a high order stem. Whilst the former are located in headwater zones of sediment production, the latter occur downstream in zones of sediment transport or deposition (Schumm, 1977 and see Section 2.7.2). Therefore, when using Strahler-Horton stream orders to describe network position it is advisable to split first and second order streams into separate categories that depend on the order of the stem they drain into (i.e. a first order stream draining into a second order stem is separated from a first order stream that drains into a fourth order stem, etc.).

Despite these shortcomings, the Strahler-Horton system of stream ordering serves as a convenient entry point for the consideration of network position, particularly when derived from a consistently produced map of streams, such as the topographic maps of KNP used for this project.

Catenal assemblages within catchments and CASSs

The distribution of water is not only systematically organised between CASSs, but also within CASSs, where catenal elements are also organised into toposequences that are repeated throughout a physiographic zone, as described by soil surveyors (see Section 2.6.1, Milne 1935; Christian, 1958; and others). The arrangement of catenal elements within these toposequences is both cause and consequence of the hydrological connectivity between catenal elements, determining the spatial and temporal availability of water at different hillslope positions. Feedbacks between morphology, soils, vegetation and water movements create highly organised landscapes that contain predictable arrangements of catenal elements (Figures 3.2 and 3.8).

Assemblages of catenal elements also vary systematically with network position. For example, toposequences in higher order CASSs are more likely to contain floodplains and other alluvial landforms, whilst such forms are either very small or non-existent in low order catchments.

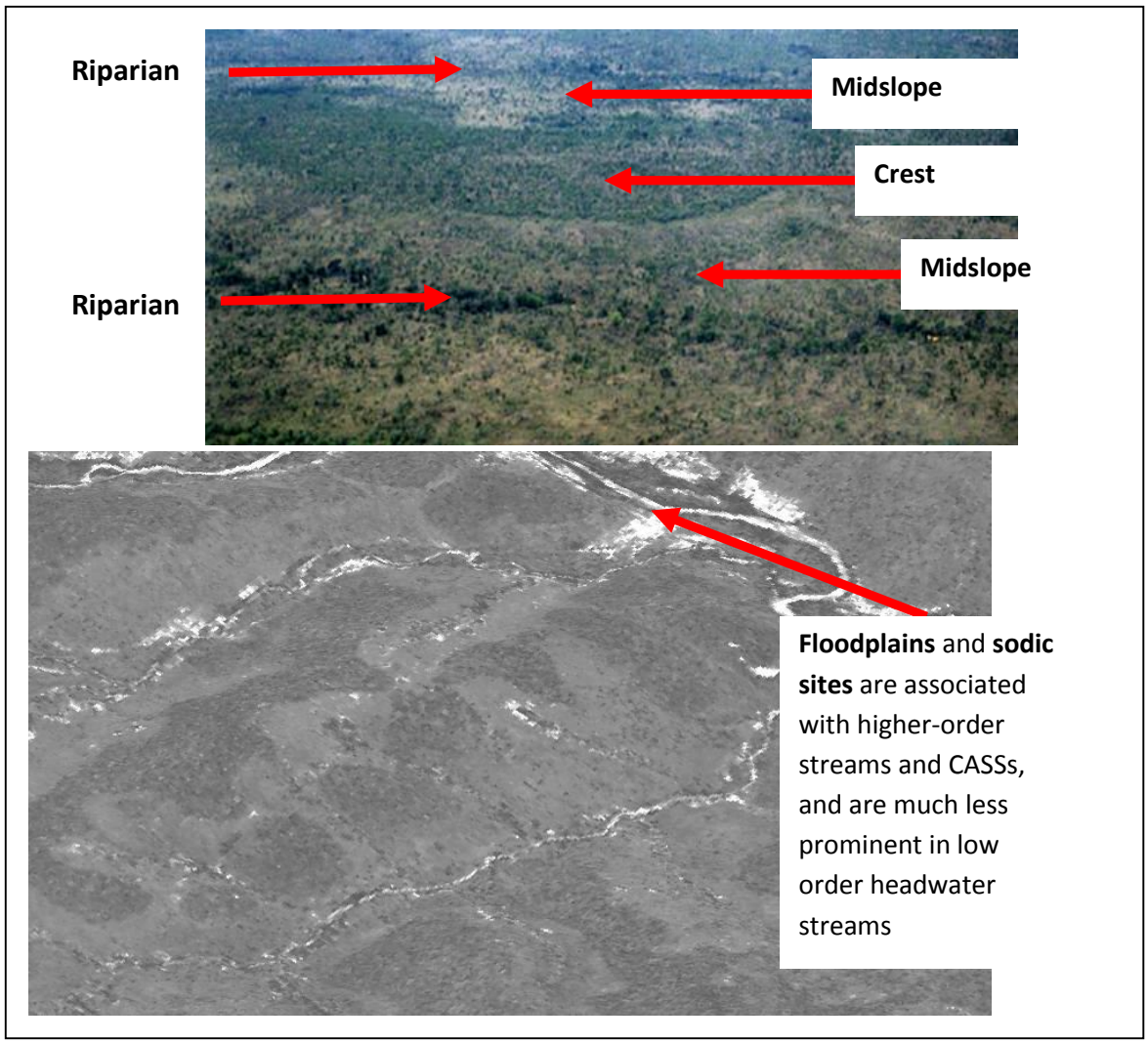


Figure 3.8: Assemblages of catenal elements in the southern granites of KNP.

The same sequences of catenal elements are repeated throughout the landscape. Photo: KR Oct 2004, Image: SPOT 5 pan layer draped over Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM) (Farr et al.*, 2007).*

3.6.5 Physiographic zones

Physiographic zones are areas with distinct patterns of landscape dissection within a geological region (Figure 3.9). Patterns of landscape dissection have been described in terms of hillslopes and relief, where zones are described in terms such as 'rolling hills', 'high mountains' or 'hummocky plains' (e.g. Hammond, 1964; Dikau, 1989; Dobos *et al.*, 2005). Others have described differences between physiographic zones in terms of drainage density (e.g. Horton, 1945; Tucker *et al.*, 2001) or the complementary measure of valley spacing (e.g. Wood & Snell, 1960; Perron *et al.*, 2009). Still others have described regional in channel head source area (Montgomery & Dietrich, 1989) or patterns of the stream network (e.g. Howard, 1967). Conversely, there have been various attempts to use variations in topography and drainage patterns to detect geological features such as fractures and faults and to map geological regions (see Coblentz *et al.*, 2014).

All these approaches are describing the same phenomenon, which results from the interplay between factors driving erosion (e.g. rainfall, runoff, relief and sediment availability) and factors resisting this erosion (e.g. vegetation cover, soil drainage characteristics). Landscapes shaped by similar processes of erosion under the same climatic and geological history tend to contain distinct patterns of streams and hillslopes, such that geographical clusters of catchments and CASSs of the same stream order have similar areas, relief and gradients, with similar spacing between ridges and channels. Collins and Bras (e.g. Collins & Bras, 2010) have used a landscape evolution model to demonstrate how a gradient of mean annual precipitation is expressed in the topography of semi-arid, water-limited ecosystems (assuming the same geology). They found that the highest drainage density, greatest relief, and highest concavity are associated with intermediate levels of rainfall in semi-arid areas. In areas with very low rainfall, stream density and relief are low, since there is little water available to do geomorphic work. In areas with higher rainfall (though still semi-arid), stream density and relief are also low, since increased vegetation cover inhibits erosive run-off processes. It has also been suggested that stream density rises again in humid climates as even dense vegetation fails to suppress runoff (Abrahams, 1972).

The interactions between climate, substrate and vegetation not only generate different patterns in the organisation of hillslopes and channels, but different processes are often implicated in the creation of these patterns. For example, the processes controlling fluvial erosion in different parts of KNP are quite different. In areas with geologies that weather chemically to form soils with high water-holding capacities (such as the basalts of KNP, see Venter, 1990), the landscape is relatively flat, with widely spaced streams that form large 'vleis' (wetlands) that are capable of holding large quantities of water. By contrast, the less permeable granites weather physically, with young streams cutting back into ridges and crests to form a dense stream network. Water is not generally stored on or near the surface, but runs off over the slopes and through the very flashy stream network, eroding gullies and incised streams on its way downstream (Figure 3.9, see also Venter, 1990; Riddell *et al.*, 2012).

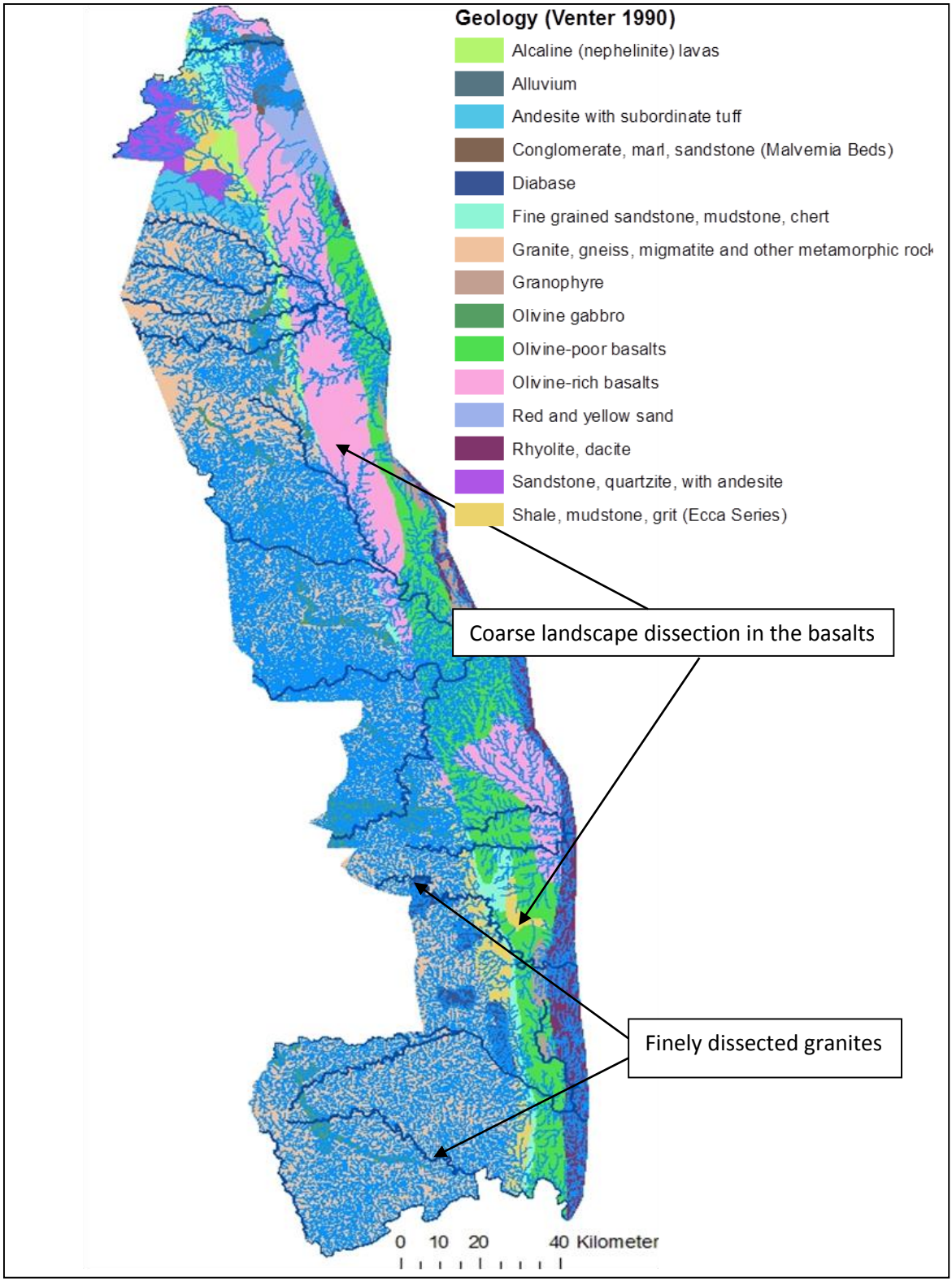


Figure 3.9: Streams of the Kruger National Park, overlaid on geology.

Different patterns of landscape dissection are clearly related to different geologies. Areas with high stream density, such as the granites, have smaller catchments, with shorter and steeper hillslopes than those seen in the flat basalts with low stream density and large catchments. (Geology: Venter 1990, Streams: 1:5000 topographical map)

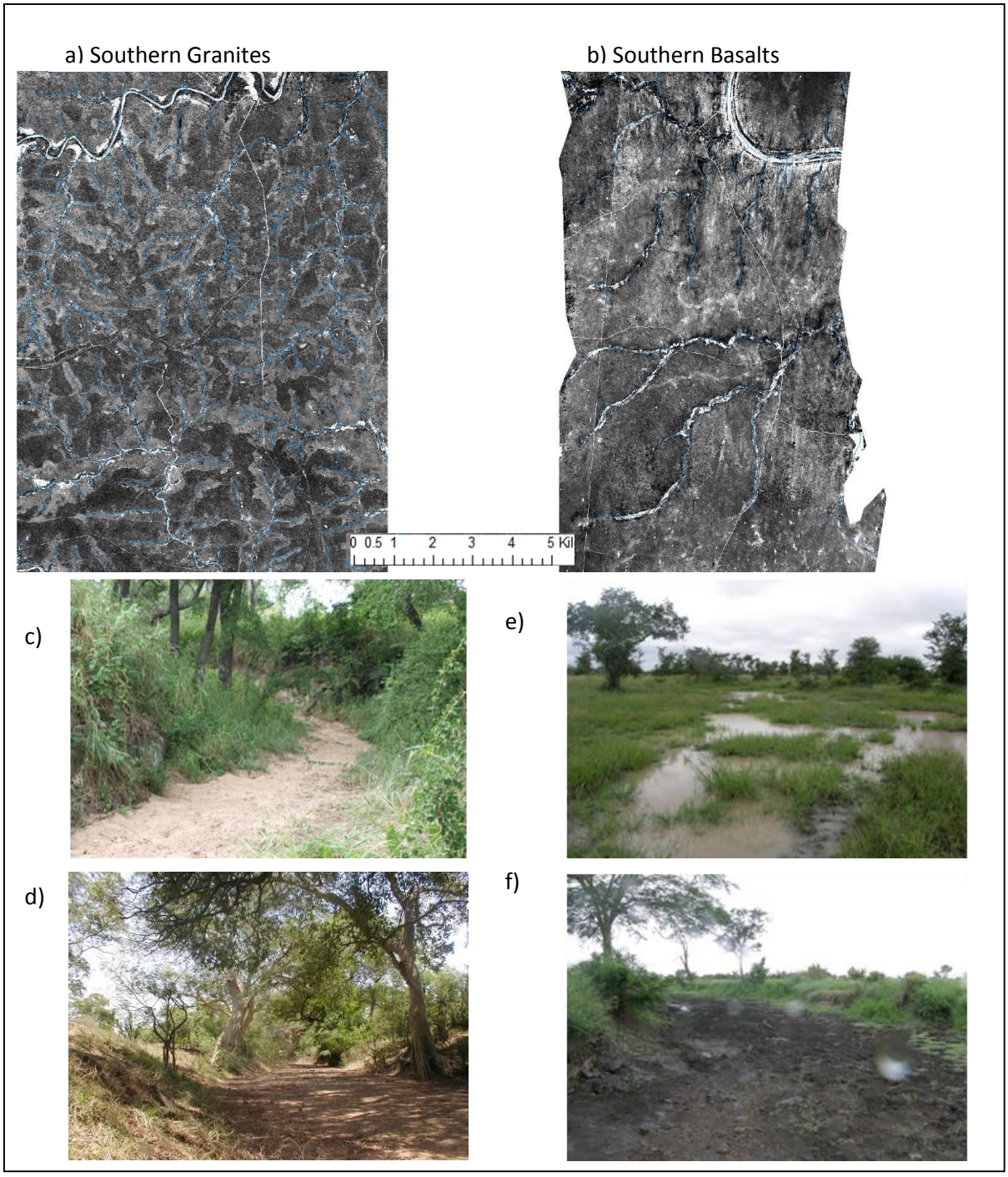


Figure 3.10: Different morphologies and drainage network patterns in the southern granites and basalts of KNP.

a) and b) Both SPOT5 pan images are shown at the same cartographic scale and resolution. A much denser stream network is seen on the more impermeable granites, together with clear catenal patterning of woody crests (darker areas on the pan SPOT imagery. In the more permeable basalts, stream density is much lower and catchments are far larger than on the granites.

Different processes in the granites and the basalts generate very different landscapes and streams. In the granites (c and d), streams are created by physical erosion, transporting gravel downstream, whereas in the basalts (e and f) streams are formed through chemical weathering and are often located in wide, flat vleis.

Photos: Photos: c) GB Mar 2010 d) KR Dec 2000 e) and f) CC Jan 2009.

3.6.6 The landscape hierarchy is a heuristic device

The landscape hierarchy presented in the preceding Section is not intended to be viewed or used as a prescriptive, universally applicable description of all possible landscape units. Nor is it intended to offer a precise description of reality. Instead, it is one of many possible windows through which savanna landscapes can be viewed. For example, the same landscape could be viewed in terms of its aesthetic qualities, its agricultural potential or its suitability as a location for hunting lion, poaching rhinoceros, harvesting thatching grass or mining coal. Each of these purposes is likely to demand a different ontology, partitioning the land in a different way, using different variables and scales of observation.

However, because so many ecological processes are dependent on water, so that many environmental attributes are tightly coupled in term of space at many scales (Section 3.4), the hierarchy presented above partitions semi-arid savanna landscapes in a way that is likely to be relevant to a very wide range of applications. This means that it can be used as a starting point for collaboration and knowledge-sharing, with the possibility of adding more layers of information that may lead to splitting or clumping of some units.

Not only is the hierarchy likely to need adaptation to suit particular purposes, adaptations are also likely to be needed in circumstances where its core assumptions are violated. For example, the hierarchy is also founded on the assumption that surface topography has a large influence on the distribution of water across and through the landscape. This may not always be the case, so there are circumstances where the hierarchy is either inappropriate or needs modification, such as areas where:

- Subsurface topography does not reflect that of the surface, such that water is diverted, stored or released underground in hillslope positions that differ from those suggested by surface topography.
- Changes to the surface topography and/or substrate have occurred comparatively recently. Changes to surface features and processes by human actions (e.g. agriculture, irrigation or drainage) or natural processes (e.g. earthquakes, volcanic eruptions or landslides) may change the relationships between soils, vegetation, topography and hydrology on which the framework depends.

The hierarchy also needs adaptation to apply it to particular landscapes. Hitherto, the hierarchy has only been described in general terms. To describe a specific landscape, units in the hierarchy need to be defined more precisely, sacrificing general applicability to increase realism and precision (Section 3.1.2).

3.7 Couclelis Levels 1- 4: Moving from the general to the particular

The next steps in constructing a landscape conceptualisation involve defining the entities found in a particular landscape and then deciding how they can best be represented on a map. This involves two separate, but related processes, both of which demand approaches that can be tailored to describe particular landscapes:

1. Refining the general landscape hierarchy entities so that they describe the particular features of a given landscape. For example, there is no standard set of catenal elements that are present on all hillslopes. Indeed, some landscapes contain features that are rarely found elsewhere (see e.g. Brierley & Fryirs, 2005). Drawing on local knowledge, previous research, field observations and imagery, concepts of frequently occurring catenal elements and toposequences can be developed that flesh out the skeletal concepts presented in the generalised hierarchy. Ideally, these concepts will involve an explanatory dimension, linking pattern and process in a mental model that identifies the dominant factors that drive and control the contemporary character and behaviour of each catenal element.
2. Selecting defining variables scales of observation and classification rules that characterise these local features and allow them to be represented on a map. The selection of scales and variables is informed by the local hierarchy of conceptual landscape units, since the definition of spatial entities solves the MAUP (Section 3.4.1). Rather than seeking to describe any pattern present in the landscape, the description is focused on purposefully seeking out and describing the patterns described in the localised hierarchy. Since the same entity can be observed and represented in many different ways (Section 3.1), the choice of defining variables, scales and classification rules will also depend on what can be observed in available data.

The conceptualisation and representation of landscape elements are interdependent, such that the process of constructing the representation can generate insights that lead to refinement of the conceptualisation, which in turn leads to adaptation of the representation. This creates an iterative spiral, in which both the conceptualisation and the representation become increasingly adapted to local circumstances, increasingly sacrificing generality to gain precision and improve correspondence with reality.

Whereas Couclelis (2010) envisages the process of constructing a geographic ontology as involving a strict descent through the ontological levels (Table 3.1), I suggest that the process is improved by repeatedly moving up and down between the lower levels of the ontology, so that observations of a particular landscape can be used to adapt and refine the *a priori* conceptualisation that is used to frame the initial observation. A strict descent through the levels would involve moving from the definition of simple objects (Level 4) through identifying measurable variables that characterise these objects (Level 3) to qualitatively observing trends in these variables (Level 2) and finally identifying basic granules of observation (e.g. pixels or groups of pixels) that determine the spatial and temporal resolution of the representation. There are at least two major problems with such a procedure. Firstly, the identification of spatial entities in satellite imagery usually proceeds in the opposite direction. The analyst starts with imagery in which both the time of capture and the spatial resolution is fixed and non-negotiable. Initial qualitative inspection reveals variables that trend in directions that qualitatively seem to align with the expected boundaries of the spatial entities to be mapped. The focus then moves to identifying values of these variables and ways of combining them that can be used to delineate the entities to be mapped. Secondly, a strict descent through the

ontological levels forecloses opportunities for the landscape itself to inform cartographical decisions and/or to shape the conceptual models of the entities that the map seeks to represent. An iterative approach that steps up and down between these ontological levels not only better describes the actual process of mapping spatial entities from satellite imagery, but also gives landscapes a 'voice' through appreciation of landscape grain and the features and toposequences that occur repeatedly.

Giving landscapes a 'voice' is important not only because it ensures that landscape conceptualisations and representations are grounded in reality, but also because it reduces the scope of subjective cartographic decisions. Although all map-making involves the cartographer making numerous small decisions, the iterative approach outlined above allows some of these decisions to be guided and constrained by the landscape itself, as will be seen in later chapters of this thesis.

The approach hinges on the notion of an adaptable conceptualisation that is tailored to fit a particular landscape and which facilitates movement between a conceptualisation and the representation of that conceptualisation. I call such a conceptualisation an 'archetype'.

3.8 Archetypes of landscape entities

3.8.1 Geographical vagueness

Although savanna landscapes are highly organised in space, there is much local variation and many exceptions to the rule. No conceptualisations will ever apply exactly to a landscape, since, by definition, abstraction and generalisation involve the omission of some detail. The art of developing and representing landscape classifications lies in deciding what features and variables are important and what can be omitted without losing the essential character of the landscape. I have already acknowledged that many different conceptualisations of the same landscape are possible: the notion of what is essential depends on the focus of interest or the purpose of a classification (Section 3.1.1). However, even if the focus and the traits that are essential are agreed, local heterogeneity means that no landscape will ever fit precisely into a generalised perspective. As Kennedy put it, we live in a 'naughty' world (Kennedy, 1979).

When dealing with geographic entities, all three points of the semiotic triangle (Section 3.1.1) are inherently vague:

- The *real entities* (e.g. A river reach, a mountain or a road) have
  - Indeterminate positional boundaries: where does a mountain begin? (Fisher *et al.*, 2004).
  - Many exceptions to the mental models that describe landscape features and formative processes (Wohl, 2013).
- The mental *concepts* or models we construct to describe those entities:
  - Indeterminate class boundaries: what is the difference between a mountain and a hill? What is a forest? (Bennett, 2001)

    - Many variations on the same concepts, which form a cluster of slightly overlapping meanings, so that we cannot say exactly what meanings are included or excluded (e.g. Rosch, 1975; Bennett, 2001).
    - Foundations that emphasise different concepts of the same entity, which may serve different purposes. For example, roads can be conceptualised in terms of their physical characteristics, function in transportation, legal status or geographic position (Fisher, 2000).
- The *representation* of concepts in language, diagrams, maps, etc.
    - Can be more or less precise, general or realistic (Section 3.1.1). An example of linguistic vagueness is the threshold vagueness described in Sorites paradox, in which a 'heap' of sand is not created or destroyed by the addition or removal of single grains (described in Fisher, 2000; Bennett, 2005).
    - Are framed in terms of entities and patterns that may appear differently at different scales of observations. Boundaries become more precisely delineated at finer scales (Levin, 1992). Changes in meaning associated with different scales of observation are one type of context-dependent variability (see Fisher 2000).
    - Are often limited by data availability or by knowledge. For example, satellite imagery, soil maps and climate data may be available for some areas, but not others.
    - Are limited by the mode of presentation and by human cognition (e.g. paper maps can only represent two dimensions, human minds can only hold a few ideas at a time).

3.8.2 The value of vagueness

In scientific discourse, vagueness is usually avoided and despised, since it is the antithesis of the precision and conceptual clarity that is demanded by traditional approaches to empirical enquiry (Strunz, 2012). In pursuit of objective knowledge and a single truth, empirical science relegates vague concepts and statements to the realm of pseudo-science and belief. Whereas the scientific method aims to separate truth from falsehood or nonsense through rigorous testing of precisely articulated hypotheses (Popper, 1959), vagueness allows for partial truths that cannot be rigorously tested, since concepts can shift to accommodate reality (Zadeh, 1996).

However, the way vague concepts have blurred, overlapping meanings and can shift to accommodate reality can also be valuable:

- As a way of describing real entities that have indeterminable boundaries. For example, the use of fuzzy classification techniques in soil mapping helps to overcome the challenges of mapping continuous gradients in terms of discrete patches (Section 2.6).
- As a way of facilitating communication without the cumbersome language required to achieve precision. There is mounting evidence that insistence on absolutely precise concepts can hinder inter-disciplinary collaboration and gaining consensus among

stakeholders, yielding deadlock rather than progress towards shared conceptualisations (e.g. Funtowicz & Ravetz, 1993; Sarewitz, 2004; Hirsch Hadorn *et al.*, 2006).

- Providing metaphors that can play creative roles in science, facilitating the conceptualisation and communication of new and/or complicated ideas (Pickett *et al.*, 1999).
- The huge growth in soft computing exploits trade-offs between precision and vagueness to deliver cost-effective (though not precise) engineering applications in the production of a wide range of manufactured goods (e.g. Singh *et al.*, 2013).
- Vagueness fuels creativity, the quest for innovative solutions and the development of constructive, open-ended science (Feyerabend, 1993; Strunz, 2012).

Recognising the value of vagueness does not mean that traditional science is rejected, merely that our toolkit for viewing, describing and explaining the world needs to be extended. Indeed, new mathematical and computing techniques are now emerging that help us deal with vagueness, mediating between natural language, precise information ontologies and the often vague nature of reality. For example, in Bayesian statistics evidence is expressed in terms of degrees of belief, whilst fuzzy logic and classification (Zadeh, 1965, 1996) can be used to (very precisely) describe objects with indeterminate boundaries or logic with partial truth. Supervaluation models define concepts in terms of sets of propositions, only some of which may be true in any single instance (Fine, 1975), whilst the 'egg-yolk' model conceives a core central zone (yolk) surrounded by an indeterminate region (white)(Lehmann & Cohn, 1994; Cohn & Gotts, 1995).

In this thesis, I do not use a mathematical technique to address vagueness, but instead use the power of semantic vagueness to harness a cluster of concepts and mental models around a central theme, which I call an archetype. As I will demonstrate, the use of archetypes to describe vague geographical and ecological entities not only helps in the description of entities with indeterminate boundaries, but also offers ways of dealing with spatial and temporal heterogeneity, integrating many different representations and perspectives on the same geographic entity and mediating between general descriptions and principles and particular examples that often deviate slightly from the 'norm'.

3.8.3 Cognitive and linguistic categories

My approach to geo-ecological classification is based upon Rosch's prototype theory of categories (Rosch, 1973, 1975). Prototype theory challenges the classical, Aristotelian approach to classification in which cognitive and semantic categories are defined in terms of necessary and sufficient conditions or rules that articulate the boundaries of each class. According to this approach, the world is divided into 'natural kinds' that are individually mutually exclusive and collectively exhaustive. We learn and communicate about the world by developing linguistic and cognitive categories that aim to mirror these natural kinds as closely as possible. The boundaries of these categories are bounded by rules that describe the yes/no conditions for class membership. Furthermore, all class members are considered to be

interchangeable, so that any randomly selected class member can represent the whole class equally as well as any other class member. This classical approach has underpinned scientific classification for millennia and forms the basis for the Linnaean taxonomy of species.

However, in the 1970s Rosch (1975, 1978) demonstrated that the classical approach offers a very limited view of cognitive and semantic classification. Many of the groups we commonly refer to in language are based upon vague 'family resemblances' (Wittgenstein, 1953), rather than on hard and fast rules. Members of classes based on family resemblance tend to share properties with each other, but no single property or set of properties is either necessary or sufficient for class membership. Thus some members may have a certain property (to a greater or lesser extent), whilst other members of the same class can lack this property, but exhibit other properties that are typical of the class. Furthermore, class membership can be graded, determined by the degree of similarity to one or more class exemplars or 'prototypes' that portray an idealised class member. Thus some class members are more similar to the prototype(s) than others and are consequently seen as better representatives of the whole class. In the classical approach a bird might be defined as an animal with feathers, a beak and the ability to fly, and all animals are then classified as either 'bird' or 'not bird'. By contrast, using a prototype approach a robin is considered to be a better example of a bird (or closer to the 'bird' prototype) than a penguin, which cannot fly, but is nevertheless a legitimate member of the class 'bird' (Rosch, 1975).

Prototype and fuzzy set theories (Zadeh, 1965) have been applied extensively in digital soil mapping, recognising that they aptly describe soil units and other spatial objects, such as landforms, that are internally heterogeneous and which have indeterminate class and/or positional boundaries (Burrough, 1989; MacMillan *et al.*, 2000; Qi *et al.*, 2006; Qin *et al.*, 2009). As Burrough explains:

> *"The strength of the fuzzy set approach is that it starts from the premise that nature may be inherently vague or imprecise, and does not try to pretend that the real world, which has been modelled by data entities created by human or machine observation, is more exact, or more perfect than it really is." (Burrough, 1989 p. 491)*

I prefer the use of the term 'archetype' as opposed to 'prototype'. Whilst both terms can be used to mean a class exemplar, the secondary meanings of the word 'prototype' imparts overtones of an early, undeveloped, tangible model.

3.8.4 Archetypal landscape units

An archetype, or a set of archetypes, is a conceptualisation of the whole of a category or class of objects. Like prototypes, archetypes can be conceived and represented in many ways: they can be real examples, abstract mental constructs or theoretical concepts (Hampton, 2007). They can also be described in terms of mental models that describe the processes, drivers and controls that have generated observable features and patterns and which are likely to determine future behaviour. If archetypes are real examples, they are purposively selected to be the most representative examples of the class, displaying all the features and properties that are most commonly associated with the class. Archetypes defined as mental constructs

are idealised representations of the central tendencies of the class. They are usually constructed using statistical analyses or from an analysis of terms used in natural language (semantic models, e.g. Burrough, 1989).

These different types of archetype correspond to the different methods commonly used in soil classification. Real examples are used in supervised classifications from training samples, whilst mental constructs are derived from statistical analyses or semantic import models (Hengl & MacMillan, 2009). Theoretical archetypes are constructed from conceptual models, either by defining *a priori* rule sets or by interpreting the tacit soil-landscape models held by experts (Qi *et al.*, 2008). In practice, all these methods are often combined in an iterative interplay between theory, language, observation and statistical analysis. For example, it is likely that conceptual models inform the selection of variables used in statistical analyses. Similarly, statistical analyses are useful ways of discovering new relationships that can stimulate new hypotheses and prompt the refinement of conceptual models.

Not only can different types of archetype be used interchangeably when developing class definitions, but a class can be conceptualised by more than one archetype. For example, different archetypes are needed to describe the same catenal unit observed in different imagery, at different times of the year or following various disturbances.

3.8.5 Practicalities of fuzzy classification based on similarities to an archetype

In classifications based on archetypes, fuzzy classification techniques are used to assess the degree of similarity between an object and the archetype(s) of each and every class. Initially, *a priori* archetypes are developed by synthesising local knowledge with interpretations of available imagery and observations in the field. Ideally, the archetypes are based around a conceptual model that links observed patterns to the processes that have generated and sustained the pattern, so that key drivers and controls can be identified and incorporated into the eventual class definitions. This conceptual archetype is gradually refined and adapted to local circumstances through an iterative interplay between general descriptions and observations of particular instances. This process draws on the methods and procedures of geomorphology, in which form, process and pattern are intimately linked in the way landscape perspectives are framed (e.g. Huggett, 1995; Wohl, 2013).

The particular instance of the archetype can be represented on a map by defining the characteristics of the conceptual archetype in terms of features that are observable in available data and imagery. Using fuzzy classification methods, the characteristics of the particular example are compared to those of the archetype. Similarity between the instance and the archetype is assessed using a basket of characteristics, each of which is described in terms of membership functions that specify the relationship between an observed value of each attribute and the degree of class membership associated with this value (Figure 3.11). Different functions express different relationships, such as maximum or minimum values that always imply class membership or curves that express the probability of class membership for each value of a given attribute. The values associated with different attributes are then combined to produce an overall membership value. For example, an archetype of the class

'gravel bed stream' could be described as occurring at the bottom of a hillslope, with a concave profile curvature and containing particles that measure between x and y cm across their longest axis. Membership functions could then be constructed for each of these attributes and their values averaged to derive an overall class membership value.

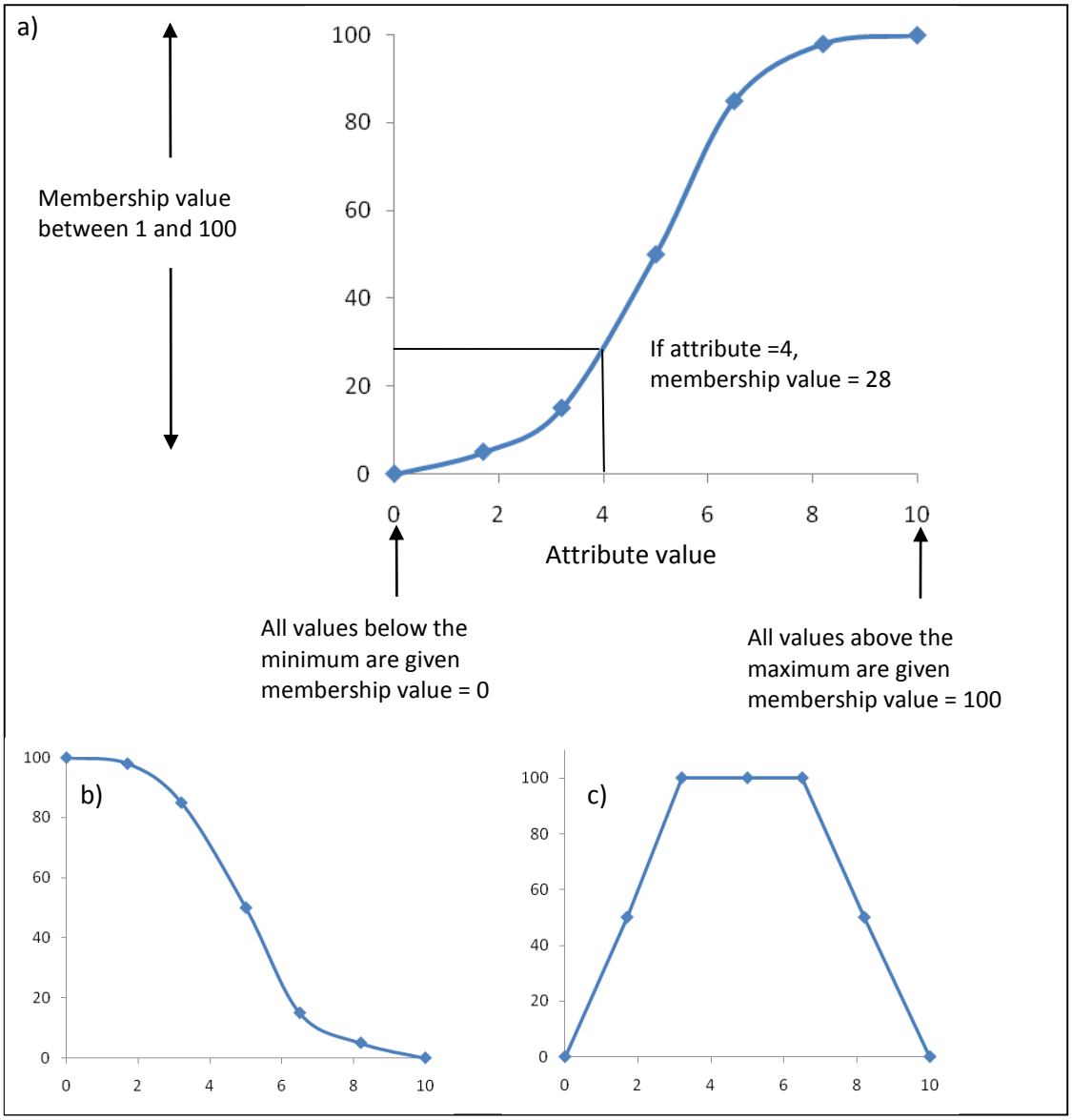


Figure 3.11: Examples of membership functions.

a) Membership increases from 0 at a minimum attribute value to 100 for all attribute values > 10.
b) All attribute values of 0 and below have a maximum membership value of 100, while attribute values > 10 fall outside the class, with membership values of 0.
c) Attribute values of 3-7 all have maximum membership values of 100, whilst attribute values <0 or >10 fall outside the class.

Fuzzy classification techniques are particularly well suited to multivariate class definitions, allowing class members to be very similar to an archetype in terms of one variable, but quite dissimilar in another dimension. Membership functions for different attributes can also be assigned different weights and combined in different ways (e.g. the maximum or minimum

membership value across all functions could be used as an overall class membership value rather than just taking the average of these functions).

Since spatial objects are assigned a membership value for each and every class, classes are not mutually exclusive, but can overlap and blend into each other. The grading of class membership also means that the degree to which each spatial object is representative of the whole class is not only described, but also quantified.

If several classes need to be mapped at once, then spatial units are assigned to the class for which they have the highest membership value. Although this allows the representation of spatial units as a traditional area-class map, it is recognised that this is but one way of presenting the results of the classification.

3.8.6 Why landscapes are better described by archetype-based classifications than by conventional classification methods

Archetypal approaches to landscape classification offer many advantages over traditional methods (Table 3.2). Whereas conventional rule-based approaches to classification focus attention on the definition of boundaries, archetype-based approaches focus attention on the central tendencies that define the core of a cluster of environmental attributes. Thus attention and effort is drawn away from attempts to identify elusive thresholds and boundaries towards identifying patch characteristics and processes that are of most interest and relevance to the end-users of a classification.

In fuzzy classifications, similarity to a class is assessed in terms of the family resemblance to an archetypal representation of the central tendency within each landscape type, rather than in terms of necessary and sufficient conditions for membership. This approach is far better suited than rule-based approaches to landscape classifications in which class and positional boundaries are likely to be blurred and/or contested and even the identification of distinguishing characteristics is likely to be imprecise.

The use of archetypes and fuzzy classification techniques is well suited to describing landscape units and classes in terms of a range of different states that fall within a range of variability that is considered to be characteristic of the units or class. Not only does the approach allow for the imprecise definition of boundaries, but several archetypes can be associated with each class, each representing a different facet of a single landscape unit. The ease of associating multiple archetypes with a single class also means that different suites of defining attributes can be used to define the same landscape units observed in different data sets or different imagery.

By acknowledging that not all class members are equally representative of the whole class, archetypal classifications allow the assessment of the range of variability that occurs within a class. Understanding this range of variability has important implications for both land management and policy, since it is a major source of uncertainty in predictions and foresighting. Furthermore, the degree of variability within a class can be taken into account when choosing sample or reference sites and when extrapolating observations or experimental results to other sites in the same class.

Fuzzy classification techniques also dampen the effect of errors or imprecision in defining the membership functions or ambiguities in the landscapes to be classified. In crisp classifications, objects or areas that nearly meet the specifications for a particular class can be rejected for reasons that are often felt to be unsatisfactory or difficult to explain. However, in fuzzy classifications this situation is less likely to arise, as a low membership value on one single attribute can be outweighed by a high value on another attribute (Woodcock & Gopal, 2000).

Within a crisp classification, all the pixels or image objects that make up a patch are assigned the same value, hiding any within-patch variation. However, in fuzzy classification, although each image object can be assigned to the class for which it has the highest membership value, objects retain their membership values for each and every class. Thus information that describes local differences within and between patches is retained.

Lastly, archetypes are both malleable and transparent. Although they may be defined in deliberately vague ways, the membership functions that define archetypes are always explicit and are therefore open to critique and refinement. Thus the functions that define archetypes are open to change as and when new data become available, new knowledge is gained or environmental changes occur (Burrough, 1989; Burrough & Frank, 1996).

Any conceptualisation or model of landscapes necessarily includes numerous assumptions and generalisations that often do not hold in real landscapes. This does not mean that general principles and conceptual models are not useful. Such principles and models serve as a starting point for the construction of local understanding, providing a basis for the assessment of when and where local differences may alter the basic model. However, in some circumstances, local differences demand that new conceptual models and archetypes are developed. This situation occurs when the underlying assumptions of the model are violated or the partial view of the world encapsulated in the model does not include the dominant processes that are responsible for generating and sustaining observed patterns.

3.9 Summary

By situating hillslopes within the drainage network, my conceptualisation of savanna landscapes has married aquatic and terrestrial perspectives. Synthesising concepts from river science (Section 2.7.2), hydrology (Section 2.7.1) and soil science (Section 2.6), a framework has been established through which landscapes can be classified and mapped. Based on a hierarchy of geographic, structural-functional entities, archetypes are used to move between the abstract concepts of the hierarchy and particular instances in real landscapes.

In the next chapters of this thesis, I explore how this conceptualisation can be applied, developing classifications for selected KNP landscapes at each level of the hierarchy.

Table 3.2: Rule-based versus archetype-based approaches to classification.

Crisp classifications based upon rule-based classes	**Fuzzy classifications based on archetypes**	**Implications for landscape classification**
Classes and class members have crisp boundaries/ fixed thresholds defined in terms of rules. e.g. If x = a and y > b and z < c …. Then class = xyz.	Classes are determined in terms of similarity to one or more archetypes. Classes and class members can have indeterminate boundaries that change in time or space.	Fuzzy classifications offer more realistic ways of describing continuous and dynamic environmental attributes that do not neatly fit into static, well-bounded patches.
Precise rules: no ambiguity is allowed. All defining characteristics are necessary and sufficient to define class membership.	Family resemblance: Imprecise and overlapping archetype characteristics can be used to define a class. Not all defining characteristics need to be present in all class members.	More tolerant of landscape variability, recognising that most landscapes that do correspond exactly to class definitions. More realistic descriptions of ecotones.
Yes/no class membership. (1 or 0 – Boolean logic) Classes are individually mutually exclusive and collectively exhaustive.	Degrees of class membership are possible. Classes may overlap and there may be gaps where objects are dissimilar to all defined archetypes.	Offers possibilities for describing within-class variability. Some locations may resist classification within a particular set of classes.
Class members are assumed to be identical and interchangeable: all class members are equally representative of the class.	Some members are more similar to the class archetype(s) and therefore more representative of the class than others.	Sample and references sites can be situated within a range of variability that is more or less representative of the class archetype.
Classes and class members are conceived as internally homogenous and static/ at equilibrium.	Classes and class members can be internally heterogeneous and can therefore change in time or space.	Enhances the prospects of accommodating a range of variability within the same class.
The same attributes are normally used to define all classes.	Different sets of attributes, with different weights can describe different archetypes for the same class.	Different classification criteria can be used to identify the same class in different imagery and at different times.
Lose information about local heterogeneity.	Information about variability is retained in membership values.	Heterogeneity within and between landscape units and classes can be quantified.
Class definitions are fixed.	Class definitions are malleable and so can be adapted to suit local circumstances or updated if new data become available or environmental conditions change.	Classification schemes can be refined and adapted, rather than needing total revision to accommodate new data or perspectives.
Inaccurate rules/ thresholds produce misleading results.	More tolerant of errors or imprecision in defining the rules and thresholds that separate classes.	Accommodates vagueness in representation as well as in reality.

CHAPTER 4: THE LANDSCAPES OF KRUGER NATIONAL PARK

The flat savannas of the KNP in South Africa lie between the Great Escarpment to the east and the Lebombo mountains that border Mozambique to the east. The high biodiversity that makes this park one of the world's foremost conservation areas results from the diverse geology and differences in rainfall that occur in this 2 million ha park. Distinct ecoregions occur in which particular combinations of geology and climate support spatial clusters of interdependent soils and vegetation, linked to specific hydrological regimes typical of the zone. Each region also has a distinctive pattern of landscape dissection, with characteristic hillslope and channel morphology. These clustered environmental attributes are both cause and consequence of the dominant ecological processes in each region. Because ecological patterns and their associated processes differ so much across the park, it has long been recognised that each area demands special consideration by conservation scientists and managers alike (Venter et al., 2003). Considerable attention has therefore been paid to the development of landscape classifications that describe the various ecoregions found within the park (e.g. Gertenbach, 1983; Venter, 1990).

Since the establishment of KNP in 1926, the guiding principles informing management practices have changed from laissez faire *guardianship to agricultural-style stock management and 'command and control' system engineering (Carruthers, 2008). Over the last two decades however, KNP has adopted an adaptive management approach that relies heavily of close cooperation between scientists and managers, who are both challenged to address issues arising from system complexity and heterogeneity (Venter et al., 2008).*

Given the semi-arid, water-controlled ecosystems and the consequent tight spatial coupling of hydrological, geomorphic and biotic processes, together with the high abiotic and biotic diversity present in the park, the history of landscape classification, the strong links between science and conservation management and the well-established and large interdisciplinary research community that exists in KNP, the park offers excellent scope for trialling a landscape classification informed by my new conceptualisation of savanna landscapes.

After introducing the entire park, I focus on two contrasting sites where LiDAR data are available to enable classifications at the level of catenal elements and catchment toposequences. The independent soil, vegetation and morphological patterns evident in the hillslopes and channels of each site are discussed, together with hypothesised hydrological connectivity between the various catenal elements.

4.1 The study area

The Kruger National Park (KNP) occupies almost 2 million ha on the Lowveld ('low fields') of South Africa, which consist of low-lying plains bounded to the west by the Great Escarpment and sloping gently to the east, where the Lebombo Mountains form a barrier between the Lowveld and the extensive coastal plains of Mozambique (Figures 4.1 and 4.2). KNP lies within the savanna biome of South Africa, which is characterised by very high biodiversity, wet

summers, dry winters, subtropical temperatures with little or no frost and a discontinuous tree canopy with a herbaceous layer dominated by C_4 grasses (Venter *et al.*, 2003; Mucina & Rutherford, 2006).

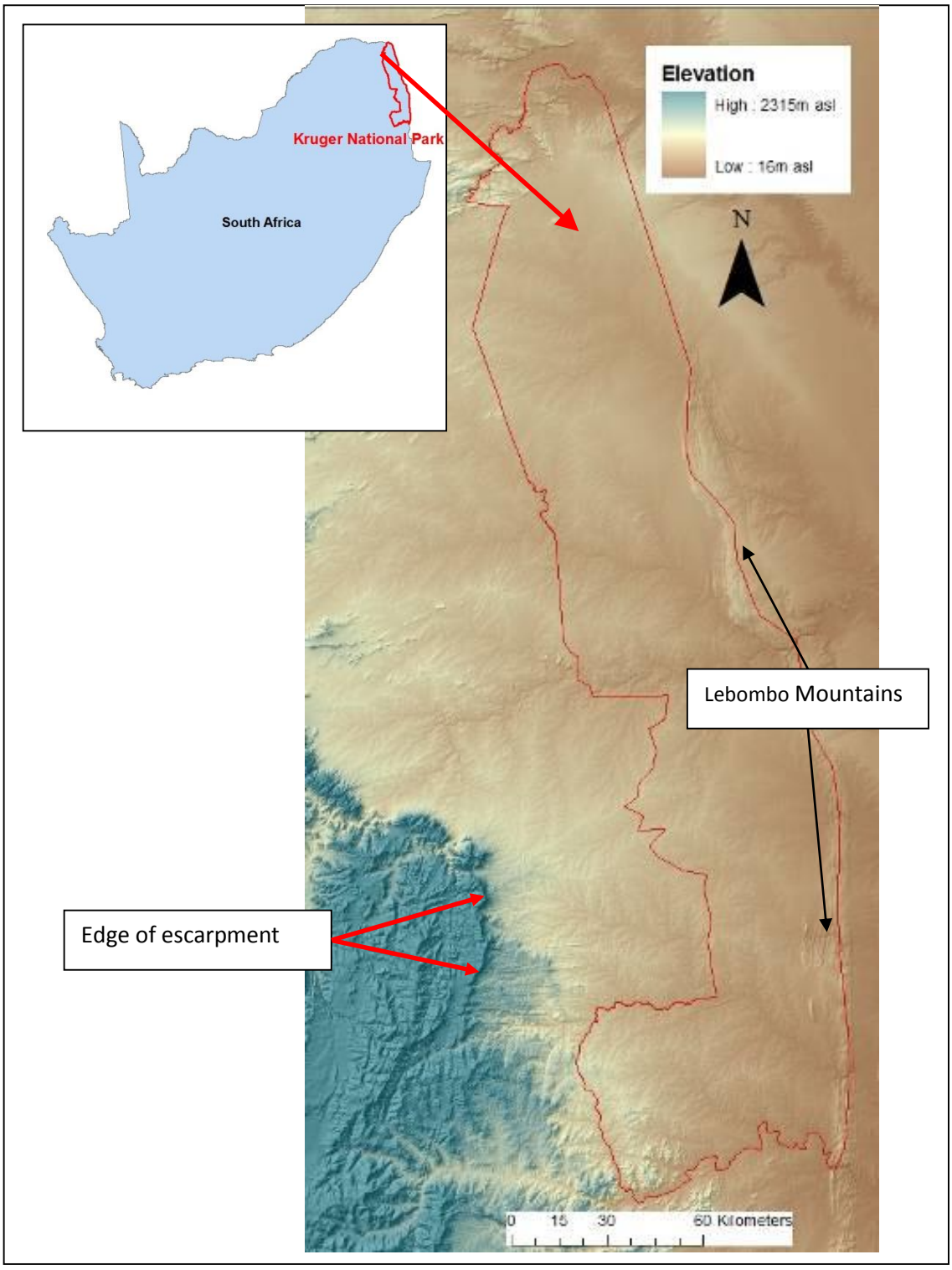


Figure 4.1: Location of Kruger National Park.

KNP is a low-lying area that nestles between the Great Escarpment to the west and the Lebombo Mountains to the east. (Elevation: SRTM)

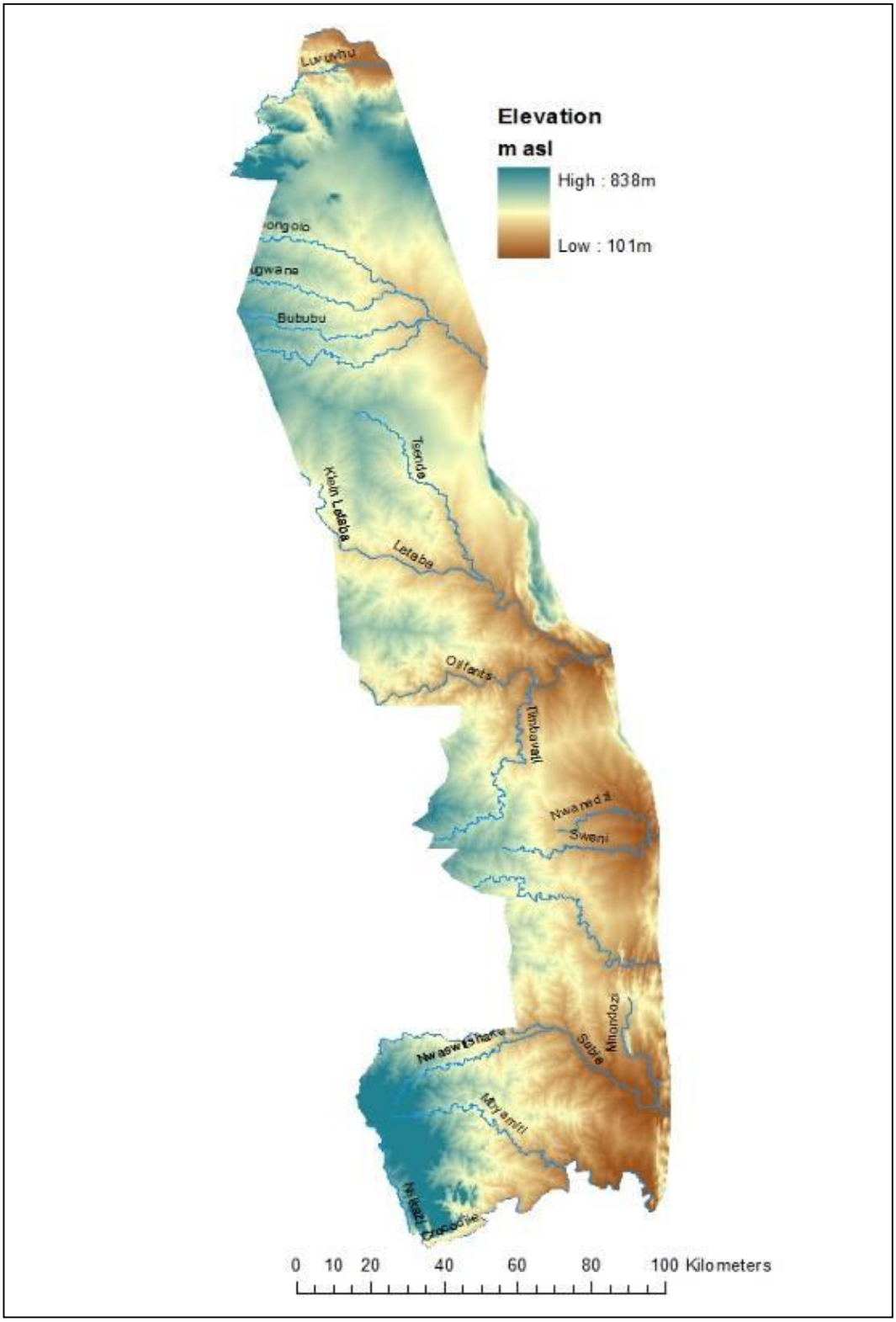


Figure 4.2: Elevation within KNP.

KNP slopes gently to the east. The western part of the park generally consists of undulating small hills with low lying plains to the east. The major rivers run from west to east, rising outside the park on the edge of the escarpment and flowing through deep gorges in the Lebombo Mountains to Mozambique, which lies along the eastern park boundary. (Elevation: SRTM)

4.2 Geology, soils and drainage patterns

KNP contains some of the oldest rocks in the world, including Archaean granites and greenstone fragments formed over three billion years ago. Following the breakup of Gondwana, the escarpment gradually retreated westwards as rivers cut back into the scarp, eroding the Lowveld plains. Subsequent uplifts and crustal deformation, together with sea level changes, triggered a number of periods of planation, but the rivers still predominantly flowed west to east, from the Escarpment to the Mozambican delta. However, after the volcanic events that created the Lebombo Mountains, these rivers had to cut gorges through the new mountains to maintain their course. Comparatively recently, around 2mya at the end of the Pliocene, there was further major uplift of approximately 900m. The land now inside KNP tilted downwards towards the east. Subsequent erosion exposed the various strata of previously deposited rocks, running in a north-south direction, with older rocks lying to the west and younger rocks to the east. Thus the geology generally follows a north-south strike, with older granites in the west (3 000-3 500mya), a narrow ridge of sandstone and shales in the centre, and young basalts and rhyolites in the east (170-200mya). Throughout the park, the granites are intruded by patches of gabbro and dolerite dikes (Schutte, 1986; Venter *et al.*, 2003) (Figure 4.3).

The various lithologies of KNP weather quite differently to form soils and morphology that have distinct characteristics. For example, the granites weather to sandy soils formed mainly of quartz grains. Crest soils tend to be leached, with fine particles and minerals transported downslope to form nutrient-rich, clayey soils in valley bottoms (the process of epimorphism, (Paton *et al.*, 1995), described in KNP by Khomo (2008)). Overall erosion rates are extremely slow, recently estimated at 3-6m over a million years (Chadwick *et al.*, 2013). However, the quartz particles that form the gravel beds of ephemeral, flashy streams are very effective at incising channels, such that the landscape is finely dissected, with a dense stream network (Venter, 1990).

By contrast, the basalts in the east of the park tend to weather chemically *in situ*, forming clayey, fertile soils that can hold far more water than the sandy soils formed from the granites (Venter, 1990). Low order streams do not have incised channels, but are situated in depressions that are sponge-like in their capacity to absorb and store water, forming ‘vleis’. These seasonally waterlogged wetlands contain discontinuous channels and pans, similar to ‘dambos’ in other parts of southern Africa. In these areas, run-off is minimal and stream density is low (Venter, 1990; von der Heyden, 2004).

Because of their different weathering processes, variations in drainage densities in KNP are closely related to geological differences, such that different geologies tend to have characteristic spacing between ridges and valleys (topographic grain) (Figure 4.4). Furthermore, drainage patterns are also closely related to geology, with streams often following the joints and fractures in granite blocks or preferentially eroding along a dyke as opposed to the surrounding, more resistant rock (Venter, 1990).

Whilst rivers established before the Pliocene erosion phase tend to run west-east, younger rivers, formed during a relatively recent period of erosion, tend to run north-south, following the strike of the geology (Venter, 1990). Incision flanking many of the major west-east rivers as they traverse the park dates from recent Quaternary erosion, as the ancient rivers cut down to new base levels triggered by the emergence of the Lebombo Mountains (Venter, 1990).

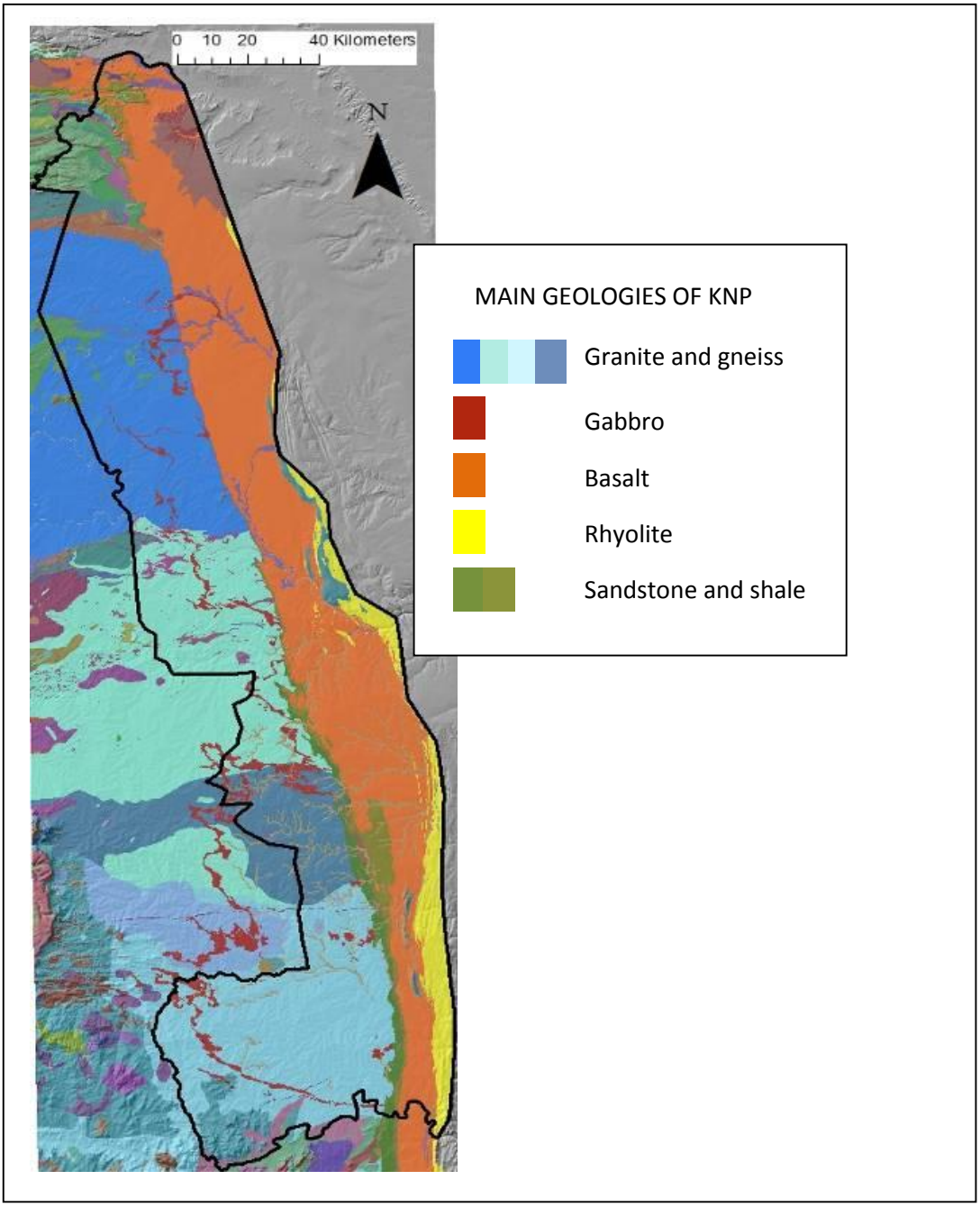
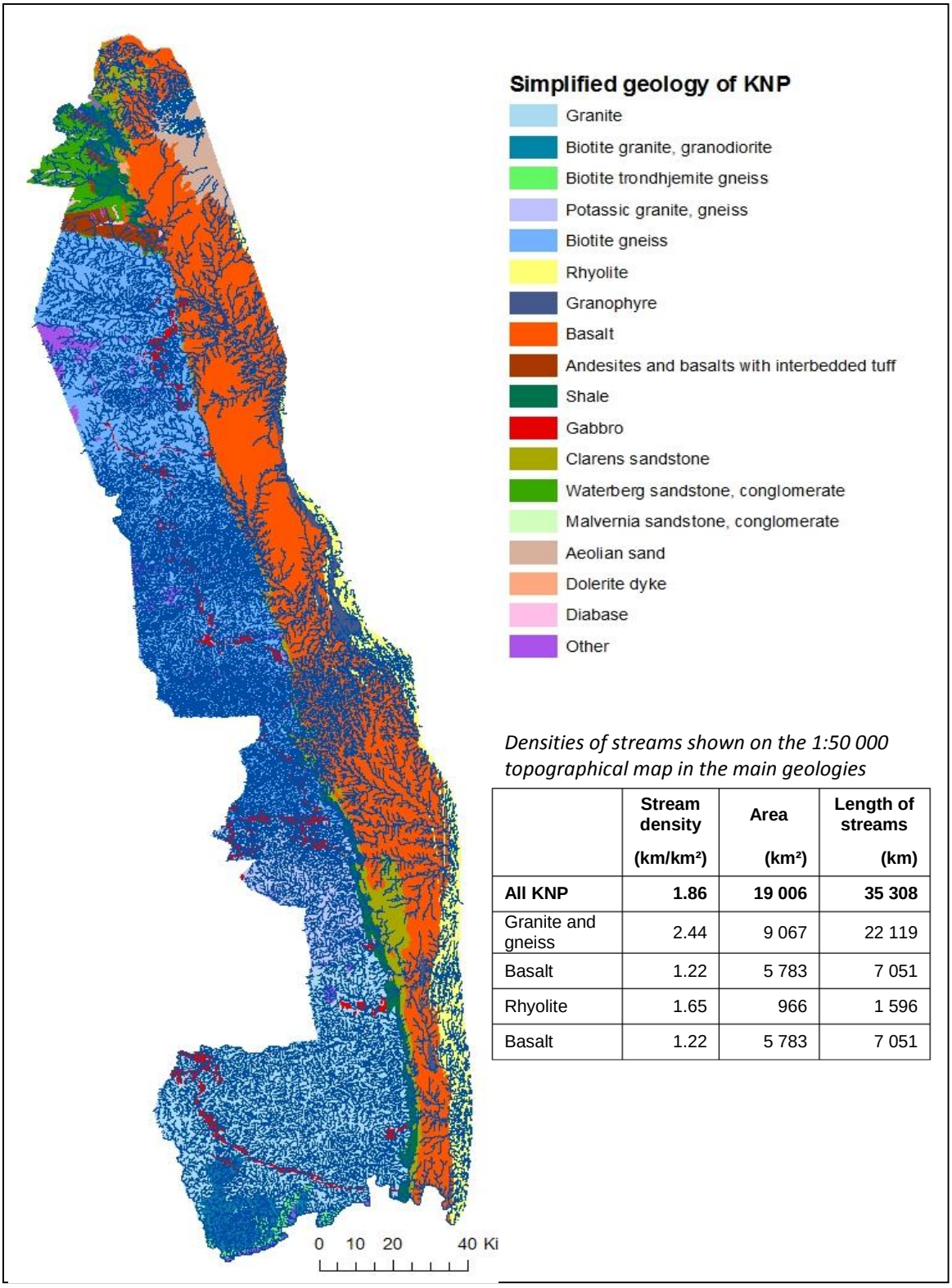


Figure 4.3: The geology of KNP.

Within KNP, the geology generally follows a north-south strike, from the youngest rhyolites in the east (yellow), across the basalts (orange) and the narrow ridge of sandstone and shales (greens) to the older granites in the west (blues). The western granites are of various types, grouped in broadly horizontal bands. Throughout the length of the park, the granites are intruded by igneous rocks, notably gabbro (red) (1:250 000 Council for Geoscience 1986).



Densities of streams shown on the 1:50 000 topographical map in the main geologies

	Stream density (km/km²)	Area (km²)	Length of streams (km)
All KNP	**1.86**	**19 006**	**35 308**
Granite and gneiss	2.44	9 067	22 119
Basalt	1.22	5 783	7 051
Rhyolite	1.65	966	1 596
Basalt	1.22	5 783	7 051

Figure 4.4: Stream density and geology in KNP.

Each geology tends to have a characteristic topographic grain. Relatively impermeable bedrock (e.g. granite and rhyolite) tends to generate more runoff than more permeable bedrock (e.g. basalt), leading to a more finely dissected landscape, with higher drainage density and steeper, shorter slopes in granites and rhyolites and lower stream densities, with long, gentle slopes in basaltic areas. (Geology:1:250 000 Council for Geoscience 1986, Rivers: 1:50 000 topographic map).

4.3 Rainfall and hydrology

KNP is a semi-arid region, with rainfall ranging from 500-700mm/year in the south to 300-500mm/year in the north (Zambatis, 2003) (Figure 4.5). The southern area also has an east-west gradient, with drier areas in the west. This gradient is reversed in central areas, where the west is generally drier than the east. Interannual variation in rainfall is very high, with coefficients of variation ranging from 25% in the north to 35% in the south (Schultze, 1997). Temperatures are less variable, with mild winters (min/max Jun-Aug: 10^0C/26^0C) and high summer temperatures (min/max Dec-Feb: 20^0C/32^0C) (Zambatis, 2006). Frost is rare, occurring only occasionally in the higher hills of the central southern area and rarely on the northern plains (Venter *et al.*, 2003).

Rainfall is concentrated in the summer months (April - October), often falling in intense thunderstorms that can lead to large volumes of overland flow, flash floods and erosion of unprotected soil. Water inputs to soils and vegetation are highly episodic, such that many aspects of the system are pulsed, with long periods of inactivity followed by a burst of activity, which may persist for several weeks after a large rainfall event (Venter *et al.*, 2003). In some years there are severe droughts (e.g. 1991-2), whereas in other years (e.g. 2000, 2012, 2013, 2014) extreme floods occur. Rainfall tends to occur in wet and dry periods, which have been linked to El Niño events (Venter *et al.*, 2003).

As in most water-limited systems, the overall mean rates of weathering, erosion and biological functioning are very slow, but there are large pulses of activity when water does become available, in which processes operate rapidly and intensely (e.g. Noy-Meir, 1973; Jenerette *et al.*, 2012). The pulsed system dynamics lead to long lag times and frequent nonlinear sensitivity to local variability, such that local events such as bank collapse occurs infrequently, but can occur suddenly and with little warning as a threshold is crossed. These dynamics, typical of complex systems, mean that many averages are meaningless and reductionist explanations and predictions of local events are difficult, if not impossible (e.g. Noy-Meir, 1973; Jenerette *et al.*, 2012).

Potential evapotranspiration almost always exceeds actual levels of evapotranspiration in all areas of the park (Schultze, 1997). In other words, the demand for water by plants always exceeds supply, except during short periods following rainfall events. The lack of near-surface plant-available water is reflected in the fact that the vast majority of KNP rivers are almost always dry. Indeed, less than 0.002% of the total length of KNP rivers permanently contain water (corresponding to 600km out of a total length of the 31 548km shown on 1: 50 000 topographical maps) (O'Keefe & Rogers, 2003). Although deep aquifers exist, these groundwater stores are rarely accessible to plants outside the few localised areas where such water rises naturally to the surface as springs or is artificially pumped to permanent water holes.

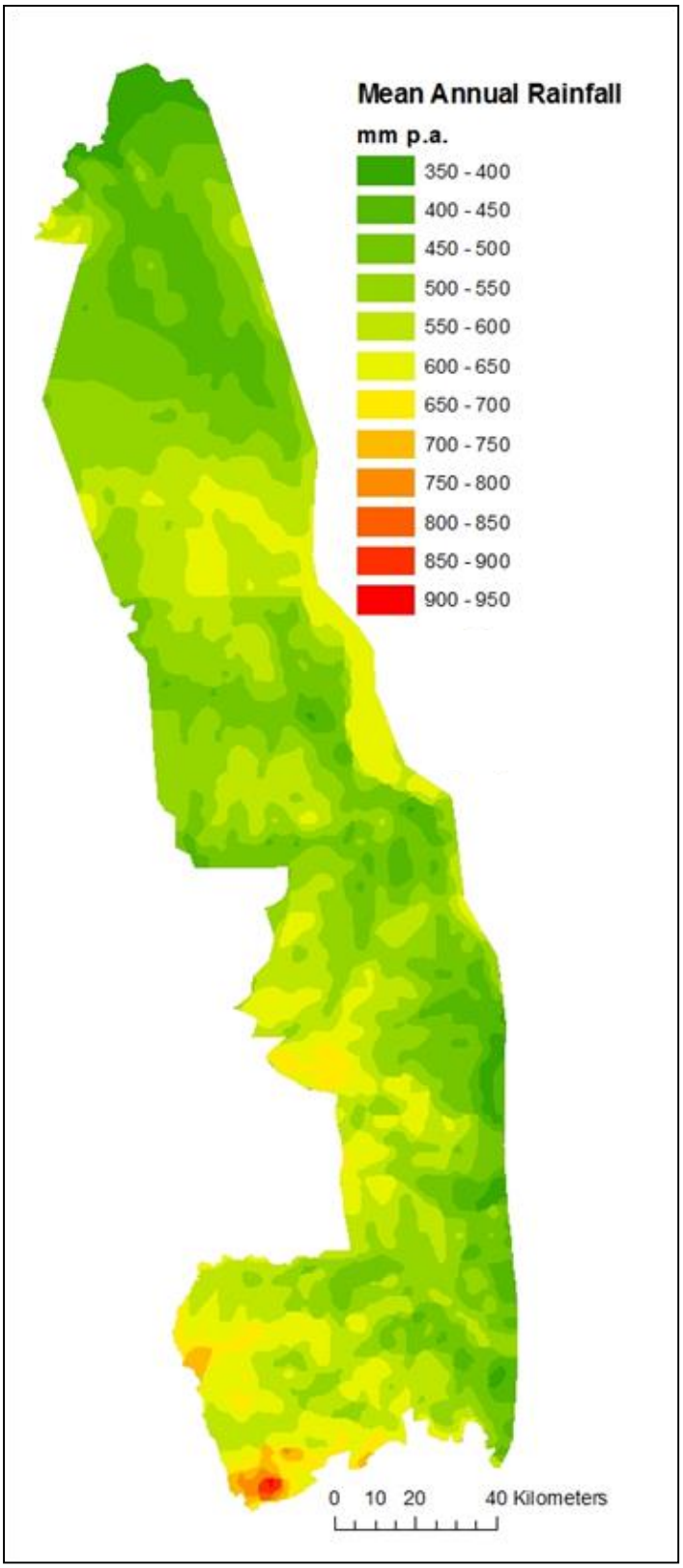


Figure 4.5: Mean annual rainfall in KNP.

KNP has a north-south rainfall gradient. The southern area also has an east-west gradient, with drier areas in the west. This gradient is reversed in the central areas, where the west is generally drier than the east. (SANParks-GIS, 2010).

Groundwater aquifers in KNP occur mainly in the crystalline granites. Although the granitic bedrock has relatively low hydraulic conductivity, frequent fractures and joints provide macropores through which water can flow and spaces between the blocks in which water can be stored. Like fractures, dolerite intrusions are more weathered, offering opportunities for more groundwater storage. Aquifers occurring at relatively shallow depths (3 - 11m below the ground surface), are likely to be mainly unconfined, offering the opportunity for more or less continuous subsurface flows. Large perennial rivers, such as the Sabie and Sand, maintain base flow during the dry season by acting as groundwater sinks during the rainy season. By contrast, groundwater recharge on the basalts is minimal, particularly in areas drained by small, low order streams (Riddell *et al.*, 2014).

4.4 Vegetation

KNP is covered by savanna vegetation, with discontinuous clusters of trees and a herbaceous layer dominated by C_4 grasses. Some 1,990 taxa of plants occur in the park, including over 400 woody plants and 224 grasses (http://www.sanparks.org/parks/kruger/conservation/scientific/ff/biodiversity_statistics.php). This high plant diversity suggests that there is a large potential pool of plants that have subtly different adaptations to survive in this semi-arid area.

Differences in rainfall and geology are strongly reflected in both soils and vegetation. The wetter south has deeper soils than the drier north. Whereas soils and vegetation vary with hillslope position throughout the park, this variation, and its resultant diversity, is greatest in the southern granites, which have both relatively high rainfall and weathering processes that generate undulating hills from physical erosion and chemical leaching of the crestal soils (Venter *et al.*, 2003; Khomo, 2008).

Although differences in species composition likely result from differences in temperature and water availability, the proportion of woody cover is strongly related to variability in the geological substrate. Cover is much denser cover on the western granites, compared to the eastern basalts (Figure 4.6). This difference in density has been linked to the relative fertility of basalts compared to the granites. Soils derived from the relatively nutrient-poor granites tend to support Combretacae (especially *Combretum* and *Terminalia* spp.), which are deciduous trees with broad leaves and no thorns and sparse cover of wiry, unpalatable grasses such as *Pogonarthria squarrosa*, *Eragrostis* spp. and *Aristida* spp.. By contrast, the more fertile, clayey soils derived from the basalts are dominated by nutritious, high-bulk grasses such as *Panicum coloratum, Themeda triandra* and *Urochloa mosambicensis,* with occasional shrubs and trees, dominated by the Mimosaceae (especially *Acacia* spp.) that have fine leaves and many thorns. In the drier north, the relative fertility of the basalts and granites still leads to differences in the density of woody cover, but the same species of tree, *Colophospermum mopane*, dominates in both basalt and granite landscapes (Venter *et al.*, 2003). The combination of rainfall, vegetation and substrate has a profound impact on ecological processes and patterns, ranging from the distribution of animals to the spread of fire and disease. Given these circumstances, many scientific studies and conservation initiatives are tailored for specific areas, and the park

is commonly partitioned into at least four areas: North and South, each divided into granites and basalts.

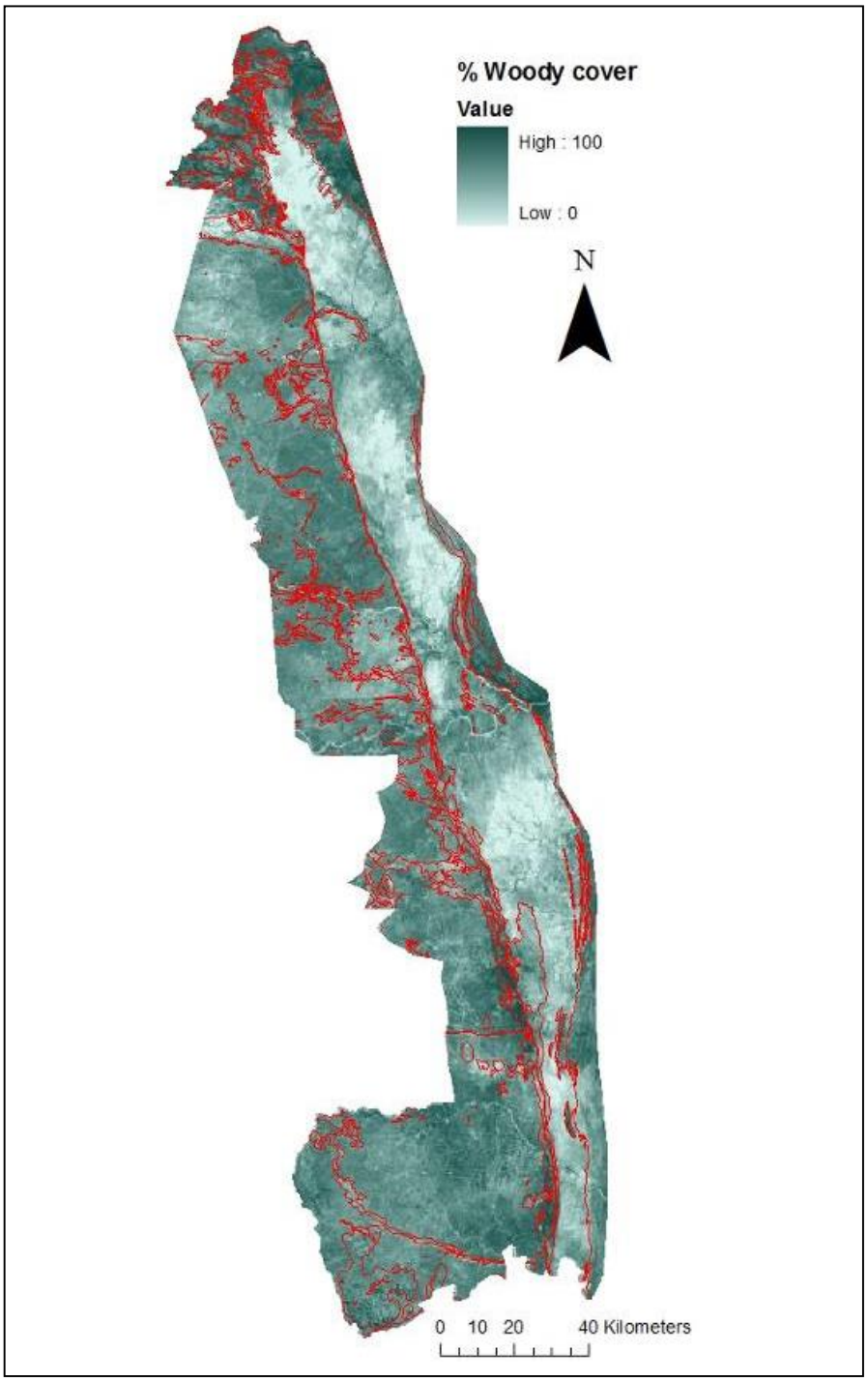


Figure 4.6: Woody cover in KNP.

The percentage woody cover in KNP reflects major geological patterns, rather than rainfall gradients. (Bucini et al*., 2010 overlaid with geological boundaries from Council for Geoscience 1986).*

4.5 Heterogeneity in KNP landscapes

The diversity of the biophysical template in KNP not only supports high levels of species diversity, but also means that the ecological processes that shape the character of landscapes vary across a few kilometres. In some cases these differences are very abrupt, as is the case in many of the geological borders (Figures 4.3 and 4.7). Other transitions are often gradual, such as the transition from *Combretum* spp. on the crest of granite hills near Skukuza to the dominance of *Terminalia sericea* on the crests of Pretoriuskop granites.



Figure 4.7: Abrupt changes in vegetation patterns between granite and gabbro in southern KNP.

Many ecological processes accompany the changes in vegetation and soils associated with geological boundaries such as this. Photo: KR Apr 2006.

Whether the changes are abrupt or gradual, differences in the biophysical template not only offer different habitat to plants and animals, but also affect a myriad of interdependent ecological processes, including tree-grass competition (Scholes & Archer, 1997), predator -prey relationships (through the availability of forage and ease of concealment (Hopcraft *et al.*, 2010; Chirima *et al.*, 2013), respiration and allochthonous inputs (Bellmore & Baxter, 2014) and invasive plants (Booth *et al.*, 2003). Geomorphic processes also differ, including rates and types of weathering, stream initiation processes and the development of different landforms (e.g. Brierley & Fryirs, 2005; Luo & Stepinski, 2008).

Although there is huge variation of ecological processes and resultant patterns in KNP, many environmental attributes are spatially clustered, forming distinct patches at many scales that are the result of millennia of co-evolution and co-adaptation of interdependent ecosystem components (Hrachowitz *et al.*, 2013; Blöschl *et al.*, 2013). Because they are generated and sustained by such different suites of processes, it is difficult to generalise across the whole

park. Instead, each of these patches demands individual study and management (e.g. Rogers & O'Keefe, 2003). The recognition of this need has led to much attention being paid to landscape classification in KNP. However, before considering these classifications in detail, I place these framings in the context of the changing paradigms within which the park has been managed and studied over the course of its history.

4.6 History of the park

The story of research and management practices within KNP reflects similar experience elsewhere, as the paradigms underpinning both environmental science and management have moved from ideas of guardianship to ideas of engineering natural systems ('command and control'), then to adaptive management of dynamic, heterogeneous, complex systems and, most recently to embracing people as part of the system (see Brierley & Cullum, 2012).

By the end of the 19th century, wildlife in much of southern Africa had been seriously depleted by commercial, subsistence and recreational hunters, such that elephant, black and white rhinoceros were becoming rare, if not locally extinct in some areas (Carruthers, 2008). To protect the remaining animals, several game reserves were established in South Africa, including the Sabie Reserve, created in 1898, which later grew into the KNP, which was established in 1926. Early management practices reflected the thinking of the first park warden, Stevenson-Hamilton, who gradually turned from the then traditional methods of animal husbandry (preventing public access, stopping poaching and exterminating predators) towards an approach based on ''leaving nature alone.'' As Carruthers explains:

> *"He (Stevenson-Hamilton) preferred being custodian of a 'faunal sanctuary' in which humans were intruders. By the 1930s Stevenson-Hamilton was warning that 'posterity will know whether this generation used its power to conserve this one remaining piece of unspoiled nature [i.e. the Kruger National Park]... or whether it permitted it to be turned into a glorified zoological and botanical garden' (Stevenson-Hamilton, 1947 p. 11), carefully manipulated for public consumption." (Carruthers, 2008 p. 209)*

Tension not only existed between Stevenson-Hamilton's *laissez faire* management style and the demands of growing tourist numbers, leading to the development of infrastructure that included metalled roads and permanent camps, but also between Stevenson-Hamilton and the trend towards scientific land management in the 1940s. By the 1950s,

> *"Wildlife management (in South Africa) was a science that linked wildlife and place in the pursuit of nationalism: it was scientific passion of a specific kind, embedded in the idea of Afrikaners as outdoorsmen, but nonetheless men of science, and of whites as custodians of a well-managed natural landscape free of black Africans. " (Carruthers, 2008 p. 218)*

Over the next few decades, KNP was managed according to an agricultural model, with stock management, biological productivity and 'carrying capacities' as guiding principles. 'Scientific Services' were separated from the practical tasks undertaken by rangers and extensive

monitoring was established, including regular 'veld condition assessments', aerial animal censuses and experimental burn plots, all of which have continued to the present day. The results of this monitoring directly informed management policy. For example, the aerial census numbers were used to set targets for the annual cull (Carruthers 2008). Strong links between science and management were forged within an ecological paradigm of "stability" and "climax", using a conceptualisation in which ecosystems respond to pressure as a result of direct causal links:

> *"Because cause and effect were thought to be directly linked, this meant that a stable ecosystem could be engineered that would maintain a climax and ''balance'' the numbers of specific species of wildlife with the amount of available water and appropriate grazing and/or predators and prey." (Carruthers, 2008 p. 218)*

Under this engineering-based approach to conservation management, often called "command and control" (Holling & Meffe, 1996), the western boundary was fenced, many artificial water points were built and the park was physically divided into fire-blocks that were physically separated from each other by fire breaks and roads and regularly burnt according to a strict schedule. It was believed that these 'cool fires' minimised the risk to fauna, flora and camps from intense wild fires, whilst providing fresh forage for herbivores and reducing the presence of long grasses that were seen as unwelcome harbours for ticks and predators (van Wilgen *et al.*, 2000; Govender, 2003).

By the 1990s, these interventionist techniques were increasingly questioned and a new paradigm emerged that demanded new ways of managing and understanding the park. The ideas of sustainability and resilience, complexity, system dynamics and heterogeneity and the practice of adaptive management that were emerging worldwide were enthusiastically embraced by post-apartheid SANParks management (Holling, 1978; Biggs & Rogers, 2003; Urry, 2005). The new mission statement for SANParks centred on the ideal of "the maintenance of biodiversity in all its facets and fluxes" (Braack, 1997). Rather than focussing on specific species, attention was now directed towards the ecosystem processes and heterogeneity responsible for generating diversity. Adaptive management approaches were adopted, embracing uncertainty and 'learning by doing' (Biggs & Rogers, 2003; Venter *et al.*, 2008). 'Thresholds of Potential Concern' were identified, indicators of these thresholds identified and monitoring programmes implemented. When the thresholds are exceeded, managers are prompted to investigate the triggers of change and to take appropriate actions. Venter (2008) has called this 'management by exception', where action is only taken in response to exceeded thresholds. More recently, an adaptive fire management policy has taken this passive management policy a step further, implementing a programme of active experimentation to develop fire policies that maximise heterogeneity (van Wilgen *et al.*, 2014).

Another recent trend has been towards the inclusion of people. The mission of SANParks is now 'Connecting to society', building constituencies towards a people-centred conservation and tourism mandate (SANParks strategic plan 2014/15 – 2018/19: http://www.sanparks.org/assets/docs/about/5_year_strategic_plan_2014-2015_to_2018-2019.pdf). This means that the ecosystems of the national parks are seen as 'socio-ecological

systems' (Folke *et al.*, 2005), parks are opening up to local communities, not only in terms of outreach and education, but also by allowing locals to gather traditionally used natural resources within park boundaries, by expanding research foci of Scientific Services to include tourism and social research (see SANParks Scientific Services, 2013).

In many ways, this thesis is a response to the evolution of science and management practice in KNP. The acknowledgement of system complexity and dynamics, as well as the value placed on heterogeneity *per se*, has meant that new conceptualisations and analytical tools are needed to describe and manage landscapes. These tools need to describe similarities, so that lessons learnt through adaptive management can be applied elsewhere, whilst recognising the heterogeneity that underpins biological diversity.

4.7 Research in KNP

The adoption of adaptive management approaches was accompanied by a massive expansion in research projects in KNP. As post-apartheid South Africa became accepted in the international community, SANParks Scientific Services welcomed external funding, collaborative projects and international researchers. KNP became a major international research hub, with 779 projects officially registered in the KNP in 2012, of which 25% were run by international researchers (SANParks Scientific Services, 2013).

Research that is particularly relevant to this thesis includes studies that relate the spatial distribution of soil properties, termite mounds, vegetation characteristics and the spread of fire to hillslope position in KNP granites (Bartlett & Smith, 2005; Khomo, 2008; Levick *et al.*, 2010; Smit *et al.*, 2013b; Baldeck *et al.*, 2014). All these studies describe the highly organised nature of this landscape, with tight coupling between many ecological attributes and ecological processes.

The vast amount of research conducted in KNP has generated understandings of many different ecological functions and processes within the same system. However, outside the long-established and well-used manipulated sites (such as the experimental burn plots and the animal exclosures) it has often proved difficult to integrate findings from these diverse studies due to mismatches in scale or context. In 2012 it was therefore decided to establish four research 'supersites', which are non-manipulated sites that represent the four major geoclimatic regions of the park: Northern (low rainfall) and Southern (higher rainfall) and basalts and granites. Extensive baseline data and ongoing monitoring will be conducted at these sites, together with *ad hoc* studies, along the lines of the data-rich long-term ecological research (LTER) sites in the USA, where baseline data, data sharing and a research-enabling environment catalyse data sharing and collaboration between over 1800 scientists (see http://www.lter.edu). The selection of the sites and the gathering of baseline data have been framed within the conceptualisation presented in this thesis, so that future research will also be contextualised within the same perceptions of catenal elements, catchments and physiographic zones (Smit *et al.*, 2013a).

4.8 Previous conceptualisations of KNP landscapes

Gertenbach (1983) was one of the first people to construct a functional landscape classification of KNP intended to inform management decisions. He defined a landscape as an areas with "a specific geomorphology, climate, soil and vegetation pattern and associated fauna" (1983 p. 10) and used existing data sets for each of these five factors to qualitatively assemble a classification, which was not drawn to a specific scale (Figure 4.8).

The more recently defined vegetation types of South Africa (Mucina & Rutherford, 2006) use a simplified version of Gertenbach's classification to describe vegetation types in KNP.

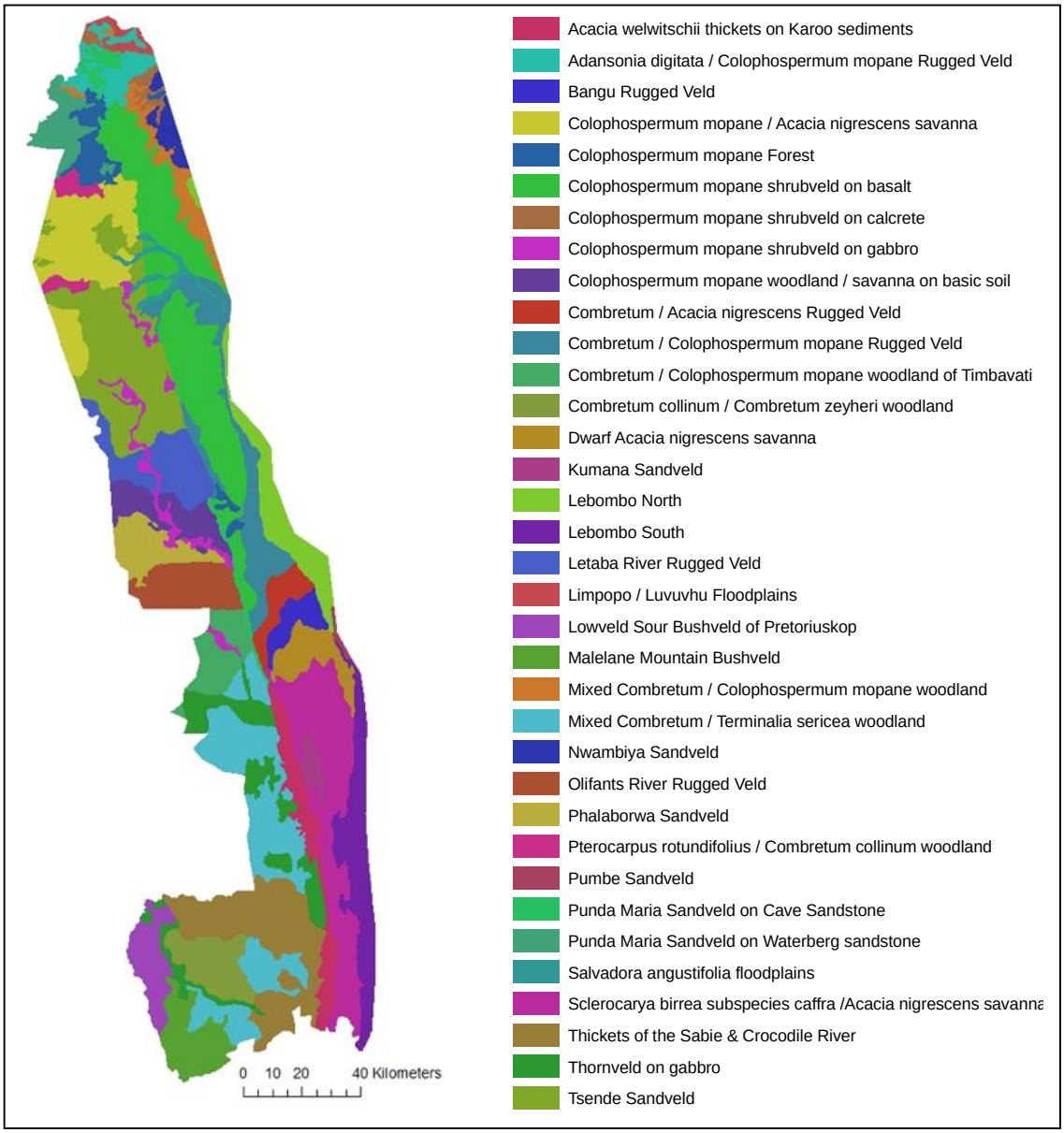


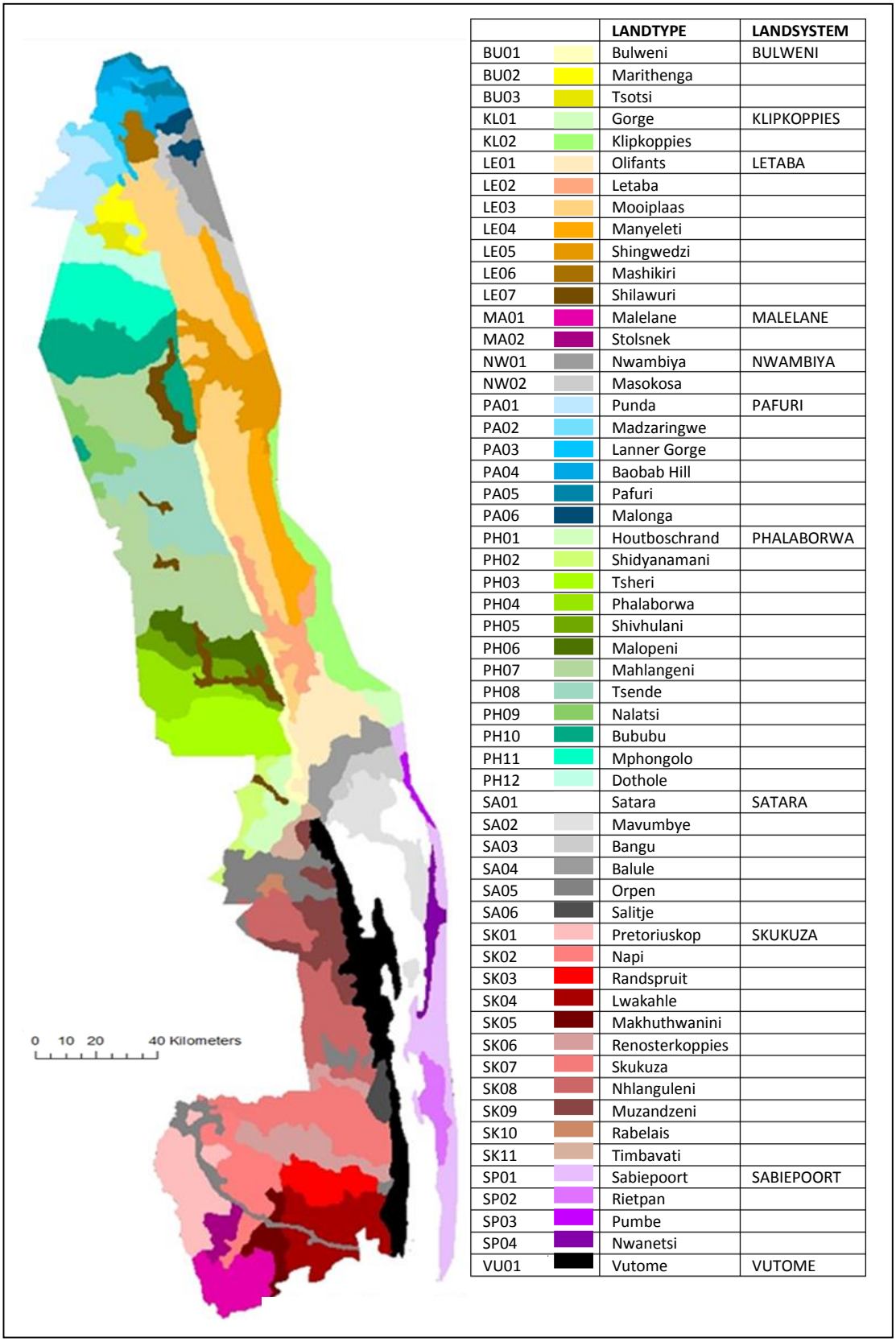
Figure 4.8: Landscapes of KNP (Gertenbach, 1983).

This qualitative, single-scale assessment of KNP landscapes focussed largely on plant communities, although abiotic characteristics and the faunal communities using each area were also described. (SANParks-GIS, 2010).

Venter's PhD thesis (1990) presented a new landscape classification (Figure 4.9). Like Gertenbach, Venter aimed to delineate land units that could be used to inform park management decisions, using more quantitative methods than his predecessor. Venter based his study on the relationships between soils, dominant woody vegetation and landform characteristics, omitting animal population data from the definitions of landscape classes and including climate data only at the coarsest scale of mapping. Furthermore, Venter proposed a multi-scale classification, with four hierarchical levels of landscape classes:

- *Land units,* which are specific sections of hillslopes, with distinct morphology (curvature and gradient), drainage, position and soil/vegetation associations. These units are based on the hillslope units of crest, scarp, midslope, footslope and valley bottom, as used in South African Land Type surveys, which were designed to inform agricultural land planning (MacVicar *et al.*, 1974). Following MacVicar's lead, Venter described land units typical of each land type, but did not map them.
- *A land type* is "an area or group of areas in close proximity over which there is a recurring pattern of distinctive land units, each with its own characteristic morphometry and soil and vegetation assemblages" (Venter, 1990 p. 33). This definition was based on a similar concept used in Australia by Christian and Stewart (1953). The South African Land Type survey also used a very similar concept, but included climate variables. Since Venter did not have confidence in the KNP rainfall data at the 1: 250 000 scale at which he was mapping land types, he adopted the Australian approach (Venter, 1990, p.33).
- *Land systems* consist of one or more land types, grouped together on the basis of similar geology, climate and geomorphology (i.e. plains, slightly/ moderately/ extremely undulating plains and low mountains and hills). Boundaries between land types are recognised by major differences in landform and/or soil patterns and/or dominant woody vegetation. Land systems are appropriately mapped at scales of at least 1: 1 000 000.
- *Land regions* are groups of land systems at scales of at least 1: 3 000 000.

Venter focused on the delineation of land types at a scale of 1: 250 000, describing each in detail, including quantitative data from transect surveys of soils, woody and herbaceous vegetation in representative assemblages of land units within each land type as well as morphometrics derived from aerial photographs and 1:50 000 topographical maps. The boundaries of each land type were delineated qualitatively, using Landsat images and stereoscopic aerial photographs, and then refined using both field and morphometric data.



	LANDTYPE	LANDSYSTEM
BU01	Bulweni	BULWENI
BU02	Marithenga	
BU03	Tsotsi	
KL01	Gorge	KLIPKOPPIES
KL02	Klipkoppies	
LE01	Olifants	LETABA
LE02	Letaba	
LE03	Mooiplaas	
LE04	Manyeleti	
LE05	Shingwedzi	
LE06	Mashikiri	
LE07	Shilawuri	
MA01	Malelane	MALELANE
MA02	Stolsnek	
NW01	Nwambiya	NWAMBIYA
NW02	Masokosa	
PA01	Punda	PAFURI
PA02	Madzaringwe	
PA03	Lanner Gorge	
PA04	Baobab Hill	
PA05	Pafuri	
PA06	Malonga	
PH01	Houtboschrand	PHALABORWA
PH02	Shidyanamani	
PH03	Tsheri	
PH04	Phalaborwa	
PH05	Shivhulani	
PH06	Malopeni	
PH07	Mahlangeni	
PH08	Tsende	
PH09	Nalatsi	
PH10	Bububu	
PH11	Mphongolo	
PH12	Dothole	
SA01	Satara	SATARA
SA02	Mavumbye	
SA03	Bangu	
SA04	Balule	
SA05	Orpen	
SA06	Salitje	
SK01	Pretoriuskop	SKUKUZA
SK02	Napi	
SK03	Randspruit	
SK04	Lwakahle	
SK05	Makhuthwanini	
SK06	Renosterkoppies	
SK07	Skukuza	
SK08	Nhlanguleni	
SK09	Muzandzeni	
SK10	Rabelais	
SK11	Timbavati	
SP01	Sabiepoort	SABIEPOORT
SP02	Rietpan	
SP03	Pumbe	
SP04	Nwanetsi	
VU01	Vutome	VUTOME

Figure 4.9: Land types and land systems in KNP (Venter 1990).
Land types are subdivisions of land systems, shown here in shades of the colours used to represent each land system. (SANParks-GIS, 2010).

Venter's land types are broadly similar to Gertenbach's classification, which is not surprising, since both classifications are based on similar criteria and tend to follow geological boundaries (see Solomon *et al.*, 1999 for a detailed comparison). In general, Venter's classification is more detailed, and many of Gertenbach's 35 landscape classes are subdivided in Venter's 56 landscape types, but no systematic differences are evident (Figure 4.10). Boundaries rarely coincide precisely, as might be expected, given hand delineation of the classes, mapping scales of 1: 250 000 and the inevitable subjectivity of delineating landscape classes without adopting an explicit conceptualisation or ontology (see Chapter 3).

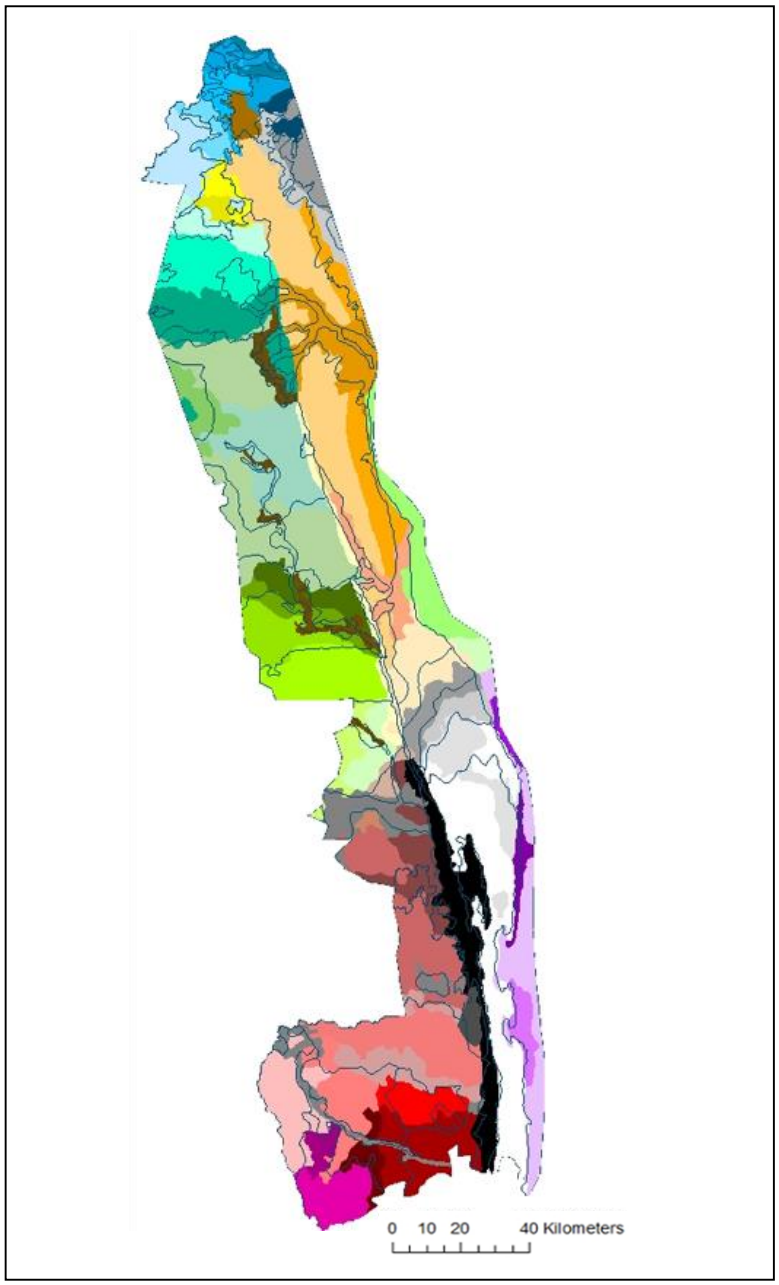


Figure 4.10: Gertenbach's landscape boundaries overlaid on Venter's land types.

The lines show Gertenbach's landscape boundaries, overlaid on a coloured map of Venter's land types. The classifications are broadly similar, both following geological boundaries. In general, Venter's classification is more detailed. (SANParks-GIS, 2010).

4.9 Building on Venter's classification of KNP

The conceptualisation developed in this thesis is founded on principles similar to those used by Venter (1990). Catenal elements are broadly equivalent to Venter's land units, whilst land types, systems and regions are equivalent to physiographic zones mapped with decreasing precision at coarser scales. Although Venter conceives land types (and higher levels in his hierarchy) as being characterised by recurring toposequences of land units, these toposequences are not explicitly situated within catchments and there is only occasional reference to the ways in which toposequences vary with network position or stream order.

Introducing the catchment level of organisation allows hillslope toposequences to be conceptually situated within the drainage network, which controls the structure and organisation of the landscape. By introducing the catchment level, the whole hierarchy is grounded in a naturally defined unit with determinate boundaries, moving away from subjectively defined ecosystem boundaries and giving the landscape itself a 'voice' in the delineation and classification of landscape units. Furthermore, integrating hillslopes and channel networks merges terrestrial and aquatic perspectives, facilitating a conceptualisation of catenal elements that are potentially connected to each other by dynamic fluxes of water. Thus the new conceptualisation of savanna landscapes builds on Venter's approach, but moves away from a conventional partitioning of landscapes into static, discrete, homogenous units towards a conceptual model that merges the patch, gradient and network perspectives in an archetypal, dynamic mosaic of interconnected patches that is tolerant of local heterogeneity (see Chapter 3).

My approach to classification also differs from Venter's in taking advantage of the fine scale imagery and sophisticated GIS tools and techniques that are now available, permitting the mapping and quantitative analysis of small landscape units such as catenal elements. Like MacVicar's land type maps of South Africa, Venter's classification of KNP is not spatially explicit below the level of land systems. The ability to map catenal elements not only offers the possibility of very detailed ecological maps, but also introduces the possibility of describing similarities and differences between catchment level assemblages (toposequences) of these units. These similarities and differences can then be used both as the basis for delineation of physiographic zones (or land types/systems) and also to assess the degree of heterogeneity within each zone (i.e. the degree to which individual assemblages differ from the archetypal conceptual model).

4.10 Advantages of trialling my conceptualisation in KNP

There are many advantages to trialling the implementation of my conceptualisation of savanna landscapes in KNP:

- The whole park is semi-arid, so that lack of water often limits many biotic and geomorphic processes. This results in tight spatial coupling of hydrological, geomorphic and biotic processes, generating a mosaic of repeating toposequences of patches with spatially aligned distributions of soil and vegetation, as described in the

conceptualisation. These toposequences have been observed and described many times, notably in the landscape classifications of Gertenbach (1983) and Venter (1990).

- The geological diversity and rainfall gradients mean that there are many different physiographic zones within the park, offering multiple opportunities to explore variations in the composition and structure of catenal elements.
- The park is undisturbed by Quaternary tectonic activity and the same rainfall gradients have existed for millions of years (Tyson & Partridge, 2000; Chadwick *et al.*, 2013). This means that the processes that have shaped the soils, vegetation and topography of the region are likely to be very similar to contemporary processes. This similarity between historical and contemporary landscape processes increases the confidence with which processes can be inferred from landscape patterns, so that classifications based on observed similarities in pattern can provide a secure basis for the extrapolation of behaviour.
- Although the park has been intensively managed (e.g. roads, fire policy, artificial water provision and herbivore culling prior to 1994), it has not been cultivated or urbanised.
- The adoption of adaptive management practices and the commitment to scientific research means that the park's staff is knowledgeable and keen to support and eventually implement projects that explore the implications of complexity and heterogeneity and build bridges between environmental science and management.
- The strong research hub that exists in KNP creates a need for integrated conceptualisations that can be used to synthesise diverse findings and provide a platform for more integrated collaborative projects in the future.

4.11 Study Sites

Although the whole park is used for the classification of physiographic zones, two particular sites were chosen for classifications at the level of catenal elements. Classifications at this level require a fine-scaled DEM (Digital Elevation Model) with at least 5m resolution to detect morphological differences at hillslope scales (Zhang & Montgomery, 1994; Kienzle, 2004). Airborne LiDAR (Light Detection and Ranging) data describing ground elevation, canopy height and vegetation patterns at 1.12m resolution were acquired in April 2008 by the Carnegie Airborne Observatory (Asner *et al.*, 2007, acquired in April 2008) for several sites in the park. These sites included permanent research sites such as the experimental burn plots and the exclosures (Sections 4.6-4.7) and four larger sites that were chosen to be representative of the main geology and rainfall gradients in the park. I chose two sites that were reasonably accessible and close to each other in two very contrasting geologies in southern KNP: one in the N'waswitshaka basin in the granites and the other in the Nhlowa basin in the basalts (Figure 4.11). The sites each include (almost) entire catchments of at least 3rd order, so that changes in assemblages of catenal elements can be contrasted on hillslopes in different positions within the stream network. SPOT5 imagery, acquired in March 2006, with resolutions varying between 2.5m (pan layer) and 10-20m (multi-spectral layers) is also available for these areas.

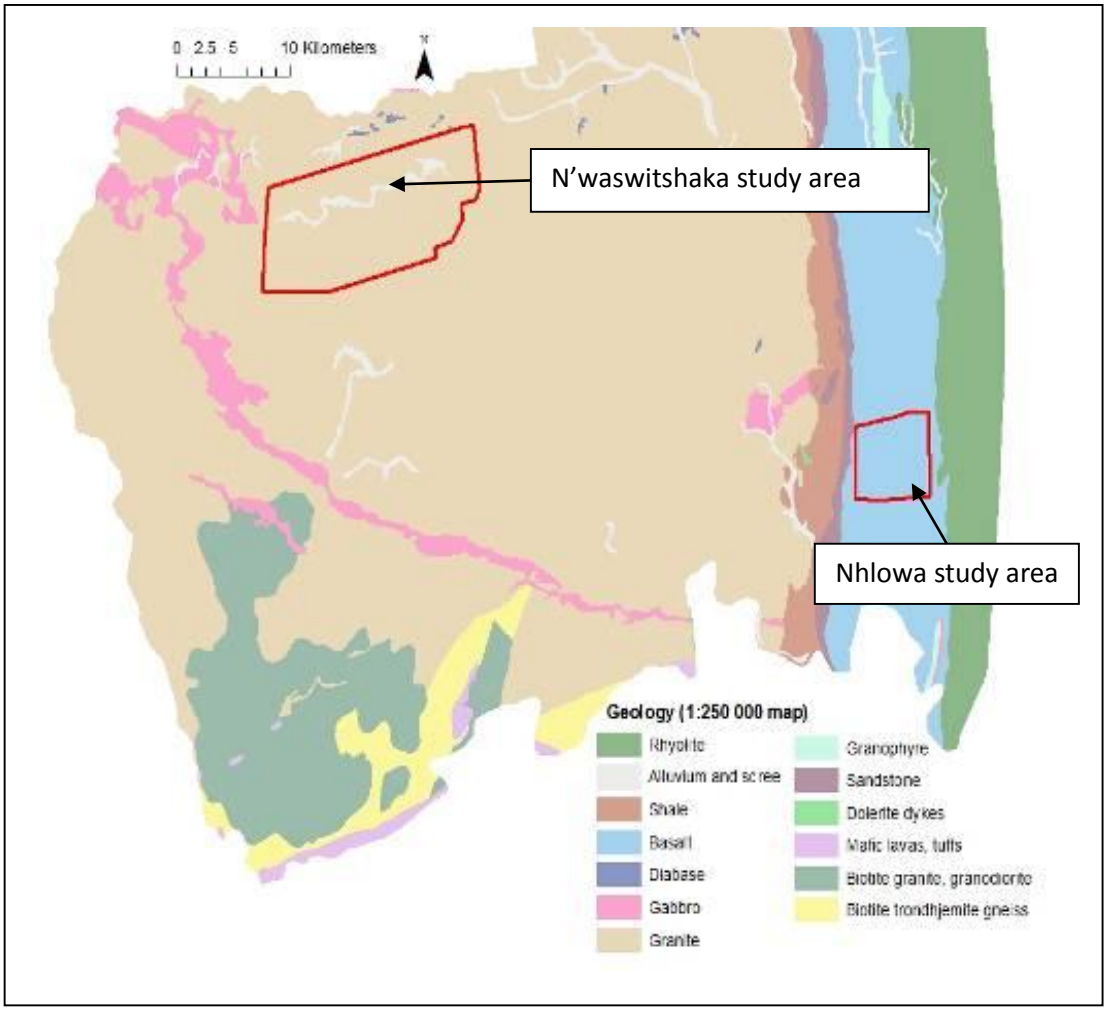


Figure 4.11: The geology of study sites for the delineation of catenal elements.
The N'waswitshaka site is situated on relatively homogenous granite, whilst the Nhlowa site lies entirely on basalt.
(1:250 000 Geological map, Council for Geoscience 1986).

The N'waswitshaka site comprises an area of 178km^2 (approx. 20km x 9km) in the N'waswitshaka River basin that includes part of the headwater zone of the 5th order N'waswitshaka River to the west (highest point 503m) and an area close to the confluence with the very large Sabie River to the east (lowest point 202m). The site lies in a transition zone between the more elevated and wetter granites around Pretoriuskop (to the south west) and the lower lying and drier areas towards Skukuza (to the north east) (Figure 4.12a).

The Nhlowa study area is about 41.5km^2 (about 6.5km x 6.5km) and encompasses the majority of the headwaters of the Nhlowa River. This river rises almost entirely on basalts before traversing through rhyolites, where the stream density increases dramatically. It joins the Sabie River about 10km south of Lower Sabie rest camp (Figure 4.12b). This area is extremely flat, with the highest point in the west some 250m a.s.l., with a drop of only 72m to the lowest point in the north east (250m a.s.l.).

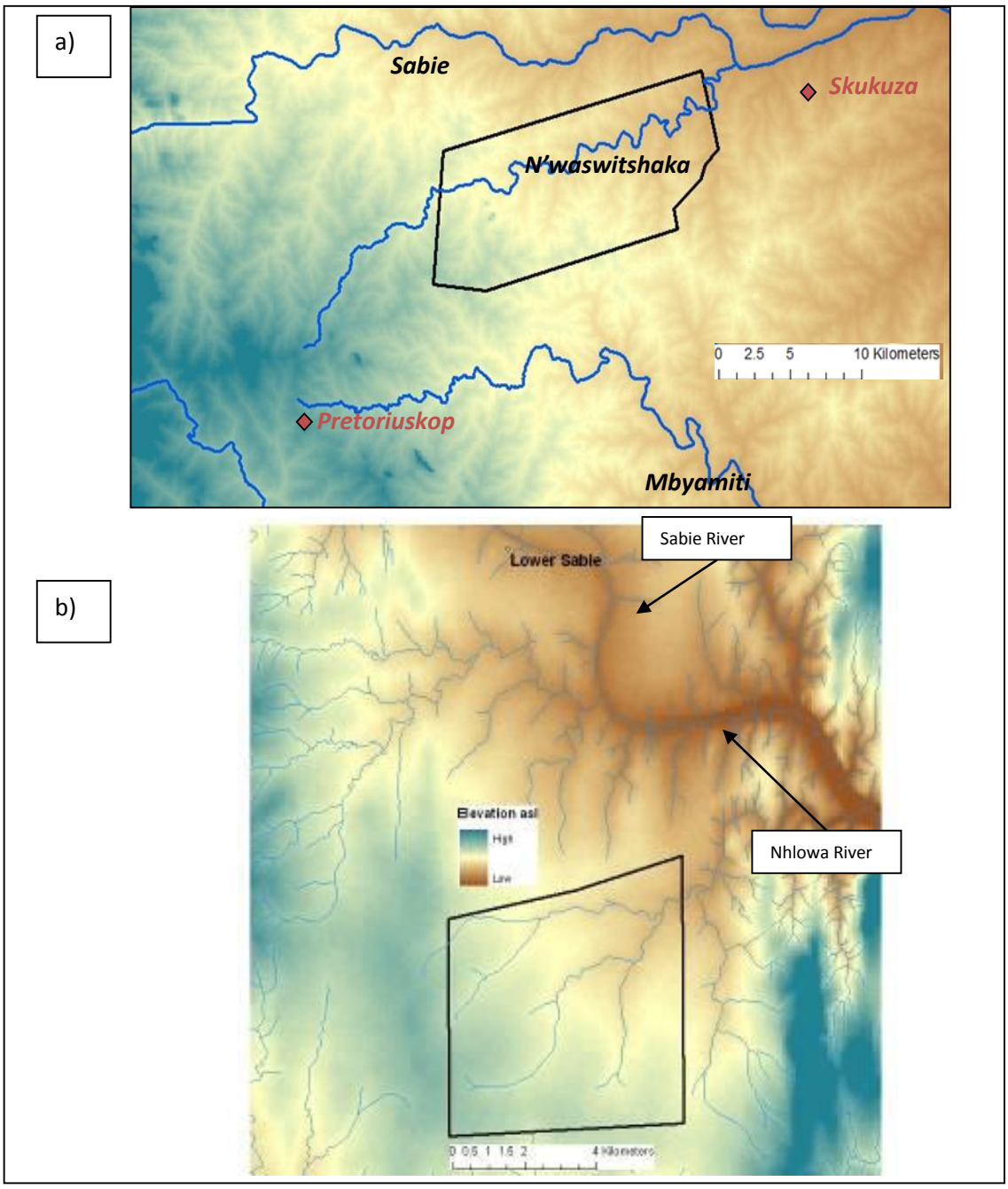


Figure 4.12: Drainage network and elevation in the N'waswitshaka granite and Nhlowa basalt study areas.

a) The N'waswitshaka study area lies in a transition zone between the more elevated and wetter granites around Pretoriuskop (to the south west) and the lower lying and drier areas towards Skukuza (to the north east). The N'waswitshaka River joins the Sabie River some 2km from the north east corner of the scene.

b) The Nhlowa study area lies on basalt and includes most of the headwaters of the Nhlowa River. The area is extremely flat, with an elevation range of only 72m over the whole site. Stream density is far lower than that seen on the N'waswitshaka study area. Note the increased incision and associated higher stream density towards the Sabie River to the north and the elevated rhyolites of the Lebombo Mountains to the east.

(Elevation: SRTM)

4.12 Contrasts between the two study sites

4.12.1 Rainfall, drainage patterns and morphology

The study sites lie on a west-east rainfall gradient. Whilst the N'waswitshaka granite site receives 500-600mm rainfall p.a., the Nhlowa basalt site only receives 400-450mm p.a. (Zambatis, 2003) (Figure 4.13).

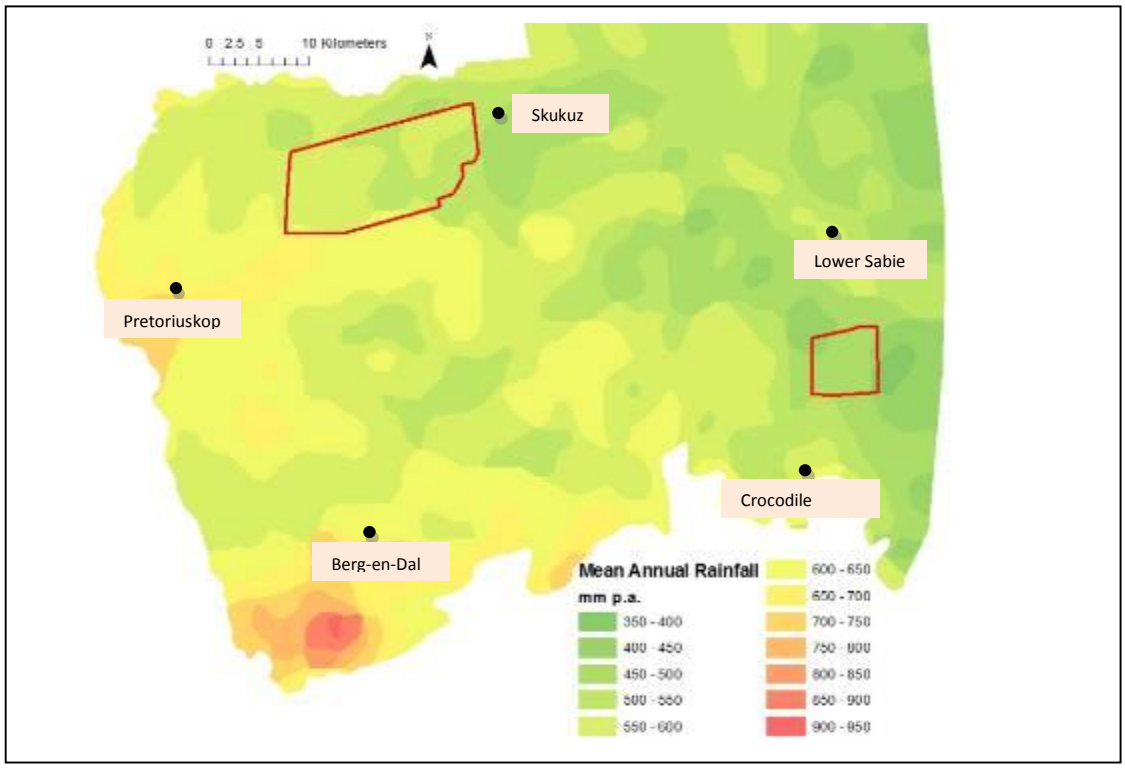


Figure 4.13: Rainfall at study sites in southern KNP.

The N'waswitshaka site receives 500-600mm rain p.a., whilst the Nhlowa basalt site only receives 400-450mm p.a. (Zambatis, 2003; SANParks-GIS, 2010).

The geology and climate of the two sites result in very different drainage densities (2.13km/km^2 in the N'waswitshaka granite study site, compared to only 0.98km/km^2 in the Nhlowa basalts, according to the streams delineated on the 1:50 000 topographical map). This means that hillslopes are much longer in the Nhlowa site: the average distance between streams is 534m in the N'waswitshaka granite site, compared to 1 737m in the Nhlowa basalt site (Figure 4.14).

Quite different processes are implicated in the creation of these drainage patterns. The basalts weather chemically to form soils with high water-holding capacities. Streams start in large vleis likely formed through subsidence associated with a geological fault or weakness (von der Heyden, 2004). These vleis are capable of holding large quantities of water, buffering the effect of early season rainfall events on downstream discharges. By contrast, the less permeable granites weather physically, with young streams cutting back into ridges and crests to form a dense stream network. Water is not generally stored on or near the surface, but runs off over the slopes and through the very flashy stream network, eroding gullies and incised streams on its way downstream (see Venter, 1990; Riddell *et al.*, 2014 and Section 4.12.3 below).

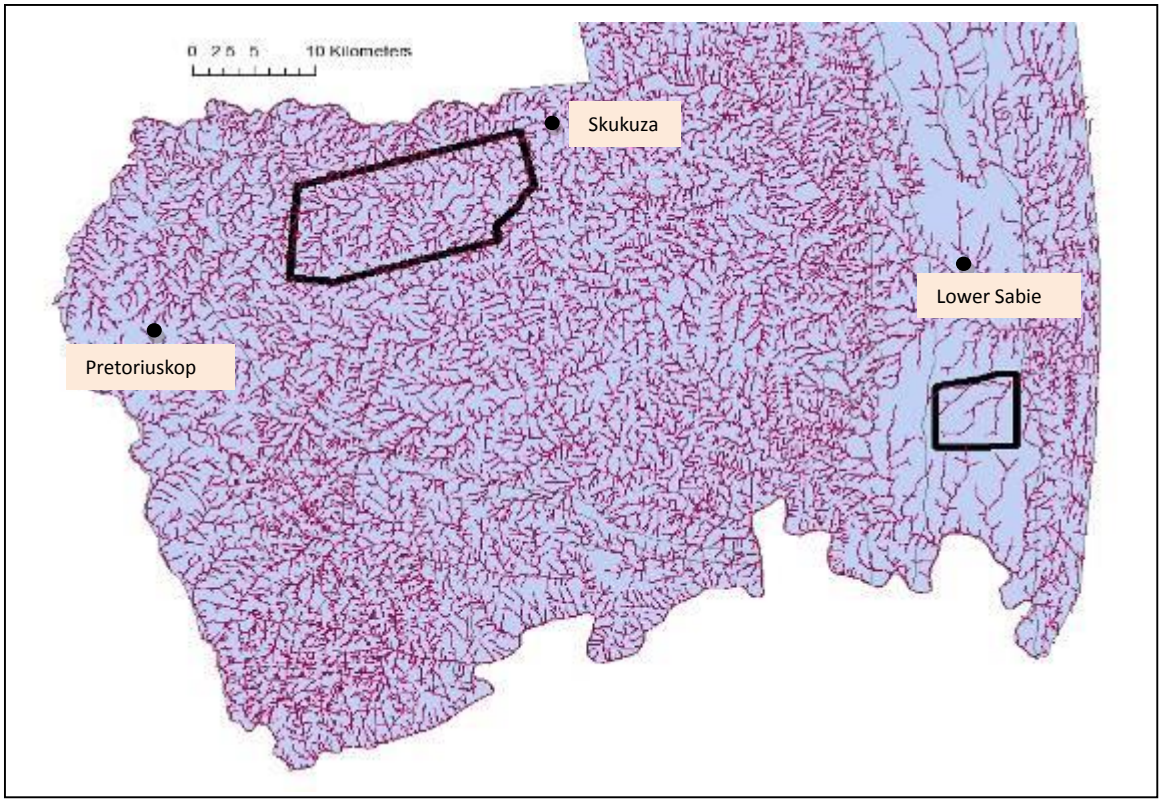


Figure 4.14: Streams in southern KNP.

The N'waswitshaka granite study site has a far higher stream density than the Nhlowa basalt site (2.13km/km^2 in N'waswitshaka, compared to 0.98km/km^2 in Nhlowa, according to the streams delineated on the 1:50 000 topographical map).

4.12.2 Land types

Catenal elements in both sites have been described in detail by Venter (1990). The N'waswitshaka granite site falls almost entirely within the 'Skukuza' land system, with a small area in the north-west that is on the very edge of an 'Orpen' patch, containing a land type that occurs on gabbro. The Nhlowa basalt study area falls entirely within the 'Satara' land system.

The 'Skukuza' land system is characterised by very distinct catenas (Figures 4.15 and 4.16). Crests generally have sandy, well drained soils and moderately dense woody vegetation, whilst midslopes are more open and grassy, with clayey soils. The transition between crests and midslopes is often abrupt, with a seepline that is subject to seasonal waterlogging. I follow Chappel's (1992) description of the catenal units, as shown in Figure 4.16, as opposed to Venter (1990) terminology, in which he refers to the seepline as 'midslope' and combines the mid-and footslopes into a 'toeslope'.

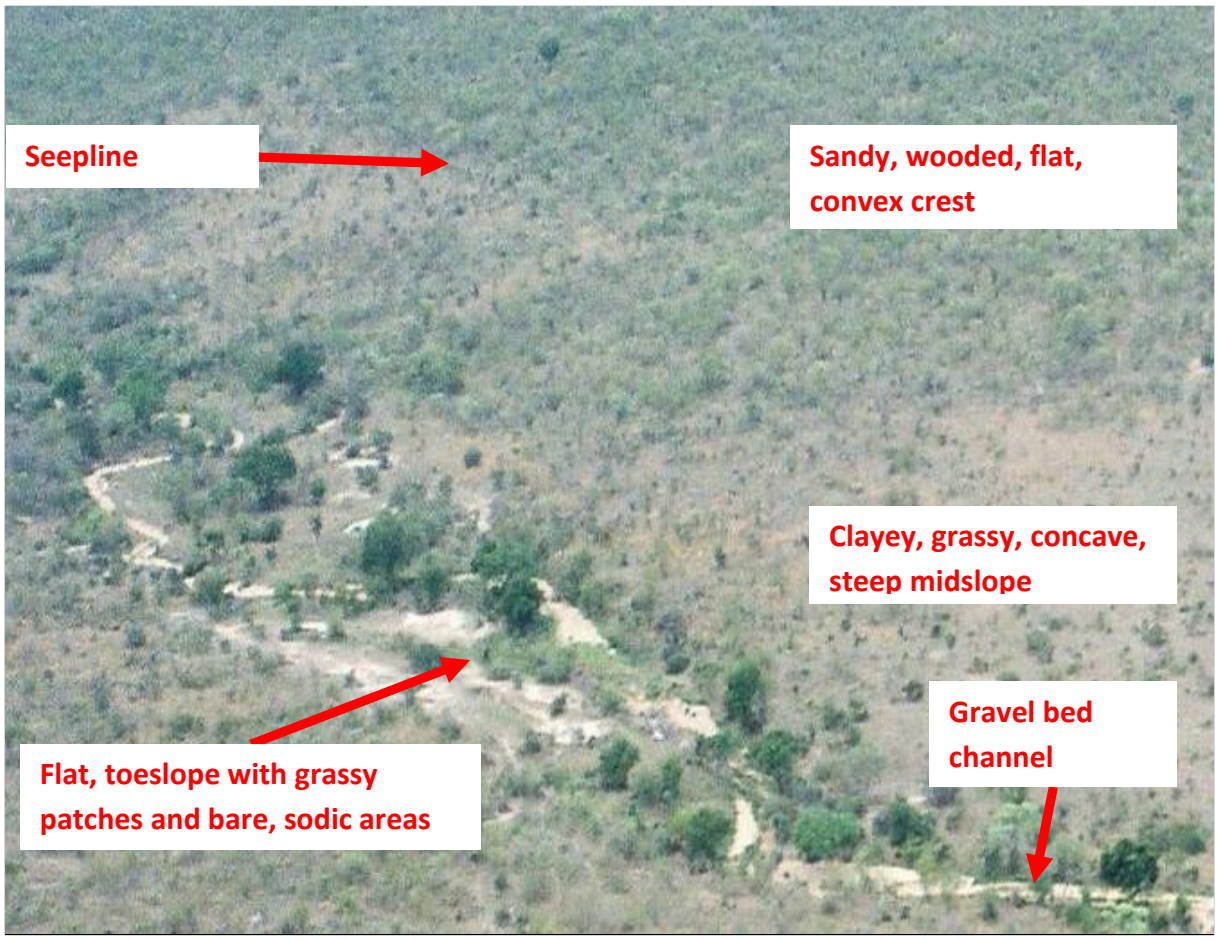


Figure 4.15: Catena in the N'waswitshaka granite study area.
Distinct catenas are seen throughout the N'waswitshaka granite study area. Photo: CC Nov 2006.

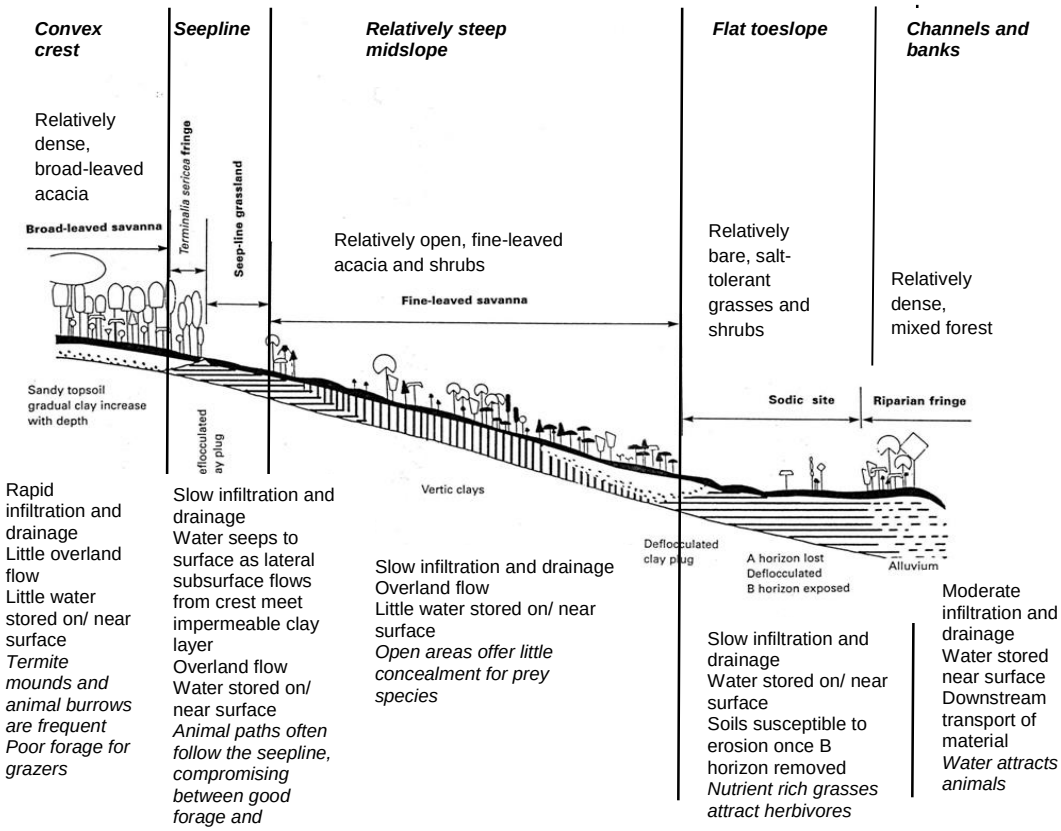
The lower parts of midslopes and footslopes usually have duplex clay soils that contain accumulations of salts (e.g. silica, sodium, calcium, potassium and magnesium) leached from the upper slopes (see Paton *et al.*, 1995; Khomo *et al.*, 2011). These salts create the conditions for deflocculation of clay particles in the B horizons, which makes these layers susceptible to erosion when exposed. Eroded areas, often with patches bare of herbaceous vegetation, are locally known as 'sodic' sites, and are characterised by xeric soils with high pH, poor infiltration and surface crusting. Although seemingly barren, sodic sites are amongst the most productive areas of the park and are well-utilised by herbivores that are attracted by the high mineral and salt content of the forage (Chappel, 1992; Grant & Scholes, 2006; Khomo, 2008; Alard, 2009). Valley bottoms typically contain dense riparian forest with a wide variety of woody species and soils with high organic content (Venter, 1990).

The N'waswitshaka granite study site contains four of the land types that Venter describes as variations of the Skukuza land system. However, these four land systems are very similar to each other, differing mainly in the woody species associated with each catenal element. The main difference occurs in the 'Skukuza' land type (which bears the same name as the land system it is part of) which occurs in the north eastern part of the N'waswitshaka study site. In

this area, open grassy midslopes and toeslopes is replaced by moderately dense thorny thickets.

Gertenbach (1983) partitioned the area slightly differently to Venter. Almost the entire site falls into his "Sabie thickets" category, with a small southern area falling into '*Combretum collinum/ Combretum zeyheri* woodland'. Gertenbach's description of the 'Thickets of the Sabie and Crocodile Rivers' broadly corresponds to Venter's 'Skukuza' land type with uplands characterised by a moderately dense, thorny shrub layer, and brackish, well utilised bottomlands with sparse grass cover and scattered shrubs. Gertenbach's '*Combretum collinum/ Combretum zeyheri* woodland', on the other hand, broadly corresponds to Venter's description of typical granitic catenas with woody crests, a prominent seepline, gassy midslopes and footslopes that often contain sodic sites.

Although most descriptions of catenas usually ignore the channel itself, this forms an integral part of the toposequence (see Chapter 3). Throughout the Skukuza land system, channels tend to have gravel beds that sometimes support reeds in areas where the bed is disturbed relatively infrequently. Most streams are ephemeral, holding water only for short periods after heavy rainfall. Permanent water is only found in large rivers such as the Sabie, outside the study area.



	Crest	*Midslope*	*Toeslope (Floodplains)*			*Channels and banks*
Vegetation	Moderately dense woody vegetation	Open/ grassy	***Bare sodic sites***	***Grassy toeslopes***	***Riparian trees***	Bare gravel bed, reeds or water
Morphology	Flat, slightly convex (profile and plan)	Steeper, flat / concave (profile) Spurs: convex (plan) Gullies: convex (plan)	Flat (profile and plan)			Concave (profile and plan) with steep banks and flat bottoms
Soils	Deep, sandy	Clayey. Wedge-shaped clay layer deepening downslope	Duplex clay Top layer eroded	Duplex clay with top layer intact	Contain organic matter	Gravel bed rivers, organic ally enriched soils on banks
Hydrology	Vertical infiltration, drains quickly to aquifers	Lateral overland flow, little infiltration or capacity for local storage	Vertical infiltration, sometimes connected to groundwater, liable to flooding			Usually dry on surface, but water stored below ground
			Seasonal pans Upward water movement via capillaries	Grass layer suggests little surface water	Can both gain and lose water to channel	

Figure 4.16: Catenal element in the N'waswitshaka granite study area.

Catenas in the southern granites of KNP have been repeatedly described in similar ways by many authors (e.g. Gertenbach, 1983; Venter, 1990; Chappel, 1992; Khomo, 2008). This diagram is after Chappel (1992).

In sharp contrast to the undulating hillslopes of the Skukuza land system and the N'waswitshaka granite site, the Nhlowa basalt study site lies within the very flat Satara land system. Venter (1990) describes this land system as being dominated by wide crests, which generally have deep clay soils. Footslopes and valley bottoms are also flat, with clay soils, such as Arcadia, that have high water storage capacities. These soils swell when filled with water, cracking when they dry, making them susceptible to rapid infiltration. However, repeated swelling and shrinking leads to erosion and subsidence, such that seasonally-filled pans frequently occur. Crests are separated from footslopes and valley bottoms by a narrow, relatively steeply sloping midslope area with sandy soils that forms a lip around the flat valley bottom (Table 4.1).

Gertenbach (1983) describes this landscape as '*Sclerocarya caffra/ Acacia nigrescens* savanna', consisting of an open tree layer (dominated by *Sclerocarya* birrea, subsp. caffra) and *Acacia nigrescens)*, moderate shrub (*Dichrostrachys cinerea* and *Pterocarpus rotundifolius*) and dense grass layers. This description corresponds to the vegetation cover described by Venter (1990) on crests. Venter describes woody vegetation in the midslope and footslope areas as 'moderately dense', dominated by shrubs such as *Dichrostrachys cinerea*. Both Venter and Gertenbach describe valley bottoms as having dense riverine forest growing on organic and alluvial soils. However, such forest is generally associated with higher-order streams than those found within the study area.

Channels in the Nhlowa site are ephemeral, lacking permanent water. However, seasonal pans are often seen on the valley bottom. Seasonal pans and wallows also occur far from the channel, in isolated, seemingly random positions on the crest.

Table 4.1: Previous descriptions of the Nhlowa basalt study area.
Both Gertenbach (1983) and Venter (1990) describe the Nhlowa site in similar ways.

	Crest	***Midslope***	***Footslope***	***Valley Bottom and channel***
Vegetation	Open, dense grass	Open - Moderately dense woody plants	Open - Moderately dense woody plants	Dense riparian forest
Morphology	Flat, slightly convex (profile)	Steeper convex gradient	Flat, slightly concave (profile)	Flat, irregular surface with occasional seasonal pans
Soils	Clay	Sandy	Clay, susceptible to cracking	Clay

4.12.3 Assemblages of catenal elements

The hydrological connectivity between catenal elements is both cause and consequence for the recurring sequences that characterise each landscape. Several authors have inferred hydrological linkages between the elements in this assemblage based upon the infiltration and water holding capacities of the soils associated with each catenal element (e.g. Ticehurst *et al.*,

2007; van Tol *et al.*, 2011). Khomo (2008; 2011) developed a similar conceptual model to explain the co-evolution of the pattern of morphology, soils and vegetation found in an archetypal granitic CASS in the KNP. These models are now being tested and quantified in the newly established supersites, where hydrological instrumentation will provide data on surface and subsurface water movements, as well as links to deep groundwater aquifers (Riddell *et al.*, 2014). Meanwhile, the best available conceptual models describing hydrological regimes in the two study sites are summarised below.

Southern granites (similar to N'waswitshaka study site)

The hydrology of the southern granites is characterised by short-lived responses to rainfall events, during which it is hypothesised that aquifers are recharged via the sandy crest soils and subsurface macropores transport interflow from the midslopes to the channel (Riddell *et al.*, 2014). Channel reaches gain water during these events from this interflow and from hillslope runoff, with fast-rising, flashy responses. Transmission losses from the gravel-bed channels to subsurface aquifers are high, so that streams flow intensely during an event, but subside quickly after the event, so that low-order channels only flow rarely. Deep bedrock aquifers connect all parts of the landscape (Figure 4.17 and Table 4.2).

The above pattern varies slightly by stream order. As stream order increases, midslopes tend to become less steep and toeslopes become more prominent as floodplains develop, often containing sodic sites (Section 4.12.2). Soil depth also increases in higher order CASSs and catchments (Venter, 1990; Khomo, 2008), offering more water storage capacity and increasing both interflow and baseflow.

Local anomalies to these general patterns are likely to be frequent. Flows will be interrupted by local geological features such as dolerite intrusions or bedrock outcrops and fractures (which are all very common in this area (Venter, 1990).

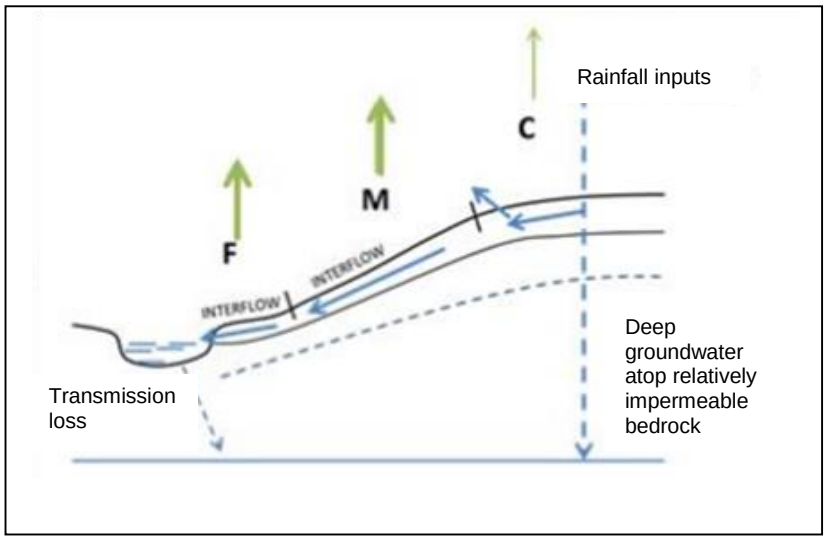


Figure 4.17: Conceptual hydrological connectivity for KNP southern granites and N'waswitshaka study area.

F= Footslope (toeslope/floodplain); M= midslope, C= Crest. Green arrows represent evapotranspiration (highest on midslope, least on crest) (after Riddell et al.*, 2014).*

Table 4.2: Soils and hydrological connectivity in KNP southern granites and N'waswitshaka study area. (Venter, 1990; Riddell et al., 2014).

	Soil	***Infilt-ration***	***Drain-age***	***Storage capacity***	***Surface flows***	***Vadose zone flows***	***Saprolite/ bedrock flows***
Crest	Sandy	Rapid	Rapid	Low	Rapid vertical infiltration to aquifers. Little overland flow.	Lateral flow, connected to channels.	Infiltration through joints to ground-water aquifers.
Seepline	Sand/ clay abrupt transit-ion	Slow	Slow	Medium	Seasonally waterlogged, occasional pans.	Interflow from crest seeps above ground as it meets relatively impermeable clays.	Slow lateral flow downslope through preferential pathways. Little vertical infiltration except where joints are present.
Midslope	Clay	Slow	Slow	Low	Lateral overland flow, high evapo-transpiration.	Lateral flow below clay and above saprolite/ bedrock, macropores.	
Toeslope	Clay Duplex	Slow	Slow	Medium	Poor vertical infiltration, little overland flow except in eroded gullies. Susceptible to erosion once B horizon removed. Liable to ponding, pans used as wallows by animals.	May connect to groundwater when saturated. Some upward capillary flows.	
Riparian trees	Loamy Organic			Medium	Little overland flow, High evapotranspirati on. Hydraulic uplift by trees.	Alternately gains and loses water to channel.	
Channel	Gravel	Rapid	Rapid	High	Usually dry on surface, high transmission losses. Occasional ponding. Some grassy patches/ soil in areas that are not frequently inundated.	Low baseflow, with event-driven contributions from hillslope run-off and interflow. Frequently connected to groundwater. Water sometimes stored locally near surface (elephants dig for it).	Deep aquifers connected to crest.

Southern basalts (similar to Nhlowa study site)

In contrast to the physical erosion and downslope transport of minerals and sediment that results in the finely dissected landscapes in the granites, soils in the southern basalts are generally formed by chemical weathering *in situ (*Venter 1990). High rates of infiltration and water storage capacity mean that the clay soils wet up quickly in the early rainy season and hold water after the rains have ended. Water is stored locally, with little or no lateral movement of water, leading to large, flat crest areas that are only occasionally punctuated by shallow depressions that are connected to form a drainage network (Figure 4.18). It is hypothesised that crests are not hydrologically connected to the valley floor except by deep bedrock aquifers that can store water in bedrock fractures. However, midslope and lower crest areas may be periodically connected to the valley bottom through vadose zone saturation that rises and falls depending on seasonal inputs (Riddell *et al.*, 2014). This zone is believed to act like a sponge (as described in von der Heyden, 2004), buffering upslope events and attenuating downstream discharges in the early wet season. Once the valley bottom is saturated, it is likely to remain waterlogged throughout the rainy season, with large pans and multiple small channels running more or less permanently during summers with above average rainfall (Table 4.3). Geomorphic 'work' is likely to be concentrated in the rainy season, when the valley bottom may occasionally be completely inundated up to the midslope lip, with undercutting of the lip also occurring from upslope seepage through the midslope.

Isolated pans occur in seemingly random positions on crests, associated with depressions that are likely to be associated with subsidence and enlarged through animal use. These perched aquifers and pans are likely to be endorheic, disconnected from the channel network (Cullum & Rogers, 2011).

Continuous channels are only seen in the Nhlowa basalt site along the short length of third order stream in the north east. Once continuous incised channels, together with associated riparian forest and floodplains develop in high order rivers on the southern basalts, the hydrological patterns described above may change. However, since no differences in hillslope morphology are evident in the low order channels seen in the site, the conceptual model described above is likely to apply across all low stream orders.

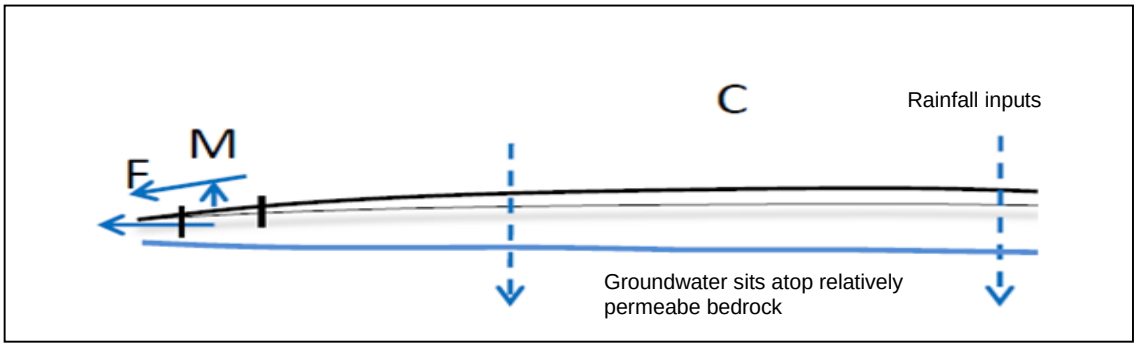


Figure 4.18: Conceptual hydrological connectivity for KNP southern basalts and Nhlowa study area. F= Footslope (valley bottom); M= midslope, C= Crest. Green arrows represent evapotranspiration (after Riddell et al*., 2014).*

Table 4.3: Soils and hypothesised hydrological connectivity in KNP southern basalts and Nhlowa basalt study area.
(Venter, 1990; Riddell et al., 2014).

	Soil	***Infilt-ration***	***Drain-age***	***Storage capacity***	***Surface flows***	***Vadose zone flows***	***Saprolite/ bedrock flows***
Crest	Clay	Medium	Medium	Medium	Vertical infiltration, little/no overland flow. Occasional pans.	Vertical infiltration to occasional perched aquifers.	Storage in fractured rock, disconnected from channel.
Midslope	Sandy loam	Rapid	Rapid	Low	Vertical infiltration, some overland flow.	Interflow to valley bottom, with seepage from the bottom of the hillslope.	Storage in fractured rock, seasonal connection to channel.
Valley bottom	Clay	Medium (rapid when dry)	Slow	High	Vertical infiltration, seasonally waterlogged, with pans and channels within confines of valley bottom.	High storage capacity and seasonal recharge of deep bedrock aquifers.	High storage potential that buffers down-stream discharge in early/ late rainy season.

4.13 Summary

The vegetation, soils and morphology of KNP are clearly linked to the variations of climate and geology within the park, forming spatial clusters of interdependent ecological attributes. Together with the history of interdisciplinary science and collaboration between science and management, the presence of tightly coupled ecological patterns and processes make KNP an excellent place to trial my new conceptualisation of savanna landscapes.

The next section of this thesis presents a landscape classification of KNP at the three organisational levels of the landscape hierarchy. In the next chapter, catenal elements are mapped for the two contrasting study sites on basalts and granites. In subsequent chapters catchments and CASSs are delineated for the entire park and assemblages of catenal elements within the study area are discussed. In Chapter 7, physiographic zones within the whole KNP are mapped and contrasted with the land classifications by Venter (1990) and Gertenbach (1983) that have been presented in this chapter.

CHAPTER 5: RESULTS PART ONE: CATENAL ELEMENTS

Abstract

In this chapter the conceptualisation of savanna landscapes is developed at the lowest hierarchical level of catenal elements. Catenal elements are parts of a hillslope that contain distinct water budgets that are both cause and consequence of particular combinations of vegetation, soils and morphology. The conceptualisation is applied to two contrasting study areas in southern KNP: the N'waswitshaka granites and the Nhlowa basalts. After a consideration of the general approach and mapping technique, a priori *archetypes of catenal elements are developed and mapped in each area. The classifications are evaluated in terms of how well they describe the landscapes in each study site and in terms of the improvements they offer over previous classifications. Finally, I reflect on the process of classification and implications for the construction of geographical ontologies.*

5.1 Introduction

Catenal elements are patches within a catchment that have a particular combination of plant cover, soil, hillslope characteristics (e.g. gradient, curvature and aspect) and hillslope position and which differ from the combinations of these attributes found in neighbouring patches (Figures 5.1). The concept of catenal elements is derived from a synthesis of

- The concept of a dynamic patch mosaic, as described in the American school of landscape ecology (e.g. Wu & Loucks, 1995 and see Section 2.3.2),
- The soil-landscape model, which describes hillslope toposequences of patches with coupled soils and vegetation cover (e.g. Huggett, 1975; see Section 2.6.1),
- Similar concepts used in hydrological modelling, in which patches are connected to each other and to groundwater aquifers by ever-changing hydrological fluxes, both on the surface and through subsurface vadose and bedrock strata (e.g. Jenerette *et al.*, 2012 and see Section 2.7.2) and
- River classifications that describe reach -scale variations, situated within the context of catchments and regional climate/geological zones (e.g. Brierley & Fryirs, 2005 and see Section 2.7.2).

Unlike many soil-landscape models, river reaches are included as catenal elements in this thesis, allowing the entire landscape to be partitioned into catenal elements, uniting hillslopes with the channels that they drain into (Section 3.4.3). Catenal elements are both structural and functional units, since the particular combination of soils, vegetation and topography that characterise each unit is both cause and consequence of a distinct water budget that varies according to the amount of rainfall inputs and the consequent degree of soil saturation. In semi-arid settings, the hydrological flows that connect catenal elements are usually intermittent, with permanent water channels or pans generally found only in very large rivers or associated with human activity (e.g. dams or artificial watering holes).

In this thesis, catenal elements are conceived as part of the biophysical template that serves as a foundation upon which ecological processes are played out (Caylor *et al.*, 2005a; Monger & Bestelmeyer, 2006). The template is considered to be bounded within a range of variability associated with decadal time scales (Section 3.6.3). Thus, whilst variability associated with the different seasons and relatively frequent floods and fires are considered as different expressions of a single catenal element, catastrophic changes associated with regime shifts (*sensu* Scheffer *et al.*, 2001) would change the identity of the element, such that new archetypes, classifications and maps would be needed.

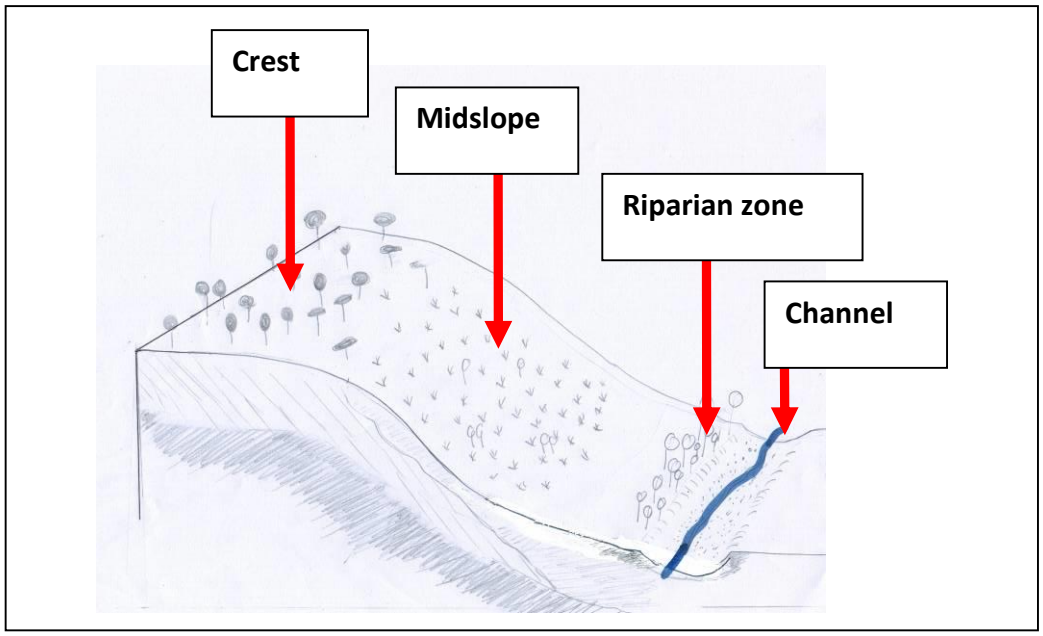


Figure 5.1: Examples of catenal elements. -
Each catenal element in the toposequence has characteristic topography, soils, vegetation and hydrology, offering different resources for animals. Although catenas are often represented as transects down a hillslope (e.g. Figure 4.16) they are more realistically conceived in three dimensions.

The variability of catenal elements in a particular place is limited by their context, both in terms of the vertical constraints imposed by their location within a physiographic zone and within a stream network, and also in terms of horizontal constraints imposed by neighbourhood relationships. These constraints limit the types of ecological processes that can occur in a catenal element, the rates of these processes and the range of biota that can be supported. These constraints generate co-evolved clusters of interdependent environmental attributes, forming a highly organised landscape (e.g. Salthe, 1985; Salthe & Matsuno, 1995; Jenerette *et al.*, 2012; Pelletier *et al.*, 2013). Reciprocal relationships also exist between the physical nature of catenal elements and the animals they support. For example, the sandy soils of granite crests in southern KNP offer suitable habitat for termites whose activity alters the hydropedological characteristics of the surrounding area (Konate *et al.*, 1998; Asawalam *et al.*, 1999; Holdo & McDowell, 2004). In turn, these changes increase nutrient availability, influencing plant species and the ways animals use the patch. For example, Holdo & McDowell (2004) demonstrated that elephants were attracted to nutrient rich plants growing on termite mounds in Western Zimbabwe, and it is reasonable to assume that an increased elephant

presence would have further knock-on effects to neighbouring vegetation. Since termites are so intimately associated with processes that create and sustain the character and behaviour of the patch, these creatures can also be considered to be integral parts of the catenal element.

The intensity and effects of disturbances such as fire and flood are also both cause and consequence of the character of catenal elements. For example, both morphology and proximity to river channels affects the likelihood and pattern of flooding, which in turn changes the character of the patch through the deposition of fertile alluvial sediment (e.g. Petts & Amoros, 1996; Hupp & Osterkamp, 1996). The juxtaposition of catenal elements with different vegetation cover also affects the spread and intensity of fire, which in turn leaves different imprints depending on the type of vegetation (Smit *et al.*, 2013b). Catenal elements can therefore be considered from multiple perspectives, expressed in terms of differences in animal usage patterns and disturbance regimes as well as in terms of differences between soils, vegetation, hydrology and morphology.

However, emphasising the geographical patch, rather than the ecological interactions that occur within the patch allows reasonably discrete areas to be defined and mapped in terms of morphology, soils and vegetation, avoiding the complications that arise from the temporal discontinuities of disturbances and from the mobility of some animals and their use of different catenal elements for different purposes. Furthermore, the spatial alignment of many different attributes means that there are many different variables that can potentially be used to identify and map catenal elements. Ideally, as many attributes as possible should be used to define and delineate catenal elements. However, it is convenient to use topographical and vegetation data derived from satellite imagery to map catenal elements, assuming that these distributions co-vary with other, less easily observed characteristics of catenal elements, such as hydrology, soils and animal usage.

Until recently, the mapping of catenal elements and toposequences has been restricted to delineating the areas characterised by different toposequences and then describing the toposequences in terms of transect surveys and two-dimensional diagrams of hillslopes (as in MacVicar *et al.*, 1974; Venter, 1990). However, the increasing availability of fine-scale remotely sensed imagery over large extents means that catenal elements can now be mapped in three dimensions over an entire landscape. This possibility opens up a raft of new questions, such as:

- Estimating the area occupied by each type of catenal element
- Assessing the range of variability within and between classes of catenal elements
- Assessing the extent to which landscapes conform to archetypal descriptions of catenal elements and toposequences
- Assessing the position of certain elements in relation to other elements or attributes (e.g. the position of sodic sites in relation to stream order and channel sinuosity)
- Mapping the boundaries between catenal elements and assessing their position in relation to other attributes (e.g. in granitic landscapes of KNP, assessing the elevation of the seepline above the level of the nearest stream).

In this chapter, I focus on the delineation and classification of catenal elements in two contrasting study sites on the granites and basalts of KNP (see Chapter 4). In the following chapters I will consider the positioning of these elements in relation to toposequences, catchments, stream networks and physiographic zones.

The overall aim of this chapter is to demonstrate how the theoretical conceptualisation of catenal elements and the archetype approach to classification (Section 3.8) can be practically implemented in two very different study areas.

Specific objectives are to:

- Develop an ecological classification of catenal elements, using the landscape hierarchy and observation of the study areas to inform the definition of archetypal catenal elements for two contrasting areas, together with the appropriate attributes, variables, scales of resolution and support (window sizes for the calculation of variables) that are needed to map these elements.
- Assess how well these classifications describe the study sites: do the archetypes fit the landscapes and *vice versa*? What are the differences, where do they occur, and why might they be important?
- Consider how this approach to classification improves on existing ecological classifications of the study areas.

The chapter is divided into method, results and discussion sections. In the method section, my general approach to mapping catenal elements is presented, together with the main techniques I used. The results section for each study site walks through the steps used to map catenal elements in each study site. Both maps are evaluated in the discussion section, which concludes with reflections on the whole process. However, the nature of the subject matter demands that reflections on methodological issues are raised and discussed throughout the chapter.

5.2 Method: Mapping catenal elements

The development and mapping of catenal elements in a given landscape can be broken down into five interrelated steps:

- STEP ONE: Construct *a priori* archetypes of the various catenal elements found in the study area, fleshing out the skeletal definition of catenal elements in the landscape hierarchy to take account of the features and attributes found in a particular landscape.
- STEP TWO: Identify the scale at which catchments and CASSs need to be defined to identify hillslopes that contain the toposequences of associated vegetation and morphology that are suggested by the archetypes.
- STEP THREE: Develop classification rules for delineating and mapping the archetypes. This involves:
- Classification of vegetation

- Classification of hillslope morphology
- An analysis of relationships between these classifications that then informs the development of an integrated rule set for the delineation of catenal elements.
- Map preparation, involving generalisation, smoothing and, if necessary, de-fuzzification to create an area-class map from the membership functions produced by fuzzy classification (see Section 3.8.5).

5.2.1 STEP ONE: The construction of a priori archetypes

- The construction of *a priori* archetypes involves:
- Situating the study area in a regional climatic and geological context
- Gathering general and local knowledge about soils, hydrology, streams and topography both in the study area and in other similar contexts
- Assessing topographic and vegetation patterns visible in imagery (qualitative and/or statistical assessment)
- Field assessment of landscape patterns (if possible).
- Ideally, the archetypes are based on a conceptual model that links observed patterns to the processes that have generated and sustained the pattern, so that the variables selected to describe and map the archetypes are demonstrably related to the dominant drivers and controls that are responsible for the pattern. This conceptual model is gradually refined and adapted to local circumstances through an iterative interplay between general descriptions and observations of particular instances.

During this process, all three levels of the hierarchy are used. At the top-level of physiographic zones, catenal elements are considered in the context of their regional setting, so that knowledge of other similar settings can be incorporated into the development of the *a priori* archetype. Catchments and CASSs are considered at various scales and stream orders, noting repeating patterns of hillslope morphology that are associated with changes in vegetation. Iteration between theoretical framings and qualitative observations in imagery and in the field (if possible) gradually generates a mental model of the catenal elements present in a given landscape, in a manner similar to the development of the mental models used by soil mappers and geomorphologists (Section 2.6.1). On the one hand, the mental model provides a window through which the landscape is viewed, whilst on the other hand, empirical observations and statistical analyses suggest ways in which the general description needs to be modified to apply to a particular landscape. Empirical observations can include visual assessments in the field, remotely sensed data such as satellite imagery or aerial photographs as well as archived data sets and existing maps. Statistical analyses can include detecting clusters and other spatial correlations between attributes (e.g. Irvin *et al.*, 1997), comparisons with field or virtual samples (e.g. Zhu *et al.*, 1997) and the detection of scales at which attributes are most tightly clustered, using techniques such as Fourier analysis or blob detection (e.g. Hay *et al.*, 2002).

5.2.2 STEP TWO: Selecting scales of observation

The conceptualisation of catenal elements as recurring toposequences down the hillslopes of a particular area implies that the first task in the mapping of catenal elements is to delineate the stream network and associated hillslopes. There are several methods for identifying stream networks from a DEM (see Wilson & Gallant, 2000 and Chapter 6). All of these methods entail two related decisions. First, a threshold must be set for the contributing area that is sufficiently large for channelisation to be initiated and a stream to start. Although this threshold can be easily determined in areas with relatively homogeneous lithology, the relevant thresholds can vary widely over quite small areas with diverse geology, vegetation and microclimates. This is because the accumulation of water in sufficient quantities to create surface/near surface flows capable of incision depends on catchment topography, vegetation and soils as well as the nature and timing of rainfall inputs. Second, a minimum mapping unit must be chosen. In many landscapes, the start of streams can be pinpointed in terms of the position where a continuous channel of a certain depth begins, so that these streams can be said to have a finite start (Montgomery & Dietrich, 1992). However, in semi-arid savanna landscapes streams are frequently ephemeral and discontinuous, often with no clear separation between hillslope flow paths and unchannelised streams. In such circumstances, it is not clear where streams start or whether each and every flow path should be mapped as part of the stream network, so that different configurations of headwaters can be mapped at different scales.

Observation of a landscape framed in terms of the conceptualisation presented in this thesis helps to address these issues. By focussing on the finest scale at which recurring toposequences of catenal units can be discerned in aerial photography or satellite imagery, the scale at which streams need to be defined to delineate the hillslopes containing these toposequences is clarified. By draping aerial photographs or satellite imagery over a DEM, topographic grain is clearly visible, as are vegetation differences associated with hillslope position and the presence of streams or places where water tends to accumulate. The finest scale at which recurring toposequences of catenal units can be discerned then informs the scale appropriate to the delineation of the drainage network. In the example for the southern granites of KNP shown in Figure 5.2, the streams and hillslope defined in the 1: 50 000 topographic map are clearly associated with catenal patterns of vegetation, whilst streams delineated at finer or coarser scales do not correspond so closely with vegetation patterns. This correspondence is unsurprising, since rivers on the topographic map were manually delineated using stereoscopic aerial photographs to detect vegetation and morphological patterns associated with stream heads in semi-arid settings (Patrick Vorster, Chief Directorate National Geo-spatial Information, pers. comm.). Thus the method used for the production of these maps makes them highly suitable for my needs.

Visual inspection of the vegetation differences associated with hillslope position that are visible in imagery also informs decisions on an appropriate minimum mapping unit (MMU). The MMU (the smallest area shown in a map) needs to be small enough to distinguish between different catenal units on the vast majority of hillslopes in the area of interest. The choice of MMU for a particular map is therefore informed by the structure of the landscape as wells as by the purpose of the map and the resolution of available imagery.

This approach to scale selection is only appropriate to landscapes with little human modification, since the construction of dams, channelisation, irrigation, cultivation, roads, houses, etc. destroy the co-evolved links between streams, soils, topography and vegetation that underlie the conceptualisation presented in this thesis.

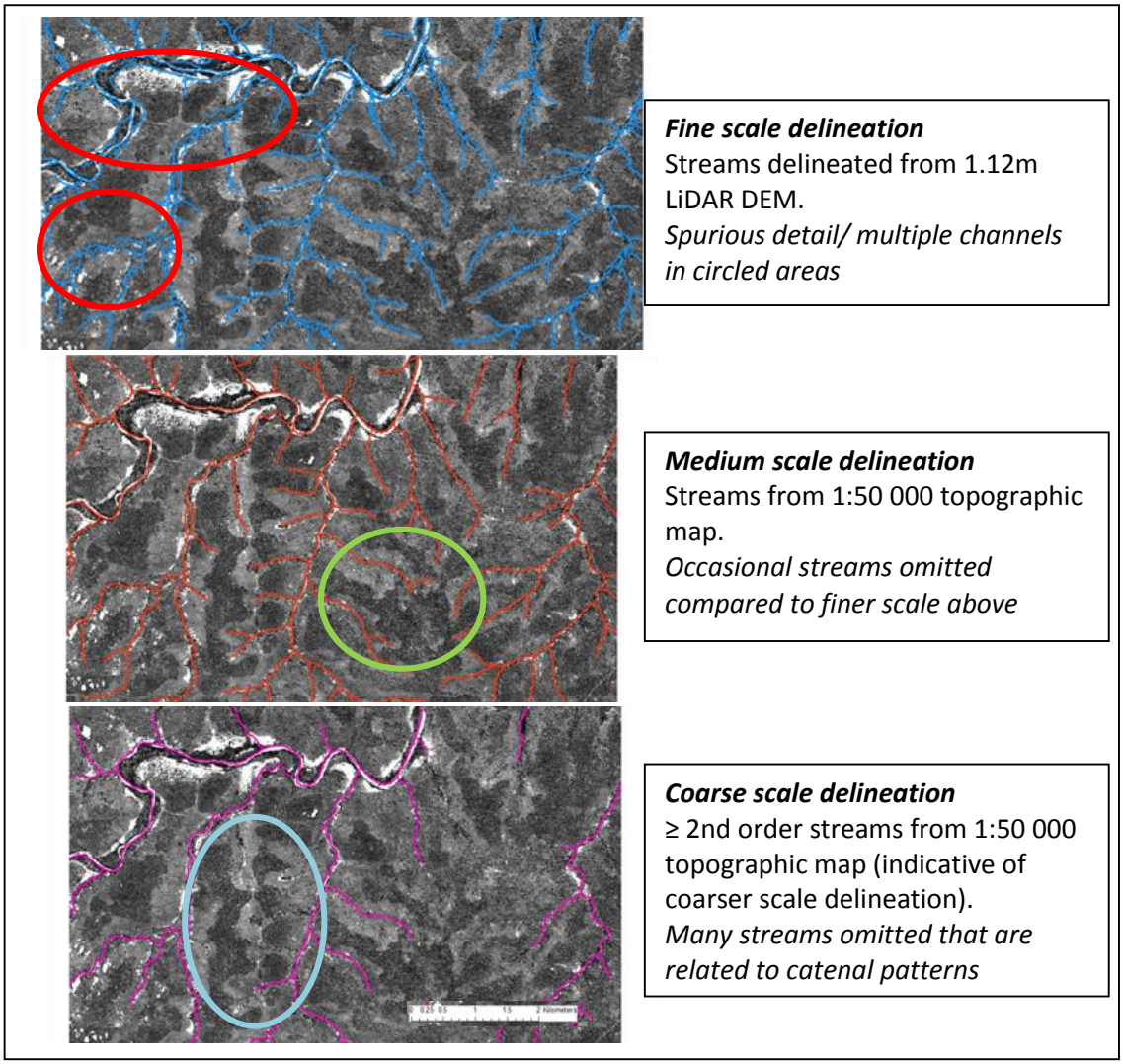


Figure 5.2: Streams delineated at various scales compared to catenal patterns of vegetation in the N'waswitshaka granite study area.

a) Streams delineated from the LiDAR DEM show channels in low lying areas near larger streams that are not associated with catenal patterns of vegetation. b) Streams delineated from the 1 50 000 topographic map, are clearly associated with vegetation patterns. c) 2nd and higher order streams from the topographic map (indicative of coarser-resolution delineation) omit some streams that are clearly associated with catenal patterns of vegetation.

5.2.3 STEP THREE: Develop classification rules for delineating and mapping the archetypes

The first task in developing classification rules for both vegetation and terrain units is to identify potential variables that will efficiently distinguish between catenal units. Even if the choice of defining attributes is limited to vegetation and topography, there is still a multitude of ways in which each of these can vary, and therefore a multitude of variables that can

potentially be used to define and map archetypal catenal elements. The range of available variables is related to differences in:

- *Particular attributes of vegetation or topography*: for example, height, aerial cover, biomass and plant species composition are all attributes of vegetation that can signal differences between catenal elements. Furthermore, the relative importance of each of these attributes in distinguishing between catenal elements varies between landscapes (Torello-Raventos *et al.*, 2013). For example, whilst granitic landscapes near Skukuza are characterised by sandy crests with relatively dense woody cover of taller *Combretum spp.* and clayey midslopes with relatively sparse and shorter *Acacia spp.*, the dominant woody species on both crests and midslopes of granitic landscapes near Pretoriuskop is *Terminalia sericea*, which tends to grow more densely on crests than on midslopes, but to a similar height in both hillslope positions (Venter 1990; personal observations; Figure 5.3).
- *How attributes are measured*: for example, canopy height can be measured as the mean, median, or maximum value over a particular areal unit, or in terms of the percentage cover at a particular height within a group of units (e.g. a window of all neighbouring units within a circle, square or hexagon of a specified size). Similarly, the basic topographic attributes of gradient, curvature and elevation can be described and measured in a myriad of ways (see Wilson & Gallant, 2000). Furthermore, different features are observed using the same topographic metric measured across different distances (e.g. gradient measured over a few metres identifies stream banks or termite mounds, whilst gradient measured over hundreds of metres identifies different parts of an entire hillslope).
- *The time at which an image is captured*: the structure of vegetation patches also changes over time, reflecting seasonal differences in phenology as well as herbivory pressure and disturbances such as fire and flood. Thus different metrics and thresholds may be needed to describe the same patch observed at different moments in time (e.g. in leaf/not in leaf, before/after fire) (Figure 5.4).
- *The type of imagery*: for example, different sensors capture different reflected wavelengths in the electromagnetic spectrum, each signalling different attributes of the earth's surface (Figure 5.4).

The choice of variables used to map catenal elements thus involves an interplay between the abstract *a priori* archetypes, which suggest attributes that are relevant to both the observed pattern and the processes that generate and sustain this pattern, the *imagery* available and differences evident in *the landscape itself*. The process is ultimately subjective, relying on the analyst to find the requisite simplicity that clearly and elegantly describes local archetypes of different catenal elements in terms of a few well-chosen variables. Indeed, subsequent maps may refine the process, developing new ways of delineating and classifying the archetypal catenal elements.

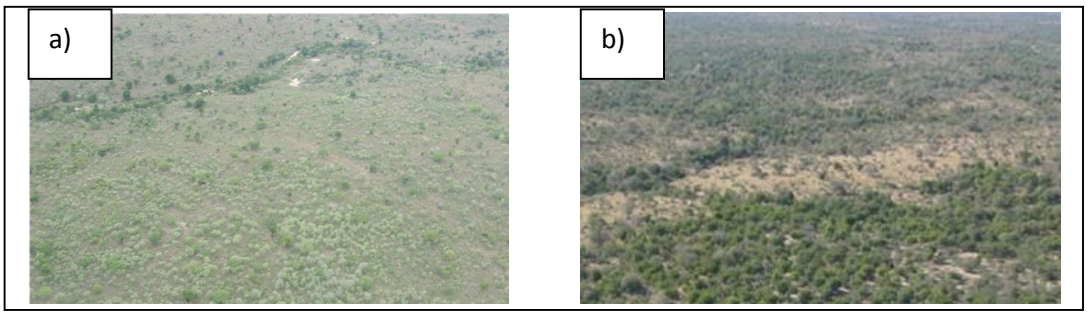


Figure 5.3: Granitic catenas a) near Pretoriuskop and b) in the N'waswitshaka granite study area.

Catenas near Pretoriuskop tend to have less pronounced grassy midslopes than those in the N'waswitshaka granite study area. In the Pretoriuskop area, the dominant woody species on both crests and midslopes is Terminalia sericea, whilst in the N'waswitshaka area, Combretum spp. dominate the crests and Acacia spp. dominate midslopes. These differences demand different variables and rule sets to describe the same catenal elements in each area. Photos: a) KR Apr 2005 b) CC April 2009

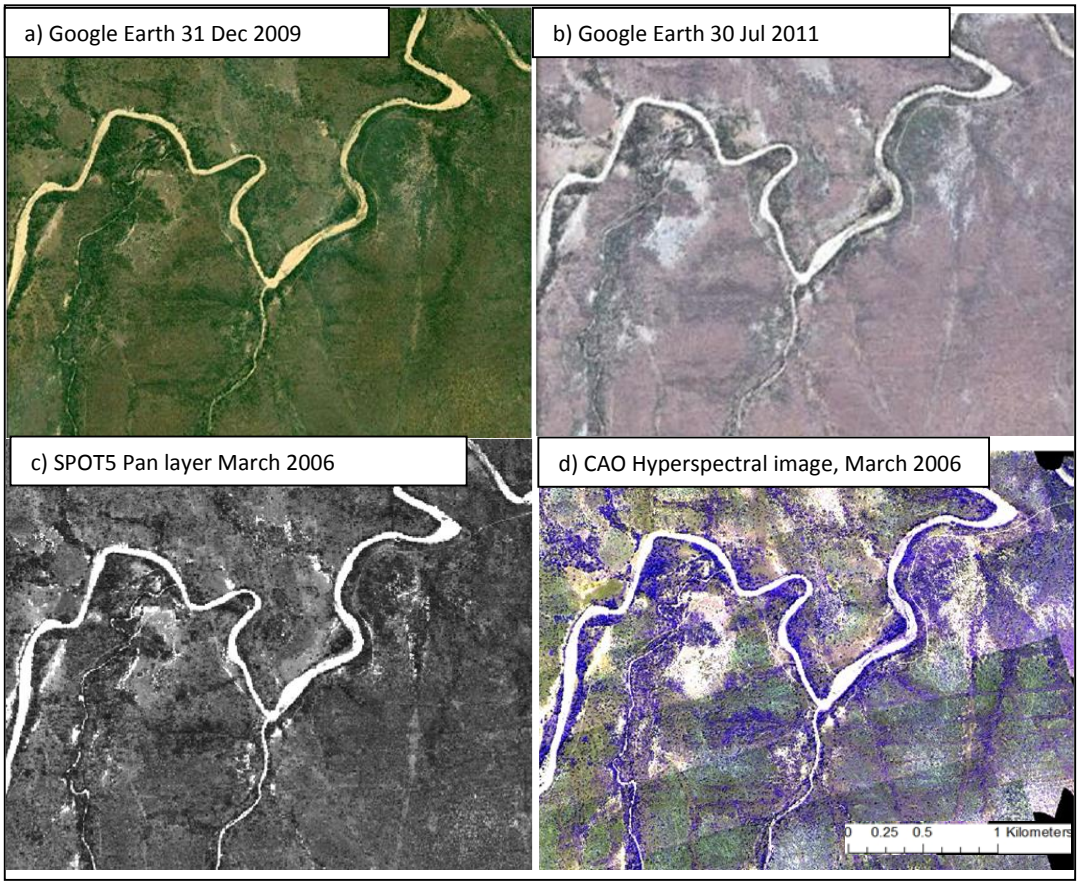


Figure 5.4: Various images of the same location in the N'waswitshaka granite study area.

Different features are more/less easily observed in each image, such that different variables and rule sets are needed to describe the same features in each image. Whereas a) c) and d) were all captured during or soon after the rainy season, b) was acquired during the dry season, when contrast between trees and grass is less clear. The vegetation and moisture changes associated with linear geological features (dykes or fractures that appear as horizontal lines in the centre of the scene)) are seen most clearly in d). Unvegetated areas (e.g. river beds, rocky areas and sodic sites) are less easily observed in a).
Note: the stripes in the bottom half of d) are artefacts a) and b) are 'true' coloured, whereas d) is a false colour composite of various spectral bands.

Once variables are decided upon, the next task is to combine them in ways that identify catenal elements. I used several techniques:

- *Object image analysis*: I started by breaking up the study areas into basic spatial objects that identified small areas that were relatively homogenous in terms of one or more of the vegetation and/or topographic metrics identified in step two. I used the segmentation algorithm encoded in the eCognition software (Trimble, 1995), which is based on a pairwise region-merging technique that iteratively groups pixels and groups of pixels into objects within which heterogeneity is minimised and homogeneity is maximised. User-determined thresholds control the amount of variation that is acceptable in any object. These 'scale' and 'compactness' parameters determine the number and size of objects produced in a segmentation (Baatz & Schape, 2000). Since this technique identifies areas based on local contrasts rather than global thresholds (van Niekerk, 2010), it is well suited to the identification of catenal elements. Furthermore, image objects identified in this way can be grouped and classified using much wider ranges of characteristics that are available for the classification of individual pixels, including contextual and neighbourhood relationships, shape and textural properties as well as the statistical characteristics of GIS layers (Benz *et al.*, 2004).
- *Fuzzy classification:* Where possible, fuzzy classification techniques are used to assess the degree of similarity between an image object and the archetype(s) of each and every class. The characteristics of the conceptual archetype are defined in terms of features that are observable in available data and imagery. The characteristics of the image objects are compared to those of the archetype, using membership functions that specify the relationship between an observed value of each attribute and the degree of class membership associated with this value (see Section 3.8.5). Fuzzy classification techniques provide a useful way of dealing with the blurred boundaries often found in natural landscapes and of describing landscape units and classes in terms of a range of variability (Section 3.8.6).
- *Terrain Units*: Morphological classification involved partitioning hillslopes into 'landforms' or 'terrain units' (see Shary *et al.*, 2002; MacMillan & Shary, 2009). Terrain units are areas of similar topography and hillslope position that define boundary conditions for many geomorphological, ecological, pedological and hydrological processes (e.g. Swanson *et al.*, 1988; Lookingbill & Urban, 2005; Deng, 2007). Although individual topographic variables (e.g. gradient, relief, curvature, etc.) all influence the rate, direction and intensity of water fluxes, these variables are often synthesised in soil mapping to produce 'terrain units' (or landforms) (e.g. Dikau, 1989; Pike, 1995; Dehn *et al.*, 2001; Pike *et al.*, 2008). This approach not only simplifies outputs, since only one result is obtained rather than multiple individual morphometrics, it has also been shown to improve correlations between soil properties and topographical position (Ziadat, 2005; Herbst *et al.*, 2006).

Most approaches to the definition of terrain units first partition slopes along a profile transect, notionally at right angles to the channel, using elevation, gradient and profile curvatures to derive units such as ridges, shoulders, backslopes, footslopes and channels. Shoulder, back- and foot- slopes are then subdivided into convergent, divergent and planar slopes using planform curvatures (e.g. Ruhe, 1956; Pennock *et al.*, 1987; Dikau, 1992; MacMillan & Shary, 2009). Boundaries between these units are based on breaks in gradients and curvatures (e.g. Metternicht *et al.*, 2008). However, hillslope breaks are often very subtle in the relatively flat KNP, and are easily confused with small changes in elevation associated with local features such as boulders, gullies or depressions. The definition of terrain units in my study areas was therefore guided by vegetation patterns and the *a priori* archetypes of catenal elements. This approach also ensured that the topographical variations captured were those most likely to be associated with spatial variations in plant available water.

In each study area I first mapped vegetation and hillslope morphology separately, allowing the definition of terrain units to be guided by vegetation differences and the definition of vegetation units to be guided by hillslope position. I then examined statistical relationships between vegetation and terrain units to quantify these relationships and used the results to refine thresholds in the rule sets that defined the various classes of vegetation and terrain classes. This iterative process ensured that all class definitions reflected the close relationships between vegetation and morphology described in the archetypes. It also revealed some common combinations of vegetation and morphology that were not described in the original set of archetypes, demanding the development of new archetypes to describe the landscape more completely. The final maps of catenal elements were produced by 'defuzzifying' fuzzy classifications to produce area-class maps, smoothing boundaries and merging areas smaller than the MMU.

5.3 Results Part A: Catenal elements in the N'waswitshaka granite study site

5.3.1 STEP ONE: Defining archetypal catenal elements in the N'waswitshaka granite study area

The first task in defining catenal elements in the N'waswitshaka granite study area was to develop *a priori* conceptualisations of archetypes, based on previous descriptions, conceptualisations and classifications of the study area, together with field observations and visual assessments of available imagery.

The N'waswitshaka site comprises a 178km^2 (approx. 20km x 9km) area of the N'waswitshaka River basin. It lies on ancient granites that have weathered to produce a finely incised landscape with a stream density of 2.13km of streams/km^2 (using the streams delineated on the 1:50 000 topographical map). The mean annual rainfall in this area is about 500-600mm p.a., with very high interannual variation (see Chapter 4 for further detail).

Catenal elements in the southern granites of KNP have been described in detail by Venter (1990) and others (see Chapter 4). The initial *a priori* archetypes are based on a synthesis of this knowledge, partitioning hillslopes into elements that are both structurally and functionally

distinct. Structurally, each element is characterised by distinct morphology and vegetation cover, whilst functionally, each element has characteristic water fluxes and a distinct water budget (Section 4.12.3). For the purposes of mapping catenal elements, I focused on structural differences, specifically on differences in vegetation and hillslope morphology that can be observed in remotely sensed imagery.

The initial archetypes for the N'waswitshaka granite study area were defined following the existing research summarised in Table 4.2:

- Crests, flat, slightly convex, with woody vegetation
- Midslopes, grassy, with steeper gradients than crests,
- Toeslopes, flat areas, divided into unvegetated sodic sites, grassy toeslopes and riparian trees
- Channels and banks.

Although crests are separated from midslopes by a narrow transition area around the seepline, even in the fine-scaled LiDAR data, this area is visible only as a boundary on most hillslopes, rather than as a distinct patch. Therefore these areas were not mapped separately.

Figures 5.5-5.8 show examples of these archetypal catenal elements in and around the N'waswitshaka granite study area.

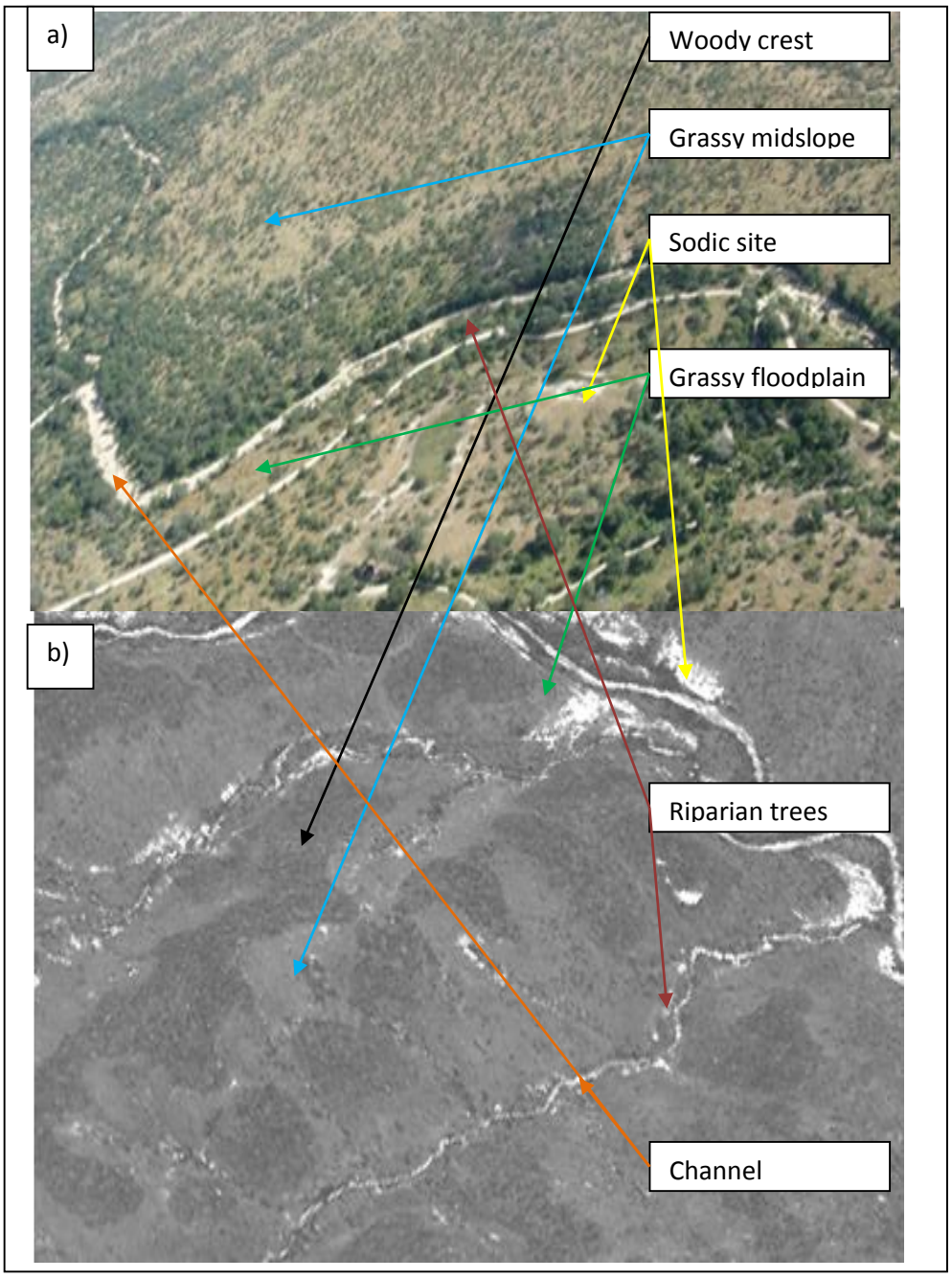


Figure 5.5: Archetypal catenal elements in the N'waswitshaka granite study area.

Areas corresponding to the archetypal catenal elements are repeatedly found throughout the landscape a) N'waswitshaka River Photo: CC April 2009 b) SPOT5 Pan (March 2006) overlaid on 4.8m DEM.



Figure 5.6: Channels and banks in the N'waswitshaka granite study area.

Both low-order (a,c,d,e) and high-order (e) channels generally have gravel beds, with occasional rock outcrops or vegetated patches. Banks on the inside bends are often steep, incised in large, episodic flood events (a). Flows are rare and very flashy (d and e). Photos: a), b) and c) GB mar 2006 and e) CC Jan 2009.

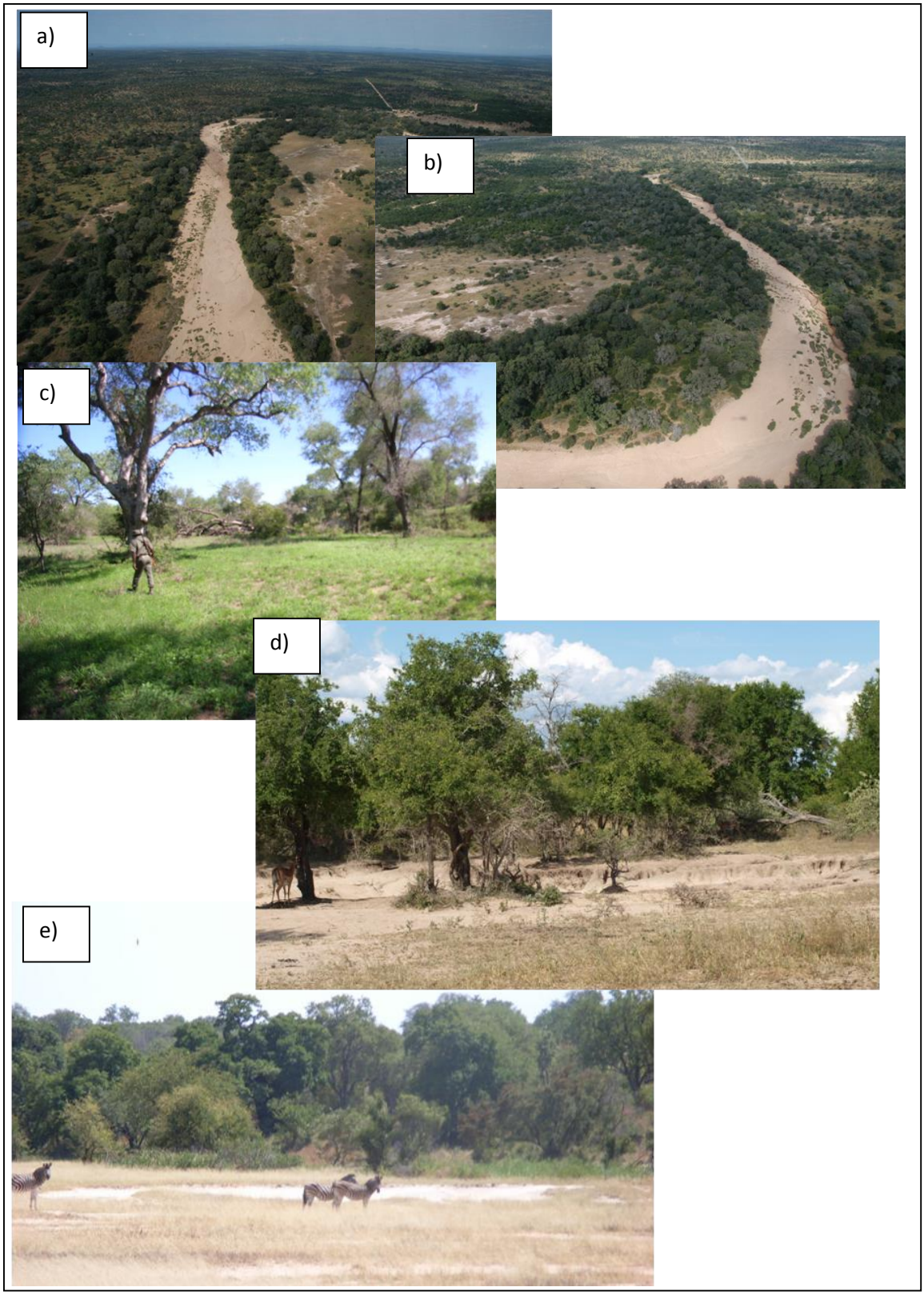


Figure 5.7: Toeslopes in the N'waswitshaka granite study area.

The toeslopes of high order rivers (a and b) often contain dense riparian forest. Sodic sites are often seen on the inside bends of these rivers (a,b,c and d). Sodic sites often eroded (note the steep sides of the eroded patch in d) and herbivores are attracted by the high level of salts in the grasses (e). Some toeslopes are grassy (c). Photos: a) and b) CC April 2009 c) CC Dec 2007 d) CC Mar 2010 d) CC Mar2007.

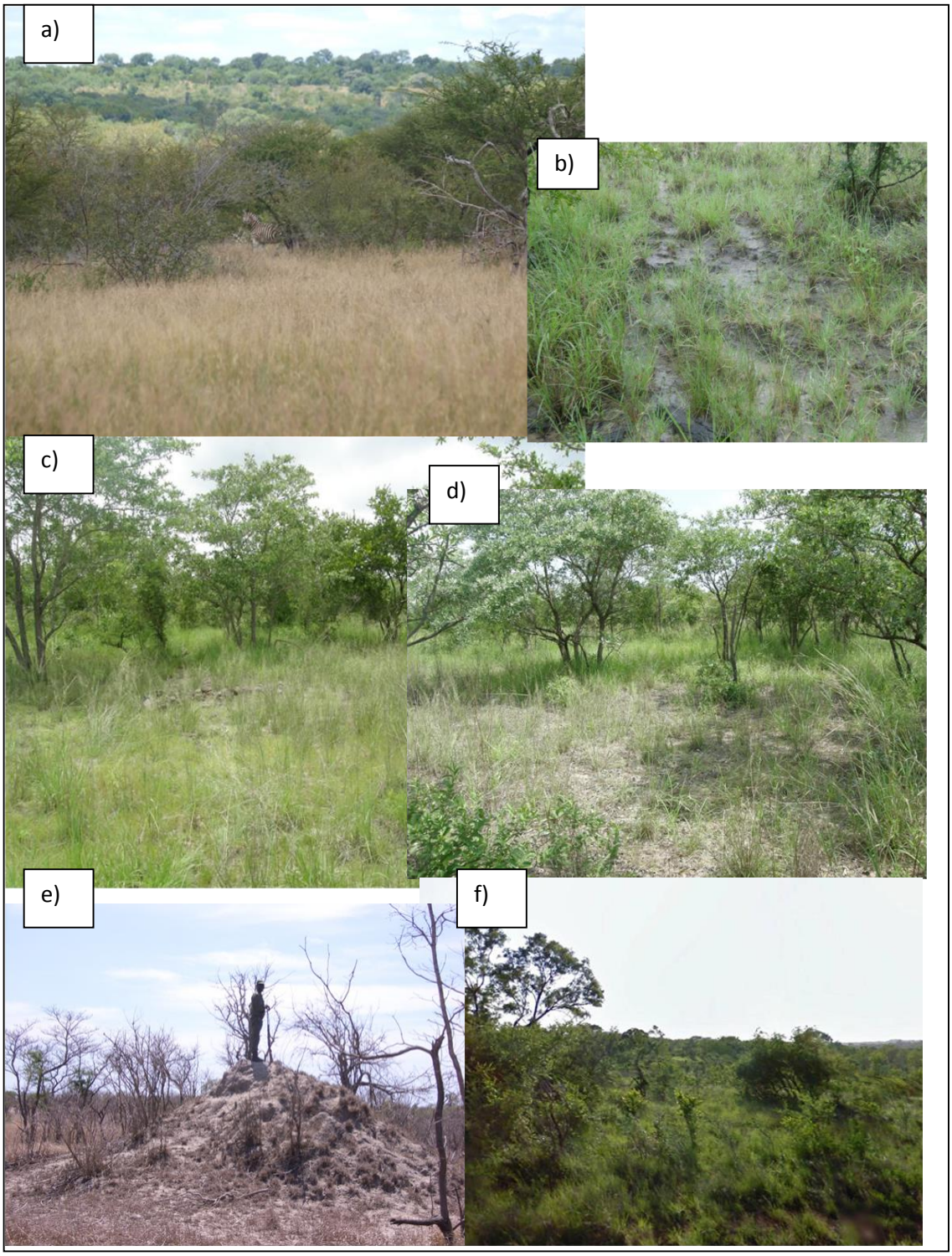


Figure 5.8: Midslopes and crests in the N'waswitshaka granite study area.

Midslopes are generally open, grassy areas (a). Despite the grass cover, surface runoff can occur after intense storms (b). The seepline is characterised by Terminalia sericea and an area subject to waterlogging that often contains sedges (c and d). Termite mounds are often found on the sandy crests (e), which are generally more densely vegetated than midslopes (f). Photos: a) GB Mar 2010 b) c) d) and f) CC Jan 2009 e) CC Nov 2006.

5.3.2 STEP TWO: Selecting scales

Streams shown in the 1: 50 000 topographic map, are clearly related to catenal patterns of vegetation (Figure 5.9b and Section 5.2.2). The average CASS width is 534m, suggesting that the mean hillslope length is around 265m. This means that the 90m SRTM DEM is inadequate for describing the morphological differences that characterise each catenal element. LiDAR data collected at 1.12m resolution was available for this site, but manipulating data with such fine resolution over a 178km^2 site would have demanded considerable computing power and time. I therefore aggregated the DEM to 4.48m resolution. I also smoothed the surface, removing termite mounds to focus on broad patterns of hillslope curvature, rather than on local features.

A similar resolution is needed in the imagery used to detect vegetation differences associated with catenal elements. The SPOT5 imagery used for the vegetation classification has a slightly finer resolution of 2.5m.

The MMU was set at 1ha, equivalent to about 500 pixels with a 4.48m resolution, which was qualitatively judged to capture most of the smallest catenal elements visible in the SPOT5 image (Figure 5.9a).

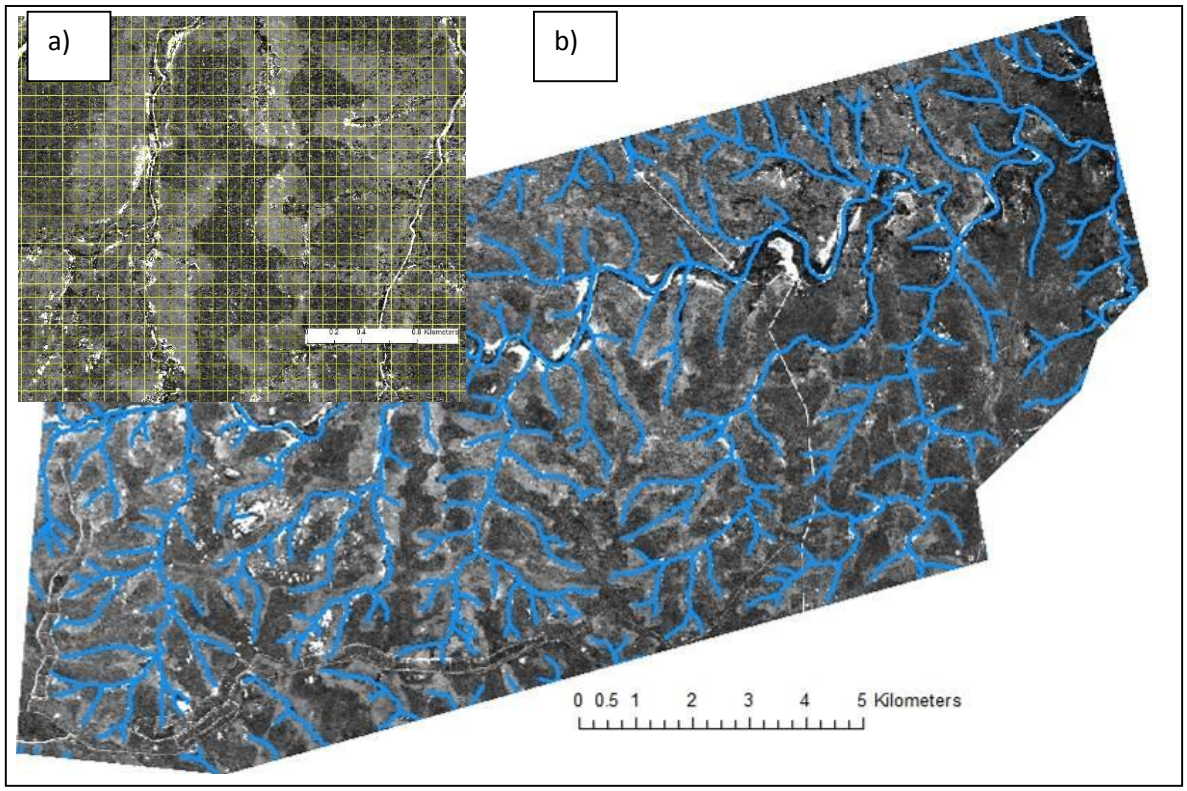


Figure 5.9: Scales of observation for the N'waswitshaka granite study area.

a) A MMU of 1 ha is equivalent to the area shown on each square of the grid overlaid on the SPOT5 image. A MMU of this size excludes the smallest 'pepper and salt' vegetation differences, which tend not to be part of repeating toposequences, but retains the smallest catenal elements
b) Streams shown in the 1: 50 000 topographic map (in blue), are clearly related to catenal patterns of vegetation (which appear in various shades of grey in the SPOT5 pan image.

5.3.3 STEP THREE: A) Vegetation classification

The initial *a priori* archetypes developed for the N'waswitshaka site require that vegetation cover is separated into “woody” (associated with crests) and “grassy/ reeds” (associated with midslopes, toeslopes and reed beds in rivers), “bare” (associated with sodic sites and gravel bed rivers) and “water” (associated with channels) (Table 4.2).

The expected variation of vegetation with hillslope position is clearly seen in the 2.5m resolution panchromatic SPOT5 data (Figure 5.10a). Trees show as darker patches, due to their shadows and green colour at the time of the image (March 2006 at 7:52am). There is a strong correlation between NDVI (Normalised Difference Vegetation Index - the normalised difference between a near infra-red (NIR) band in a remotely sensed image) and a band in the region of visible light (e.g. Band 3 and Band 2 in SPOT5 images) and the reflectance of the panchromatic image (Figure 5.10b). A similar pattern is seen in the percentage cover over 2m in height, derived from the LiDAR data. However, this pattern is complicated by the varying height of woody patches on crests in different parts of the image. In the east of the image, crest positions in the shrubby Skukuza thickets are dominated by *Dichrostachys cinerea,* whilst in the centre and west of the scene, the taller *Combretum apiculatum* dominates crests, and trees of a similar height to *D. cinerea* are found on the midslope (Section 4.12.3). The relative density of woody cover is therefore shown more clearly in the SPOT5 imagery.

However, even in the SPOT5 imagery, the pattern is challenging to classify automatically as there is no single threshold that separates the generally more dense woody cover on crests from the generally less woody and grassier cover on the midslopes. The relevant threshold of woody cover varies considerably over small areas (under 4km^2) in relation to factors such as species composition, burn history, geology, aspect, etc.. I therefore developed a classification procedure based on the *relative* 'woodiness' and grassiness' of neighbouring patches.

Vegetation classes were delineated and classified by first segmenting the SPOT5 panchromatic layer into image objects (using eCognition Developer 8.0 (Trimble, 1995) and then classifying these objects (Box 5.1). Scale parameters for the segmentation were chosen to produce small enough objects to separate the various features of riparian areas (e.g. to differentiate between bedrock/ sand river beds and unvegetated sites near, but not within, a channel). The objects also had to be large enough to group patches of vegetation that need to be considered as a whole when using contrasts to distinguish between patches of relative grassiness or woodiness.

To classify the *relative* 'woodiness' and grassiness' of neighbouring patches, the extreme ends of the grassy-woody spectrum were defined first, using thresholds of pan reflectance that clearly corresponded to areas that are definitely 'woody' and 'grassy'. After re-segmenting unclassified objects at a finer scale, this procedure was repeated. The remaining unclassified objects were then compared to the mean pan values for ‘definite’ tree and grass objects. Membership values for new ‘fuzzy’ ‘tree’, ‘grass’ and ‘both’ classes were evaluated using membership functions. The mean pan reflectance values of each object were compared to the mean values of neighbouring objects. If the difference between an object and a neighbour classified as ‘tree’ was +10 or more, then it was given a maximum membership value for ‘grass’.

If the difference was less than 10, then a lower membership value for 'grass' was assigned, according to an S shaped membership function with a minimum value of 0 (Box 5.1). The same object was also compared to neighbouring objects classified as 'grass'. If the difference was -10 or more, then a maximum membership value to 'trees' was assigned, with decreasing membership values being assigned as the difference narrowed to 0. If the object was equally similar to the mean of both classes (difference of +/- 10 in the reflectance value), then it was classified as 'both'. Objects were then assigned to the class with the highest membership function. 'Fuzzy' trees and grass objects were then grouped with the 'definite' tree and grass objects respectively, whilst 'fuzzy both' objects remained unclassified, reflecting the true ambiguity of the landscape in these areas.

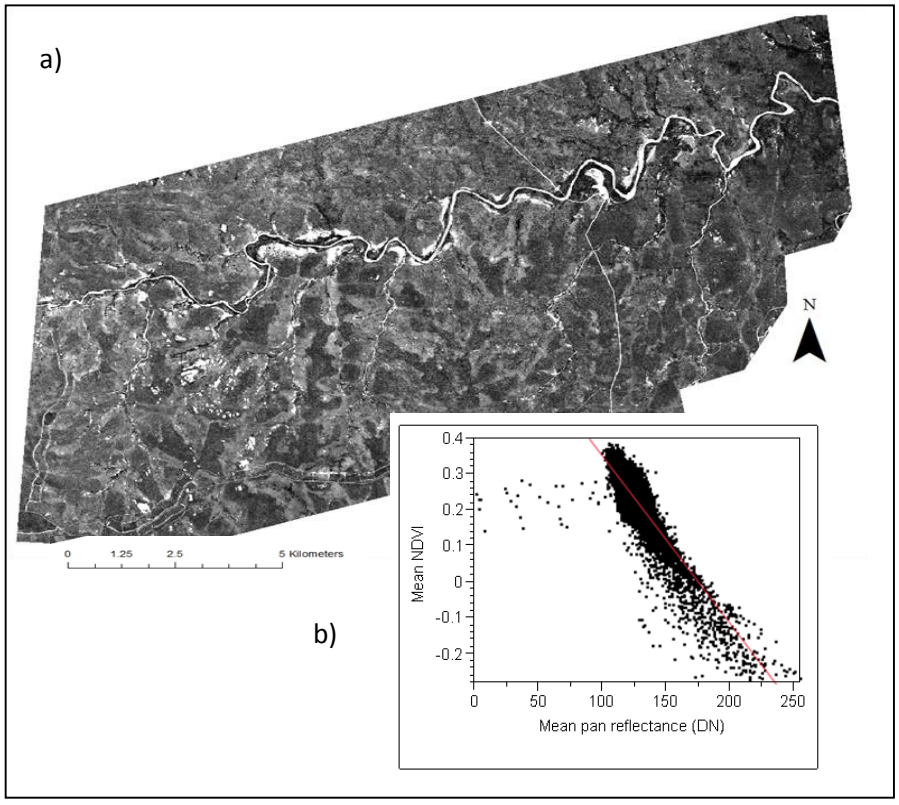


Figure 5.10: Vegetation patterns in the N'waswitshaka granite study area.

a) SPOT5 panchromatic layer in which catenal elements are clearly visible to the naked eye. Woody areas appear darker than grassy (grey) or bare (white) areas.

b) Strong correlation between the mean reflectance of SPOT5 panchromatic layer and mean NDVI of image objects generated in eCognition (n=38 897, r= -0.84).

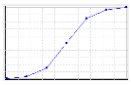
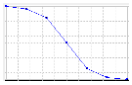
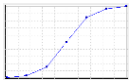
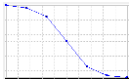
To produce an area-class map, image objects were assigned to the class for which they had the highest membership value. Vegetation patches smaller than the MMU (1ha) were then merged with the neighbouring unit with which they shared the longest common border. The image was further smoothed by assigning the majority value in a 5 cell radius circle around each 4.48m pixel.

The resulting image (Figure 5.11) clearly separates woodier crest and grassier midslope vegetation in both the grassy west of the image as well as the more wooded areas to the east. Only a very small area remained unclassified.

Box 5.1: Procedure for vegetation classification in the N'waswitshaka granite study area.

1) Segment into objects based on SPOT5 pan layer aggregated to 4.48m resolution (Shape 0.1, compactness 0.5, Scale parameter =50)
2) Initial classification of objects with unambiguous class membership

   Bare rock/sand: mean NDVI[1] <=0.11
   Water: Bare and mean NIR <100
   Woodier: pan >= 129
   Grassier: pan <118
   Dubious: pan 118> <=129
3) Dubious objects re-segmented at a finer resolution (scale parameter = 30)
4) New smaller objects that meet class criteria unambiguously are then classified.
5) Remaining dubious objects are then classified using fuzzy classes, as defined below

Class	***Variable***	***Membership function curve***	***Min value***	***Max value***	***Comments***
Fuzzy grass	Difference to mean pan value for objects already classified as trees		0	10	Higher membership values are more different to trees
Fuzzy trees	Difference to mean pan value for objects already classified as grass		-10	0	Lower membership values are more different to trees
Fuzzy both	Difference to mean pan value for objects already classified as trees AND *(min value of both curves)* Difference to mean pan value for objects already classified as grass	 	0 -10	10 0	Mean difference to objects classified as trees >=10 AND mean difference to objects classified as grass <= -10

6) Reclassification

   Fuzzy grass and trees reclassified as grass and trees respectively
   Fuzzy both reclassified as Unclassified.
7) Smoothing
8) Export to ArcGIS as raster file and execute focal majority on 5 cell radius

[1] Mean NDVI is calculated as ([Mean NIR (SPOT5 Band 3)]-[Mean Red (SPOT5 Band 2)]) / ([Mean Red (SPOT5 Band 2)]+[Mean NIR (SPOT5 Band 3)])

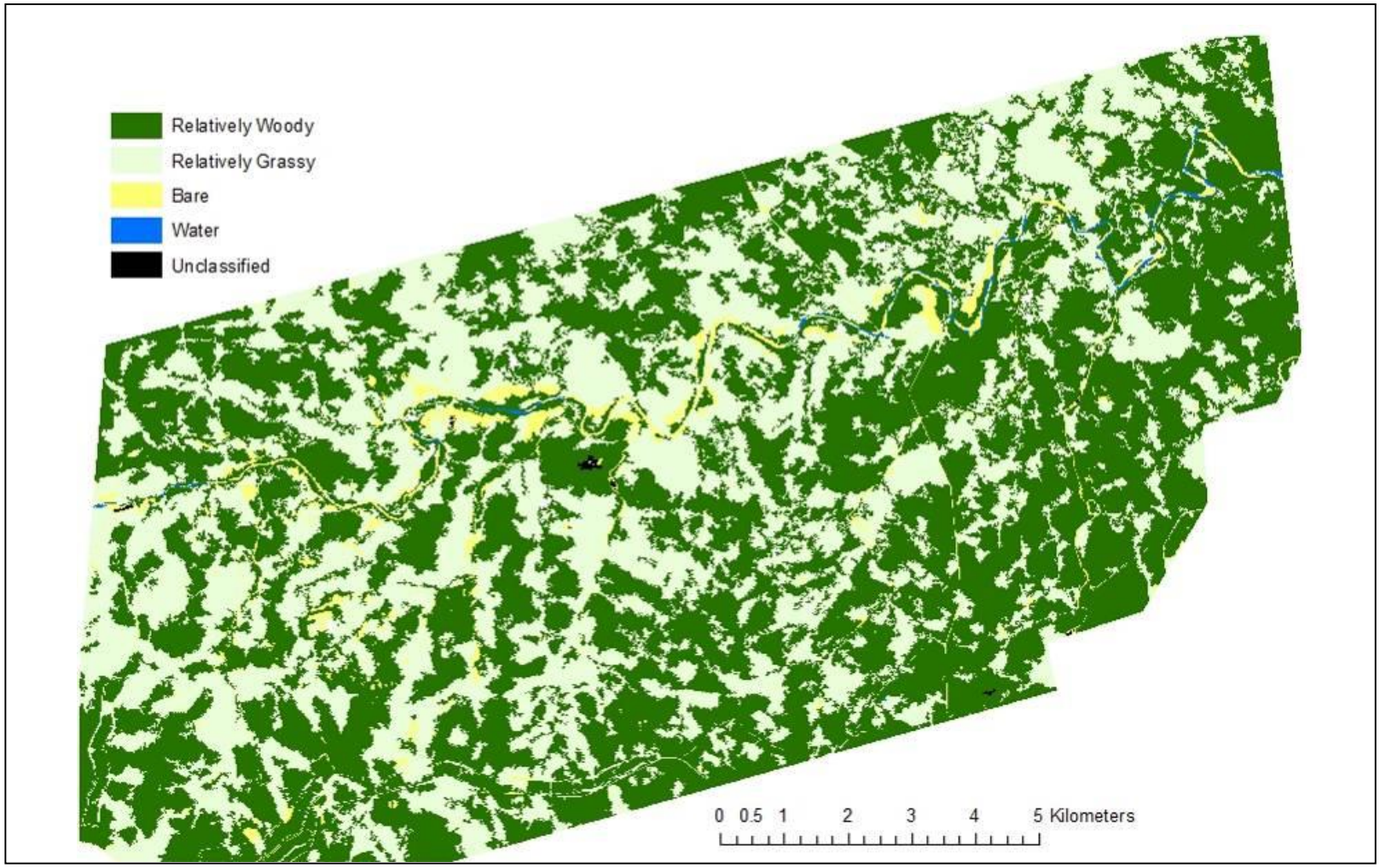


Figure 5.11: Vegetation classification of the N'waswitshaka study area.

Note the RELATIVE definition of 'woodier' and 'grassier' cover that separates crest and midslope vegetation in both the grassy west of the image as well as the more wooded areas to the east. Only a very small area remained unclassified.

5.3.4 STEP THREE: B) Classification of terrain units

Terrain units were defined as suggested by the *a priori* archetypes: crests, midslopes, toeslopes, channels and banks. To parameterise these units, various metrics were explored, including Topographic Position Index (TPI), a measure of relative elevation, gradients measured across various distances and both plan and profile curvatures. To reveal the underlying surface morphology, termite mounds were clipped out of all morphological maps, which were then smoothed to fill the holes left behind.

Topographic Position Index: A measure of relative elevation

Topographic Position Index (TPI) is the difference between a cell elevation value and the average elevation of the neighbourhood around that cell (Jenness, 2006). Positive values mean the cell is higher than its surroundings, so the point is likely to be at or near the top of a hill or ridge, and water will disperse away from this point. Negative values imply the cell is in a run-on area at or near the bottom of a valley. TPI values near zero can indicate either a flat or a midslope area where a cell is surrounded by equal areas of high and low elevation.

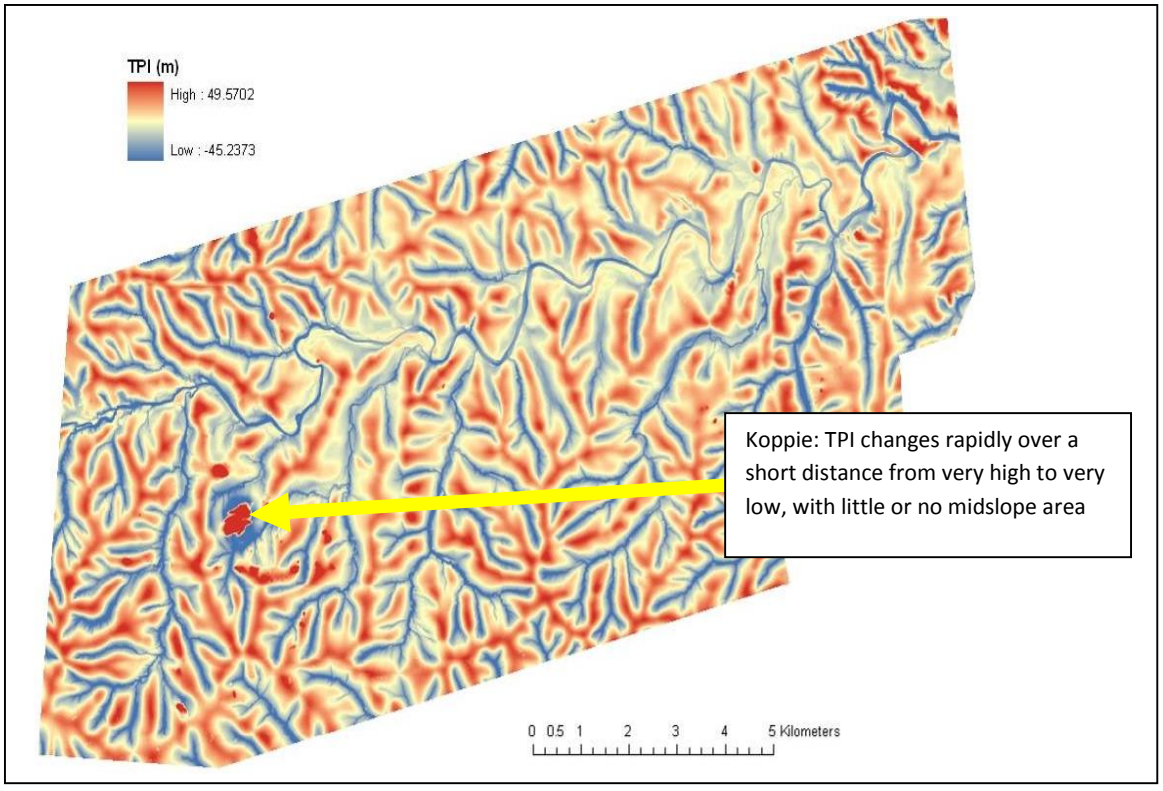


Figure 5.12: TPI (calculated over 300m) in the N'waswitshaka granite study area.

CASS crests are clearly shown as red areas (high, positive TPI), whilst valley bottoms are blue (low, negative TPI). The koppies in the west are clearly associated with a high TPI, but surrounding slopes have a low TPI, due to rapid change in elevation over short distances associated with the steep slopes of the koppies.

TPI is very scale sensitive, describing different patterns at different scales. Using the index to describe hillslope position, from crest to valley bottom, involves calculating TPI over a distance that is at least equivalent to the mean hillslope length in the area of interest. In the N'waswitshaka granite study area, where the mean hillslope length is 267m (half the mean

CASS width of 534m), a circular neighbourhood with a 300m radius (67 x 4.48m pixels) was used to calculate TPI. Calculated at this scale, TPI effectively captures hillslope position within CASSs in the N'waswitshaka site, distinguishing between CASS crests, midslopes and valley bottoms (Figure 5.12).

An anomaly is clear in the south west of the scene, where several CASSs surround a koppie (a koppie consists of elevated rocks, known elsewhere as an inselberg or tor). Since the koppie has tall, steep sides, relative elevation in these CASSs changes rapidly over a short distance from very high to very low, with little or no midslope area.

'Local' and 'long range' gradients

Gradients calculated over different distances not only show different amounts of detail, but also reveal different features within a landscape. When 'local' gradient is calculated over a distance of 15m (3 x 4.48m pixels), the steep and variable slopes associated with incised channels are clearly visible. By contrast, a 'long range' gradient, calculated over 184m (41 x 4.48m pixels), shows channels and riparian zones as relatively flat (Figure 5.13). Crests appear flat from both perspectives. Thus whilst 'local' gradient is useful for defining smaller scale features, such as river banks, 'long range' gradients are needed to describe hillslope differences associate with hillslope position (i.e. crest vs. midslope vs. valley bottom).

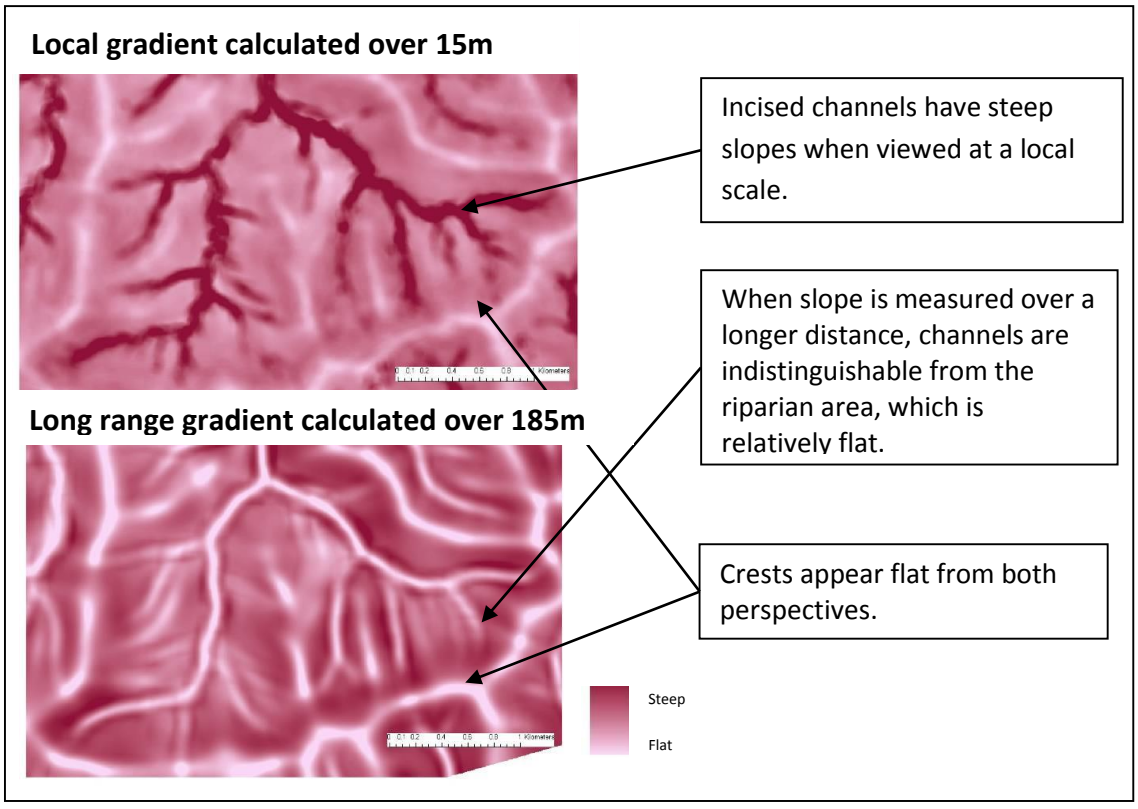


Figure 5.13: 'Local' and 'long range' gradients measured in degrees over 15m and 185m in the N'waswitshaka granite study area.

'Local' gradient shows the steep slopes associated with incised channels (dark red in top image), which contrast with the flat areas on top of the crests (light blue). By contrast, 'long range gradient' shows channels as flat (light blue), and only koppies and midslopes appear to have steeper slopes (red).

Curvature

Curvature was calculated over a distance of 185m (the same distance as 'long range' gradient), to reveal trends associated with hillslope positions. As was expected, crests show convex curvature in both profile and planform directions, while channels are concave in both directions (Figure 5.14).

Differences in curvature were also used to distinguish between convex midslopes, which are divergent slopes that tend to disperse water, and concave, convergent midslopes, which concentrate water flows.

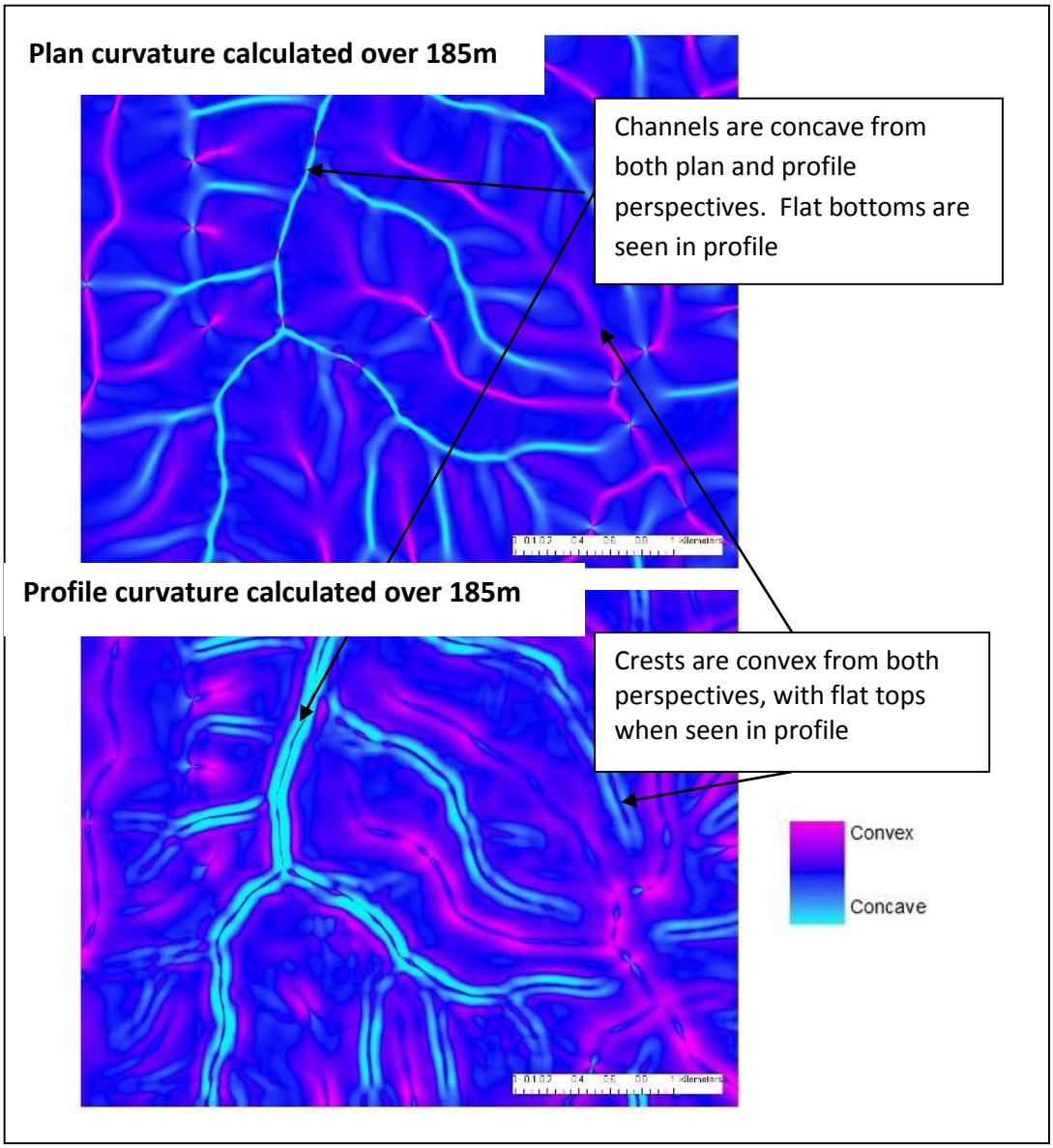


Figure 5.14: Planform and profile curvatures measured over 185m for the N'waswitshaka granite study area.

From both perspectives, crests are convex and channels are concave, as expected from the archetypal descriptions of these terrain units.

Archetypal terrain units for the N'waswitshaka granite study area

The terrain units suggested by the *a priori* conceptualisation of catenal elements for the N'waswitshaka granite study area were broadly confirmed and the expected differences in gradients and curvatures could be visually discerned. However, the koppies (inselbergs) in the south west of the scene consistently appeared as anomalies that did not fit easily in any of the proposed classes. Since it is unlikely that the hydrology, vegetation and soils on koppies conform to the underlying conceptualisation of hillslope toposequences, a new 'koppie' class was developed (Figure 5.15).

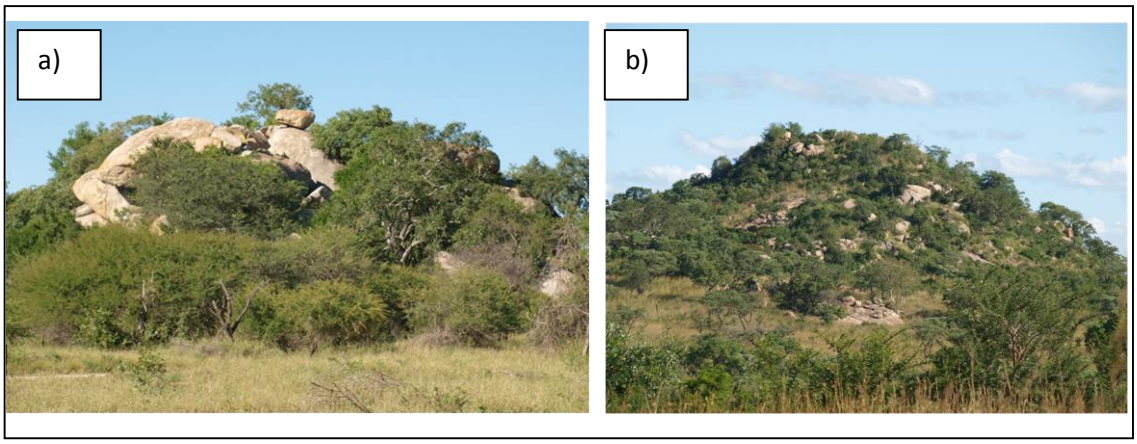


Figure 5.15: Koppies in the southern granites of KNP.

Koppies (inselbergs) rise steeply above the surrounding area and consist of unweathered granite outcrops, with little soil cover and somewhat specialised vegetation (i.e. vegetation includes specialist plants adapted to steep rock outcrops, such as rock figs (Ficus glumosa) as well as species commonly found on other crests in the area) The hydrology of koppies clearly differs to that found on other crests, if only because the presence of bare rock encourages surface runoff as opposed to incised channels. Photos: a) GB Mar 2010, b) CC Mar 2010.

Thus five *a priori* classes were used to define terrain units in the N'waswitshaka granite study site. Each class was initially recognised in terms of hillslope position, as indicated by TPI and also in terms of gradient and curvature as follows:

- **Crests**: flat 'long range' gradient
- **Midslopes**: steep 'local' and 'long range' gradients
- **Toeslopes**: flat 'long range' gradient and profile curvature
- **Channels**: Concave profile curvature over 185m, but flat gradient over 'long range' and **Banks**: steep 'local' gradient, highly concave over 15m, but flat gradient over 'long range'. Although defined separately, the areas are combined when mapped, since most 'bank' areas are smaller than the 1 ha MMU.
- **Koppies**: steep gradient, both 'local' and 'long range'.

The image objects used for the vegetation classification was segmented again to derive fine-scale objects with distinct morphology, capable of separating stream banks from adjoining midslopes (scale parameter = 10, shape 0.1, compactness 0.5). In this segmentation

topographic layers were included alongside the SPOT5 pan layer, including the DEM, TPI over 300m, gradient over 15m and 185m, and plan and profile curvatures over 85m.

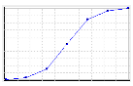
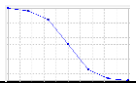
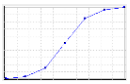
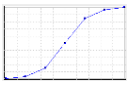
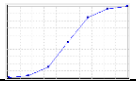
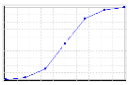
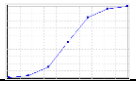
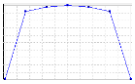
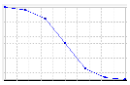
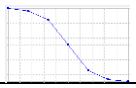
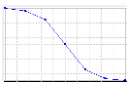
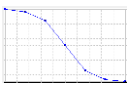
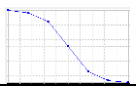
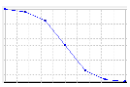
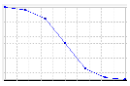
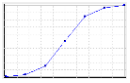
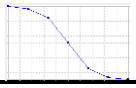
Vegetation cover was used to guide the final selection of variables and to determine the appropriate thresholds between classes, according to the cover that was expected to be associated with each archetypal terrain unit (Table 4.2). In particular, vegetation cover was used to separate crests from midslopes, since TPI was strongly associated with vegetation class, with significant differences in TPI between all four vegetation classes (based on points sampled at 100m intervals, n=25 524, one-way ANOVA $F_{3, 25520} = 243$ $p < 0.0001$; Tukey-Kramer HSD $p < 0.05$). Considerable overlap was evident between the 'woodier' and 'grassier' vegetation classes. This is not surprising given that trees occur in riparian areas with low TPI as well as on the high crests. However, over 90% of grassy areas occur below a TPI of 1.5m, suggesting that a threshold of TPI =1.5m would successfully separate (woodier) crests from (grassier) midslopes.

Once the rules for the definition of archetypal terrain units were developed, a fuzzy classification was used to map them. Membership functions for each class define the similarity of each image object to the archetype for each class (Table 5.1). If the rule defining a class archetype included more than one variable (for example, 'crests' were defined both in terms of TPI and in terms of 'long range' gradient), then the individual membership values for each variable were averaged to generate an overall membership value for the class.

Lastly, the image was smoothed by merging terrain units that were smaller than the MMU (1ha) with the neighbouring unit with which they shared the longest common border. The image was further smoothed by assigning the majority value in a 5 cell radius circle around each 4.48m pixel.

The resulting classification clearly partitions the landscape by hillslope position, as well as identifying koppies and the increasing area occupied by flat floodplains down the course of the N'waswitshaka River (Figure 5.16).

Table 5.1: Rule set used for the fuzzy classification of terrain units in the N'waswitshaka granite study area.

Class	***Variable***	***Membership function curve***	***Minimum value***	***Maximum value***	***Comments***
Crest	Mean TPI (300m) *(weight =2) AND*		0	1.5	100 /100 degrees of membership if TPI >1.5, falling membership until TPI is 0 (90% grass occurs <1.5 TPI)
	Mean 'long range' gradient		0	15	Steeper areas (>15) are likely to be koppies
Koppies	Mean 'local' gradient *AND*		2	5	Steep gradient both local..
	Mean 'long range' gradient *AND*		0	4	... and 'long range'
	Mean TPI (300m)		3	10	High in landscape- TPI at least 3
Midslope	Mean TPI (300m) *AND*		-10	5	90% grass occurs <1.5 TPI
	Mean 'long range' gradient *AND*		0	2	Fairly steep, both 'long range'
	Mean 'local' gradient		0	5	...and locally
Flat toeslopes (possible floodplains)	Profile curvature. over 185m *AND*		-0.0001	+0.0001	Flat
	Mean 'long range' gradient *AND*		1	3	Flat
	Mean TPI (300m)		-1	1.5	Low in landscape
Channel	Mean TPI (300m) *(weight =2) AND*		-4	-2	Low in landscape
	Mean profile curv 185m *AND*		-0.0001	0	Concave over 185m
	Mean 'long range' gradient		0	5	Flat
Banks	Mean profile curvature over 15m *(weight =2) AND*		-0.2	0	Concave over 15m
	Mean TPI (300m) *AND*		-2	0	Low in landscape
	Mean local gradient *AND*		2	5	Steep local gradient
	Mean 'long range' gradient		0	3	Flat 'long range' gradient

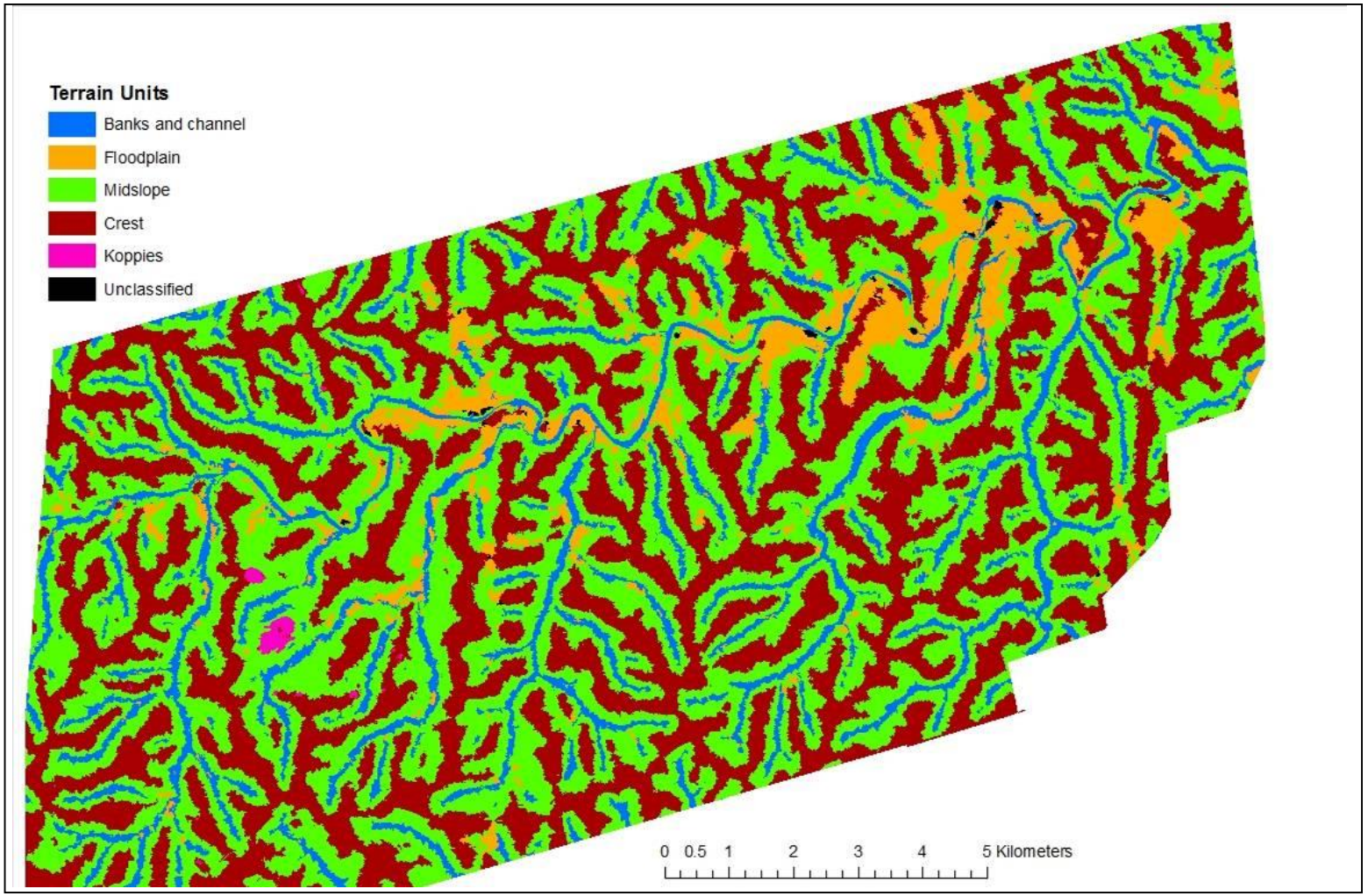


Figure 5.16: Terrain units in the N'waswitshaka granite study area.

The classification partitions the landscape by hillslope position, as well as identifying koppies and the increasing area occupied by flat toeslopes (floodplains) down the course of the N'waswitshaka River. Only a very small area remained unclassified.

After the initial classification, I investigated whether or not midslopes should be further divided into divergent ridges and convergent gullies. There was little difference between the vegetation classes found on divergent and convergent midslopes (Figure 5.17, based on points sampled at 100m intervals, n = 11 515). Although divergent ridges were more wooded than the slopes of convergent gullies, vegetation differences only occurred at relatively high elevations. Thus the woodier, divergent ridges were generally classified as part of the crest. This finding also supports the assumption that the scale of 1:50 000 used to define streams and catchments is adequate to distinguish catenal elements defined in terms of associations between morphology and vegetation patterns at a resolution of 4.5m (Section 5.3.2).

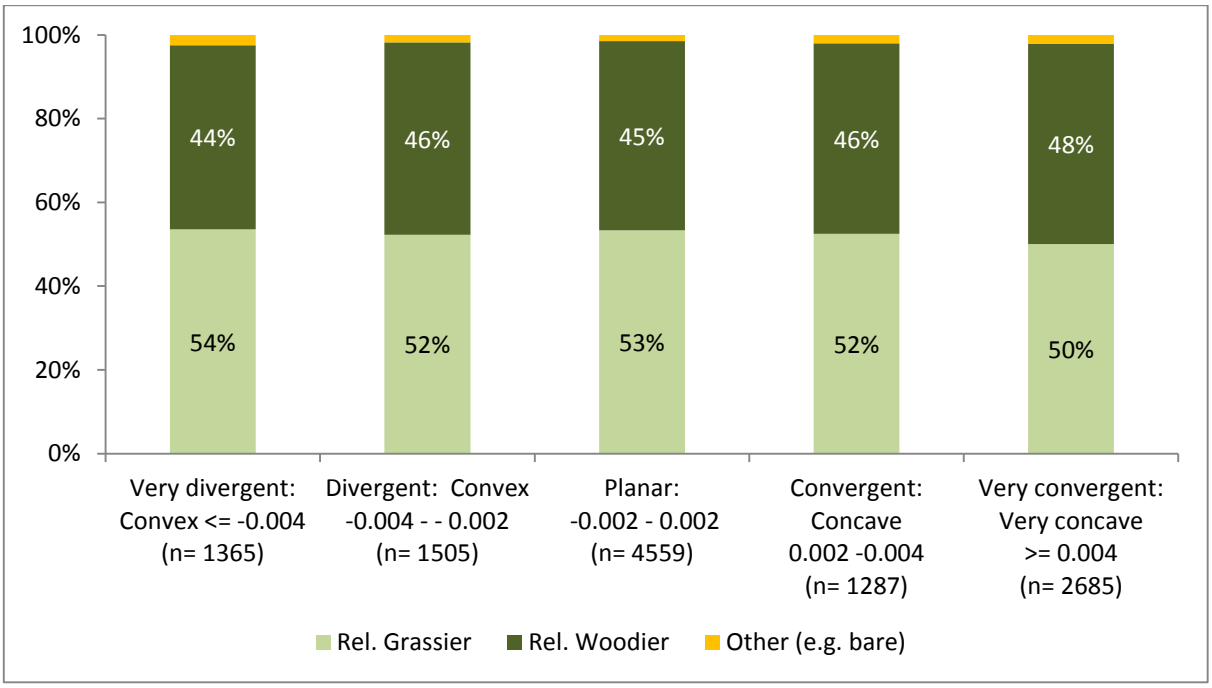


Figure 5.17: Vegetation cover on divergent, convergent and planar midslopes in the N'waswitshaka granite study area.

There is little difference between convergent, divergent and planar midslopes in terms of the area classified as 'grassier' and that classified as ' woodier'. Based on points regularly sampled at 100m intervals (n = 11 515).

5.3.5 STEP THREE: C) Relationships between vegetation and terrain units in the N'waswitshaka granite study area

The relationship between vegetation class and terrain units was further explored to validate the archetypal *a priori* catenal elements and to develop any new archetypes needed to fully describe catenal elements in the study site.

As suggested by the *a priori* archetypes, crests tend to be relatively woody (71% of sampled points) while midslopes are relatively grassy (52%) (Figure 5.18). However, there are many exceptions to these rules. Many crests are grassy (28%) and almost as much of the midslope area is woody (46%) as grassy (52%). Furthermore, the vegetation map (Figure 5.11) shows that these anomalies are geographically clustered. For example, woody midslopes are common in the south east of the scene, whilst many grassy crests are seen in the west.

Some 12% of flat toeslopes are bare, indicating possible sodic sites, whilst the remaining areas of toeslopes are almost equally likely to be relatively open grassland or relatively closed woodland. About half the area of channels and banks is relatively woody (which includes trees overhanging the channels), with 39% grassy (or reedy) and 11% are bare (gravel or bedrock).

The high occurrence of woody vegetation on toeslopes, banks and in channels, not anticipated in the initial definition of archetypes, suggests that a new archetype 'riparian trees' should be included alongside the existing archetypes for grassy toeslopes, bare sodic sites and grassy, reedy or unvegetated banks and channels. The other newly introduced archetype is 'koppies', which are almost equally covered by trees, grass and bare rock.



Figure 5.18: Associations between vegetation cover and terrain units in the N'waswitshaka study area. Crests are mainly covered with woodier vegetation, as expected from the archetypal catenal element. Whilst over half the midslope points are relatively grassy, as expected, but many are wooded, in contradiction to the archetype. Flat toeslopes (floodplains) are almost equally woody and grassy, with some 12% bare. The high proportion of woodier vegetation in banks and channels reflects riparian trees, which often overhang the channel. Koppies are almost equally likely to be wooded, grassy or bare rock. Based on the classification of points regularly sampled at 100m intervals throughout the study area (n= 25 373).

5.3.6 STEP THREE: D) Catenal elements in the N'waswitshaka granite study area

As suggested by the analysis of relationships between vegetation classes and terrain units, crests, midslopes and toeslopes were separated into 'relatively woody' and 'relatively grassy'. A class corresponding to the archetype of 'riparian trees' was developed by merging relatively woody image objects that were within or adjacent to banks, channels or toeslopes and which were located in low-lying parts of the landscape (TPI <1). Unvegetated objects on toeslopes are assumed to be sodic sites, together with neighbouring bare objects that form part of channels, banks or midslopes. In addition, koppies were extended to include adjoining objects classified as bare crests or midslopes, which are likely to be bare rock that forms part of the koppie. The final suite of archetypal catenal elements mapped in the N'waswitshaka granite study area therefore consisted of:

Relatively woody crests Relatively grassy midslopes Relatively grassy toeslopes Bare toeslopes (sodic sites) Channels and banks (grassy/ bare/ water)	As suggested by the *a priori* archetypes
Relatively grassy crests Relatively woody midslopes Riparian trees Koppies	As suggested by actual relationships between vegetation and terrain units

The image was smoothed by applying a low-pass filter (majority value in neighbouring circle of 5 cell (25m) radius) and then merging units that were smaller than the MMU (<1ha) with the neighbouring unit with which they shared the longest common border. After this process, three classes each only contained one object, and these were reclassified manually.

The final image (Figure 5.19) reveals areas to the north of the main river and in the west of the scene where large crest areas are relatively grassy. To the south and east, on the other hand, midslopes are often relatively woody. The original *a priori* conceptual model of toposequences of woody crests and grassy midslopes applies best in the centre of the scene.

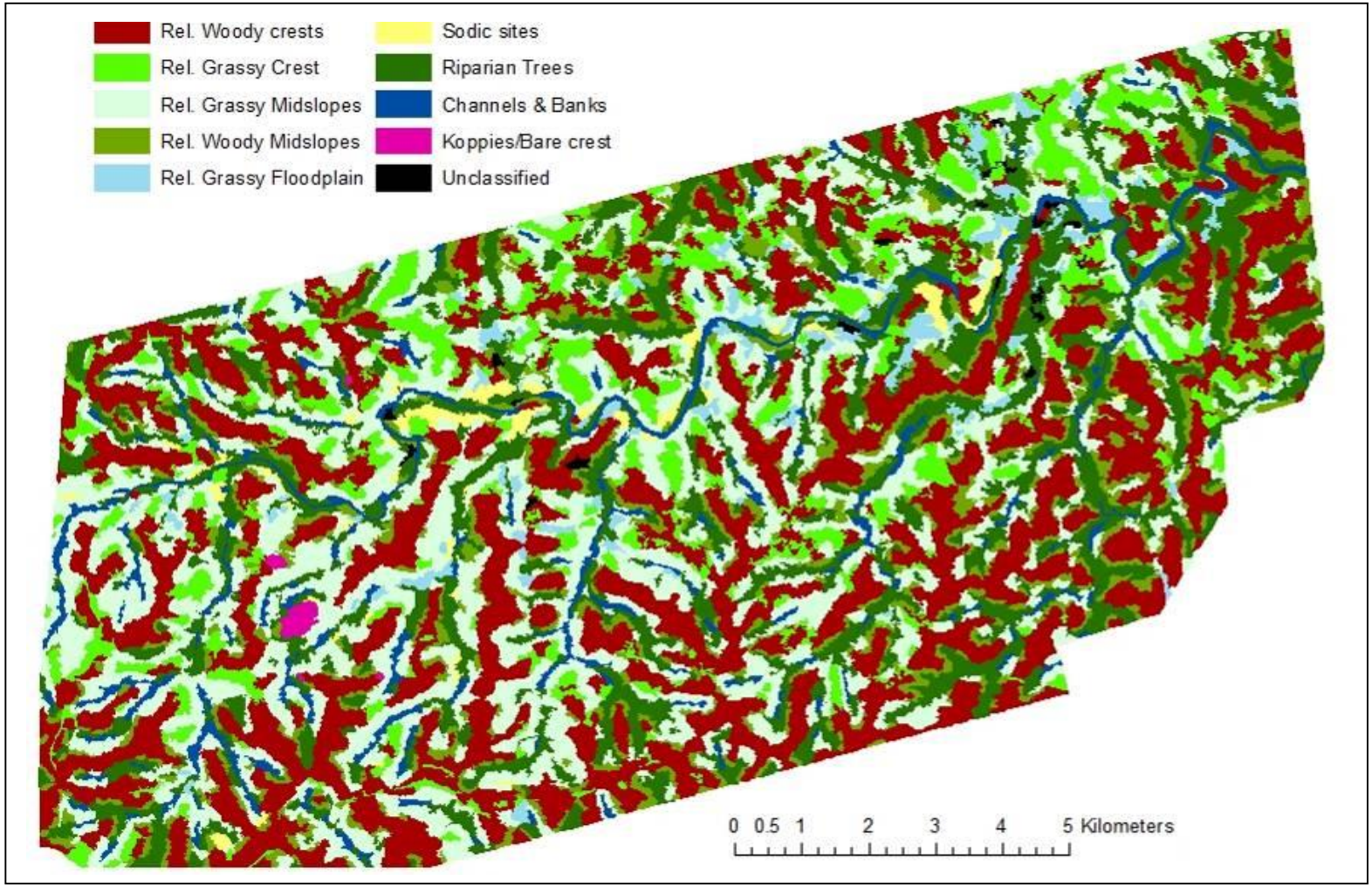


Figure 5.19: Catenal elements in the N'waswitshaka granite study area.

Areas to the north of the main river and in the west of the scene contain large areas of relatively grassy crests. To the south and east midslopes are often relatively woody. The idealised conceptual model of woody crests and grassy midslopes applies best in the centre of the scene.

5.4 Results Part B: Catenal elements in the Nhlowa basalt study area

5.4.1 STEP ONE: Defining archetypal catenas in the Nhlowa basalt study area

The Nhlowa site consists of 41.5km^2 (about 6.5km x 6.5km) in the southern basalts of KNP. It is extremely flat, with an elevation range of only about 72m over the whole area. Stream density is far lower than in the N'waswitshaka granite study area, with a 0.98km of streams/km^2 (using the streams delineated on the 1:50 000 topographical map). The mean annual rainfall in this area is about 400-450-600mm p.a., with very high interannual variation (see Chapter 4 for further detail). The site has been selected as one of the research 'supersites' recently established in KNP (Smit *et al.*, 2013a).

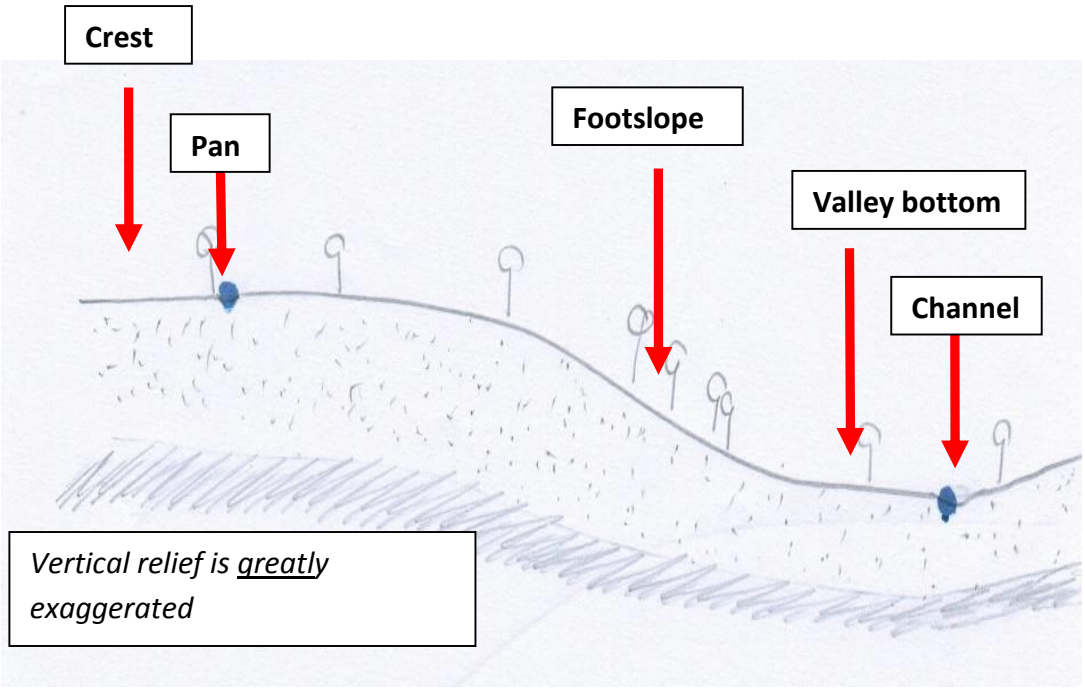
The study area falls entirely within the Satara land type described by Venter (1990) and the '*Sclerocarya caffra/ Acacia nigrescens* savanna' described by Gertenbach (1983) (see Section 4.12.2 for more detail). Hydrological flows at this site have been conceptualised by Riddell *et al. (*2014). The initial *a priori* archetypes are based on a synthesis of this knowledge, partitioning hillslopes into elements that are both structurally and functionally distinct (Figure 5.20).

Most of the landscape is occupied by open crests with dense grass, occasional trees and clusters of shrubs. Both Venter and Gertenbach describe valley bottoms as having dense riverine forest growing on organic and alluvial soils. However, the study area consists mostly of headwaters, in which little riverine forest is evident. Instead, wide vleis occur, characterised by a wide valley floor with occasional discontinuous channels and pans. The valley floor is bordered by a narrow lip, corresponding to the 'midslope' described by Venter. I therefore decided to omit the densely forested 'valley bottom' described by Venter and Gertenbach which is associated with higher order streams than those found in the Nhlowa basalt study site and which would be more aptly described as 'riparian trees/ forest'. Instead, I refer to Venter's footslopes as 'valley bottoms' and his midslopes are here called 'footslopes'.

Three *a priori* archetypes were therefore used to inform the mapping of vegetation and terrain units in the study area:

- **Crests**: Open, grassy and flat, with planar or concave curvature.
- **Footslopes**: Relatively steep, convex area bordering the valley bottom, with denser tree/shrub cover than on crests (equivalent to Venter's 'midslope').
- **Valley bottoms**: Flat, similar woody cover to midslopes, concave or planar with discontinuous channels and pans (equivalent to Venter's 'footslope').

Figures 5.21-5.23 show examples of these archetypal catenal elements in the Nhlowa basalt study area.



	Crest/ midslope	Footslope	Valley bottoms
Vegetation	Open grassland with occasional trees and clusters of shrubs	Open grassland with trees and shrubs	Open grassland with occasional trees
Morphology	Planar/ very slightly concave	Convex, forms a narrow lip around valley bottoms	Concave/ planar, with an irregular surface containing discontinuous channels and occasional pans
Soils	Deep clay, with medium infiltration, drainage and storage capacity	Clay-loam, faster infiltration and drainage than crests or valley bottoms	Clays, subject to cracking when dry, allowing rapid infiltration. Slow drainage and high storage capacity.
Hydrology	Vertical infiltration to bedrock aquifers. Only lower slopes connect occasionally to channel via subsurface interflow.	Lateral flow into channel/ channel bed via surface runoff and near surface seepage.	Water stored subsurface, forms waterlogged area during rainy season. Insufficient surface flow to create continuous channels.

Figure 5.20: A priori archetypes in the Nhlowa basalt study area.

For mapping purposes, I focused on the structural differences between catenal elements, especially differences in vegetation and hillslope morphology that can be observed in remotely sensed imagery. Derived from Venter (1990), Gertenbach (1983), Riddell (2014) and personal observations.



Figure 5.21: Nhlowa basalt study site from the air.

Unfortunately clouds shadow much of this photo. However, the tall trees bordering the stream are clearly seen in the mid distance, contrasting with the relatively open, grassy crest. Photo: CC Apr 2009.

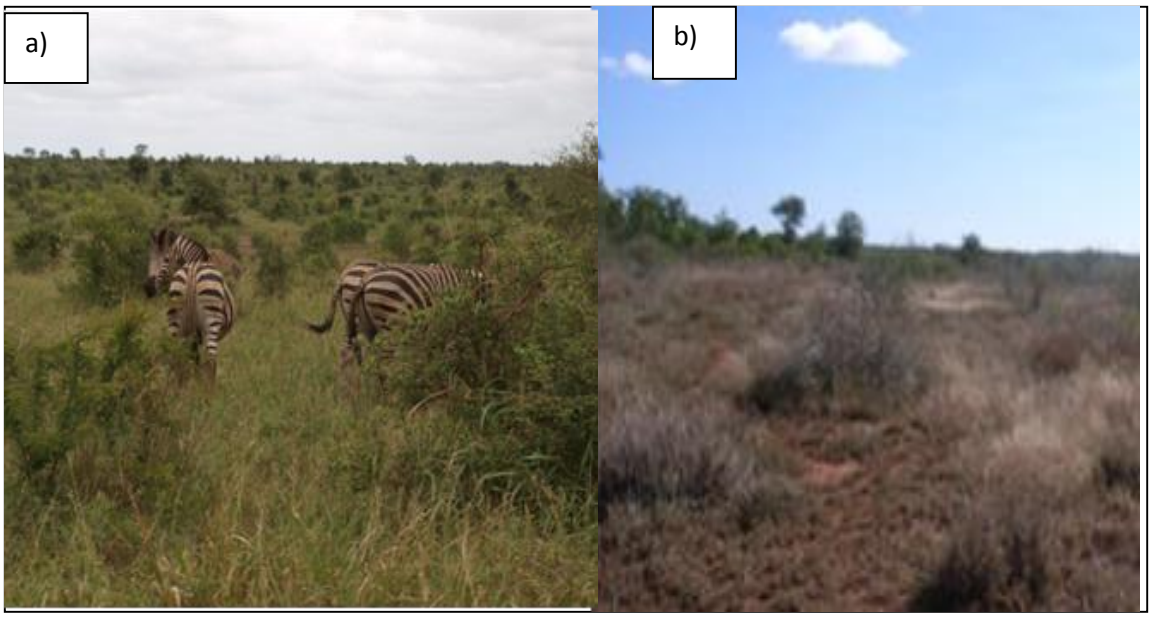


Figure 5.22: Crests in the Nhlowa basalt study area.

Crests generally have dense grass, with moderate shrub cover and a few trees (a). Occasional pans, often enlarged by animal use are scattered on the crests (b). Photos: a) CC Mar 2010 b) CC Apr 2007.

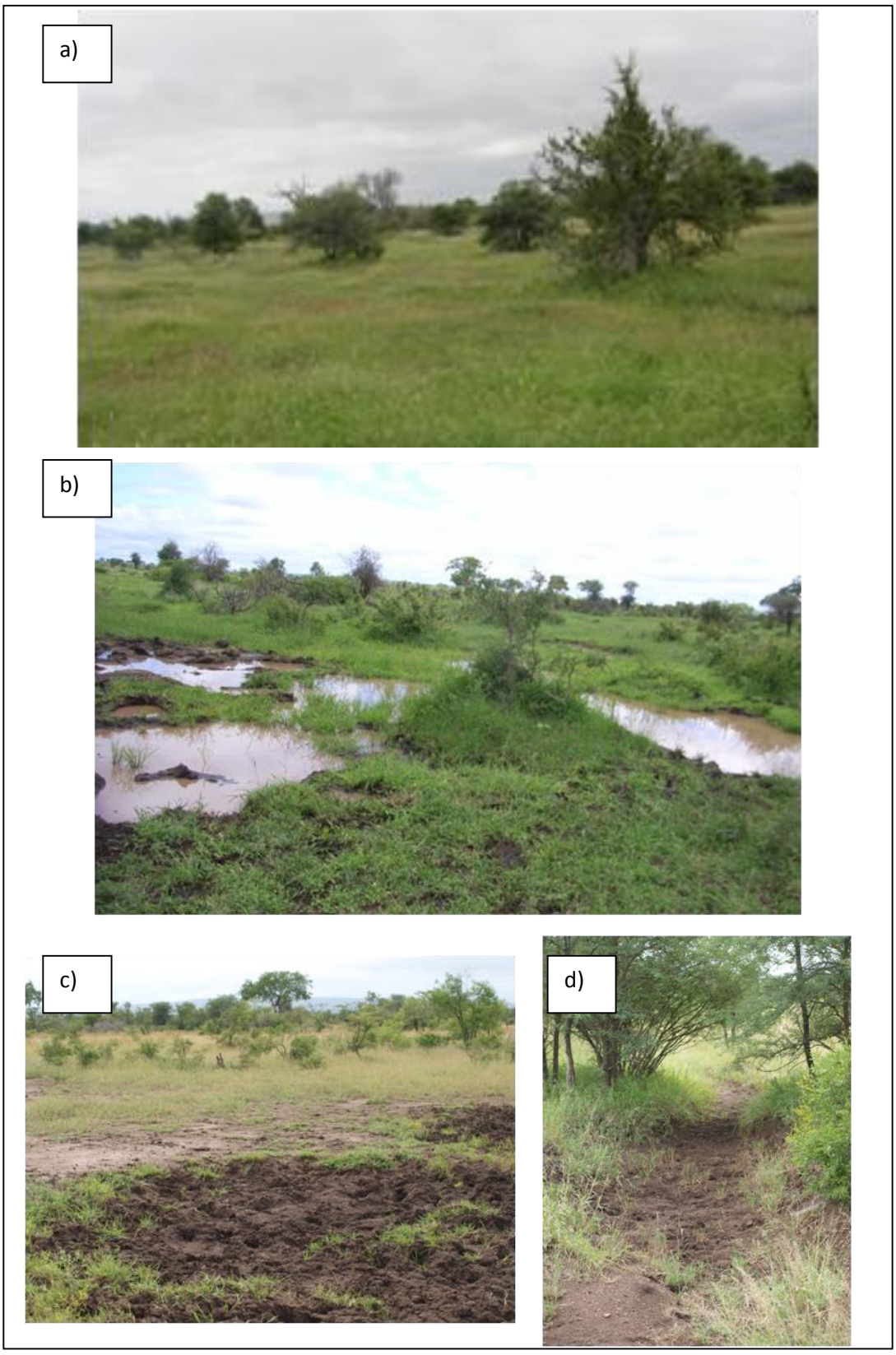


Figure 5.23: Valley bottoms in the Nhlowa basalt study area.

Extensive valley bottoms generally have an irregular, hummocky surface (a) with occasional tall trees. These areas are subject to waterlogging in the rainy season (b) and contain occasional pans (c) and discontinuous channels (d). Photos: a) CC Jan 2009 b) Dec 2007 c) and d) GB Mar 2010.

5.4.2 STEP TWO: Selecting scales

Streams shown in the 1: 50 000 topographic map are clearly related to the changes in gradient associated with the archetypal catenal elements (Figure 5.24a). The average CASS width is 1 737m, suggesting that the mean hillslope length is around 870m. However the narrow footslope is only about 100m wide in most places, and fine vertical resolution is needed to detect morphological difference in this extremely flat landscape. This means that the 90m SRTM DEM, which has vertical resolution of about 16m (Farr *et al.*, 2007) is inadequate for describing the morphological differences that characterise each catenal element. LiDAR data collected at 1.12m resolution was available for this site, and was aggregated to 4.48m resolution, as for the N'waswitshaka granite study area.

Given the sparse tree cover in this area, the finest-resolution LiDAR data at 1.12m was used to detect canopy height, resolving the data almost to an area occupied by the crowns of individual shrubs and trees.

The MMU was set at 1ha, as for the N'waswitshaka granite site, which was qualitatively judged to be more than adequate to capture the archetypal catenal elements of crests, footslopes and channels and also able to capture the small pans that are scattered over the crest (Figure 5.24b).

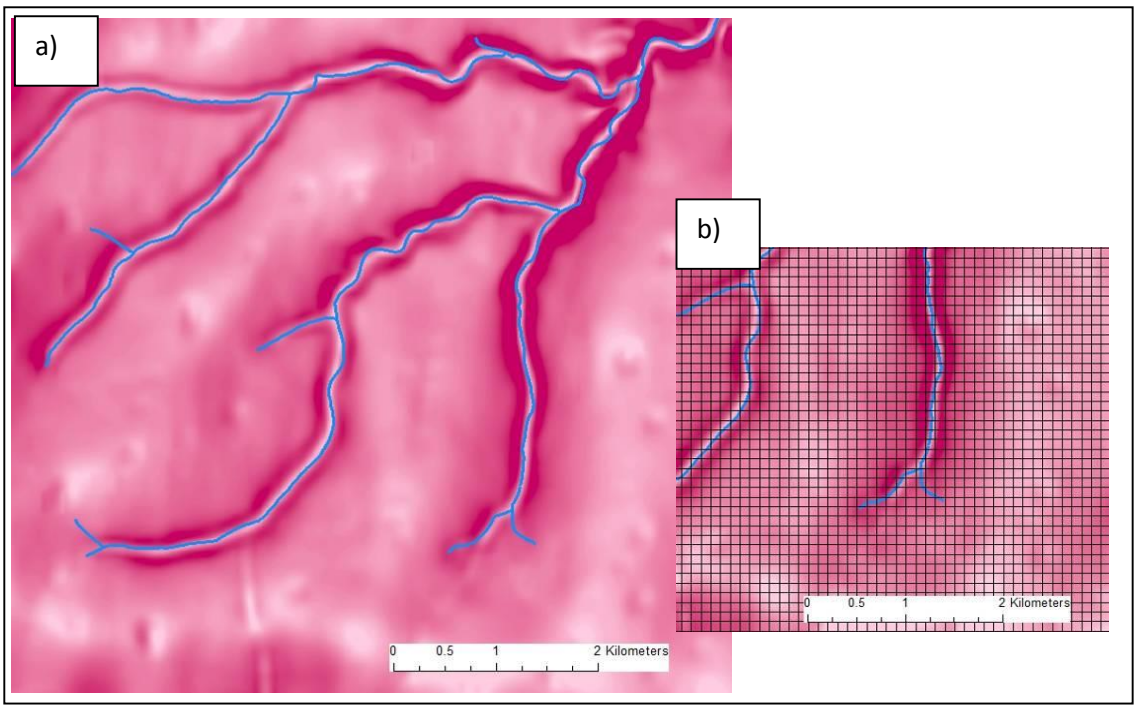


Figure 5.24: Scales of observation for the Nhlowa basalt study area.

a) Overlaying streams from the 1: 50 000 topographic map (shown in blue), shows that they are clearly related to the channels seen in a map of gradient measured over 49m.
a) An MMU of 1 ha is equivalent to the area shown on each square of the overlaid grid. A MMU of this size is more than adequate to capture the archetypal catenal elements of crests, footslopes and channels and is also able to include small crestal depressions (pans).

5.4.3 STEP THREE: A) Vegetation classification

SPOT5 imagery acquired in the late rainy season (March 2006) clearly shows water (blue) and scattered bare (pink) patches in the study area (Figure 5.25a). Although the pale green colouring around the channels hints at topographically controlled differences associated with moisture or vegetation, it is not clear what the signal represents. The dark/light contrasts that are clearly associated with woody crests and grassy midslopes in the SPOT5 pan image of the N'waswitshaka granite study site (Figure 5.25b) cannot be seen in the equivalent imagery for the Nhlowa basalt site.

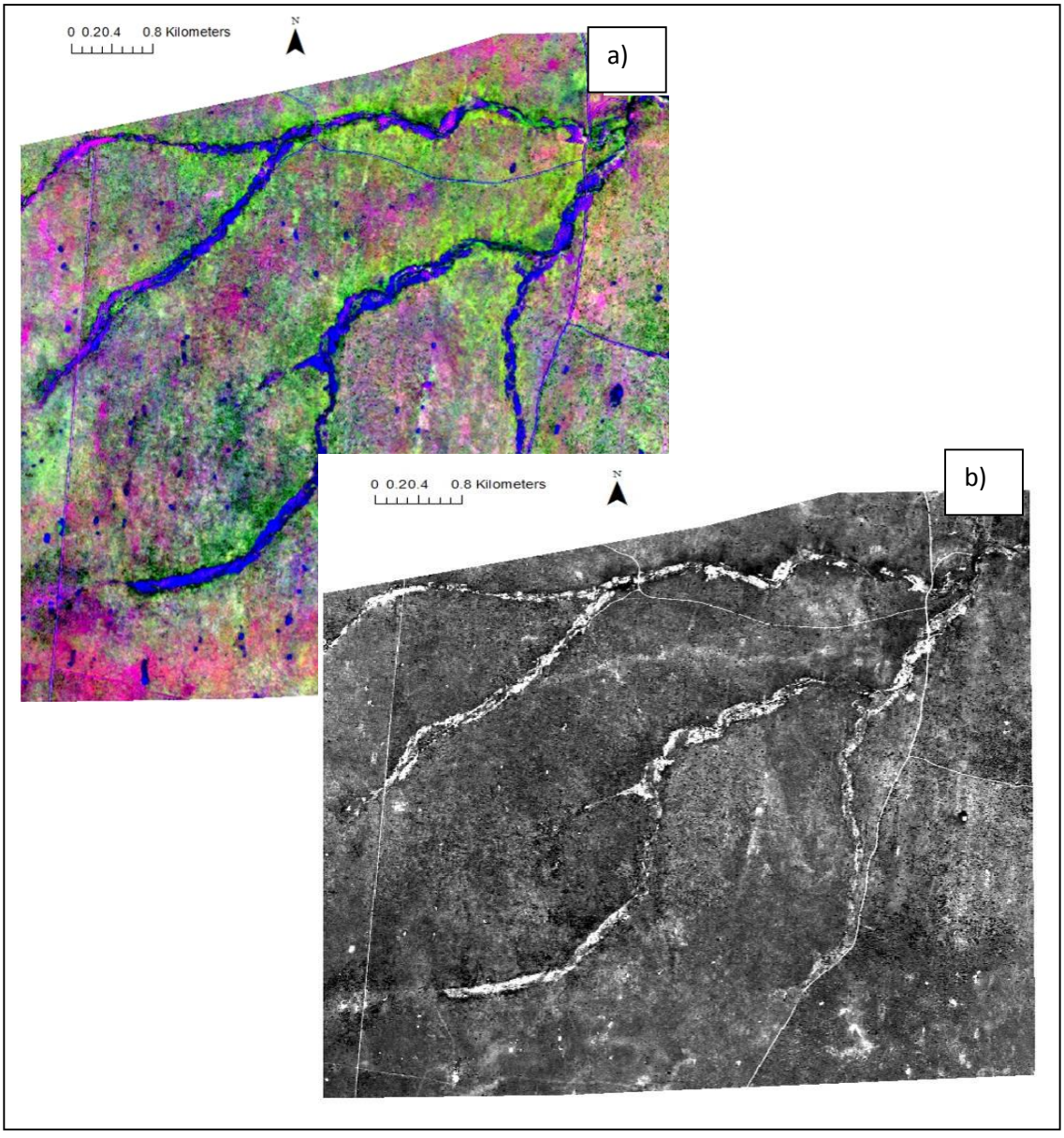


Figure 5.25: Multi-spectral and panchromatic SPOT5 images of the Nhlowa basalt study area.

These images, acquired in March 2006, towards the end of the wet season, show inundated valley bottoms. Isolated pans on the crest also contain water. No catenal vegetation patterns are evident in either the multispectral (a) or pan (b) images, although the green areas in the coloured image do suggest changes in vegetation and/or soil moisture associated with footslopes.

In the SPOT5 multispectral image (a), the red band (associated with water), is coloured blue, whilst the Near Infra-Red band (NIR, associated with photosynthesising vegetation) is coloured green. The Short Wave Infra-Red band (SWIR, associated with a lack of vegetation) is coloured red.

However, some variations in canopy height that are broadly associated with hillslope position can be seen in the LiDAR data (Figure 5.26). Vegetation height differs on either side of some of the roads. This is likely to be due to the road acting as a fire break, with short trees and shrubs being burnt on one side of the road but not the other. If these effects are disregarded, then it appears that tall trees are most often found near rivers, whilst crests appear to be slightly more open than valley bottoms.

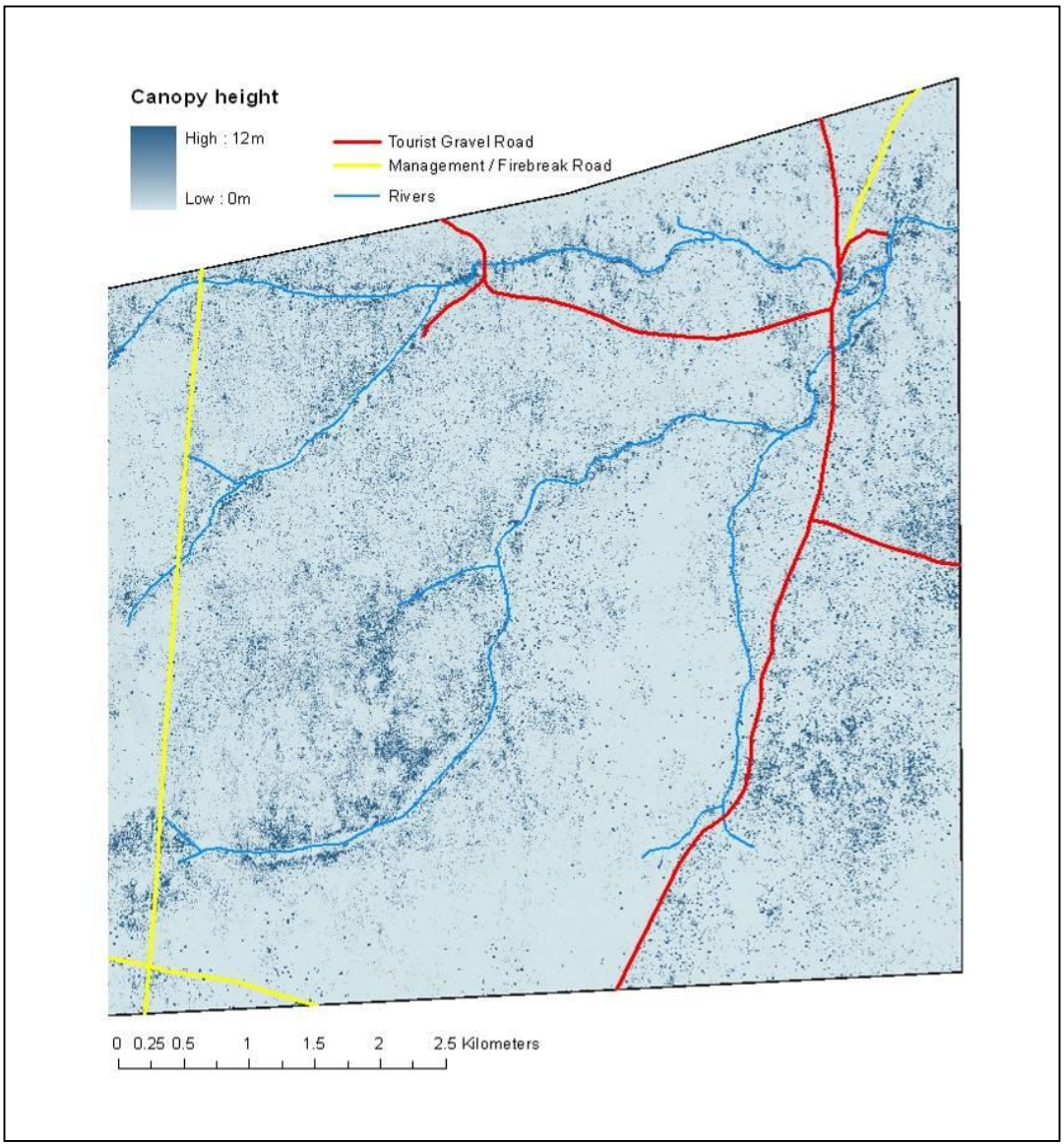


Figure 5.26: Vegetation height in the Nhlowa basalts.

Many tall trees appear to be located near rivers, whilst there appears to be no systematic pattern for shorter trees. It also seems that tree height differs either side of some roads (e.g. the management road to the west and the southern part of the tourist gravel road), which is likely to be a fire effect.

The vegetation patterns in the Nhlowa basalt study area are far more subtle than those seen in the N'waswitshaka granite study site, where the boundaries between woody and grassy patches are frequently abrupt. In circumstances where change is subtle and/or continuous, decisions on class breaks are inevitably somewhat arbitrary. Three classes were defined in terms of the percentage canopy cover at heights associated with grass (<0.5m), trees of intermediate height (0.5-5m) and tall trees (>5m). Classes for 'unvegetated' areas and water complete the vegetation classification (Box 5.2).

Box 5.2: Procedure for vegetation classification in the Nhlowa basalts.

Segment into objects based on:

- SPOT5 pan, NIR and red layers resampled to 4.48m resolution
- Canopy height: CAO LiDAR data at 1.12m resolution
- TPI, gradient, profile and plan curvatures, all calculated within 11 cell (49m) kernels
- TPI calculated within a 190 cell (851m) kernel
- Shape 0.1, compactness 0.5, scale parameter =3

Class definitions:

1. Unvegetated: mean NDVI <=0.22 and mean NIR (SPOT band 3) > 120
2. Water: mean NDVI <=0.22 and mean NIR ≤ 120
3. Tall trees: > 10% canopy over 5m high (LiDAR canopy layer, focal mean calculated over a 10 cell (11.2m) radius)
4. Grass: < 5% canopy over 0.5m high (LiDAR canopy layer, focal mean calculated over a 10 cell (11.2m) radius)
5. Intermediate trees: remainder of scene

Smoothed:

Focal majority, 5 cell radius, merge patches < 0.5 ha with the neighbours with which they share the longest common border

The classified scene (Figure 5.27) shows considerable expanses of water resting in the valley bottoms and in pans that are some distance from streams. Although tall trees are mostly found in riparian areas, there are many exceptions to this rule.

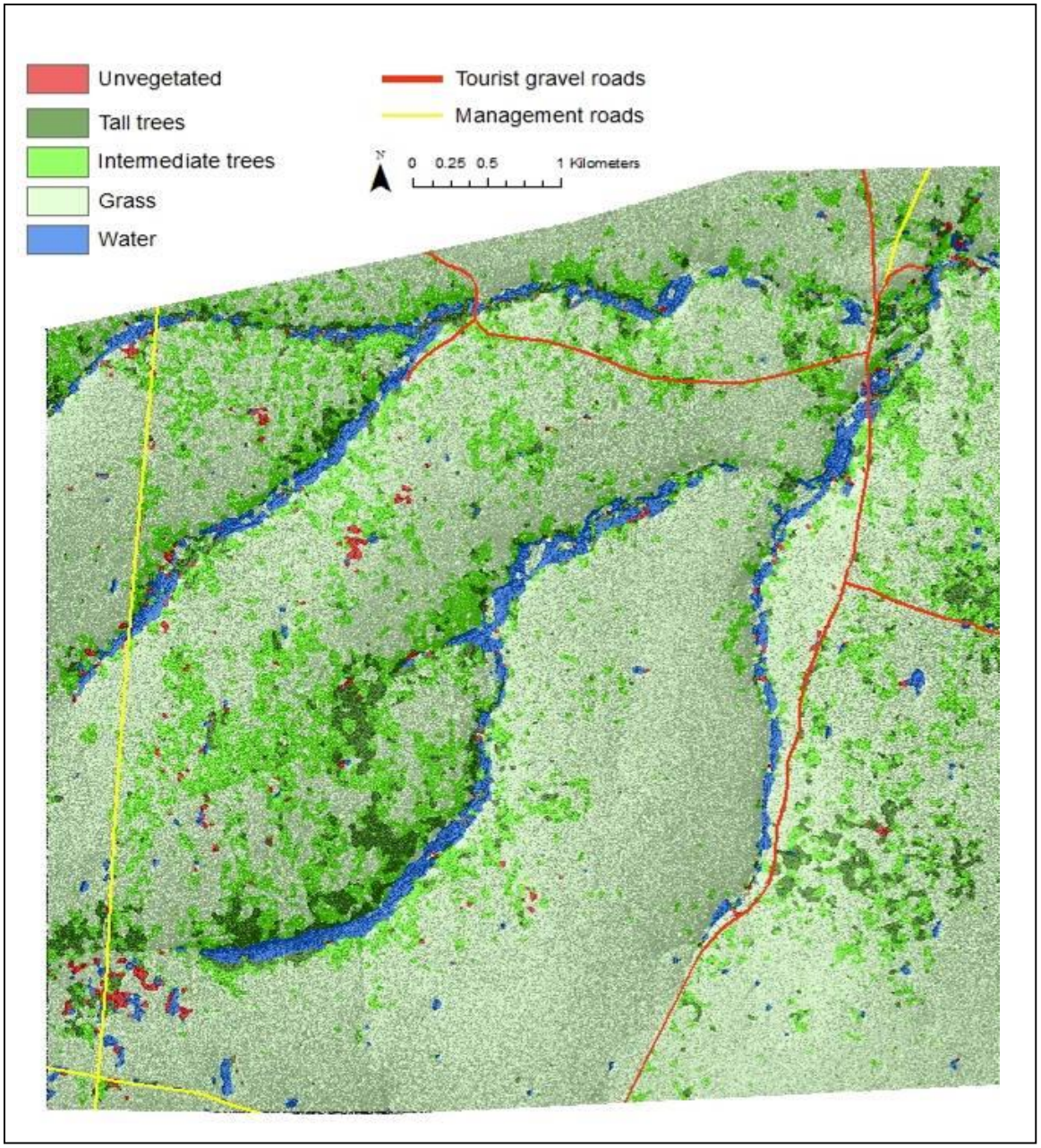


Figure 5.27: Vegetation classes in the Nhlowa basalt study area.

Note the presence of water in pans that are some distance from the drainage network. The north-south vegetation boundary seen in the west of the scene runs alongside a road. Another road runs north-south on the eastern side of the image, with a similar vegetation boundary along part of its length.

5.4.4 STEP THREE: B) Classification of terrain units

The wide valley spacing in the Nhlowa basalts means that in order to indicate hillslope position, TPI needs to be measured over a much larger distance than in the N'waswitshaka granite study area. The mean CASS width in the Nhlowa basalt study area is 1 737m, so a circular kernel of 850m (190 cells) radius was used to calculate TPI in this region to capture variation over a complete hillslope (Figure 5.28a).

To capture detailed channel topography, TPI was also measured over a much smaller distance of 49m (11 cells), approximately half the average width of valley bottoms. At this scale, variation across the width of the valley bottom is captured and incised channels and lateral gullies are clearly visible (Figure 5.28b). Isolated pans are also revealed, scattered across the landscape in a seemingly random fashion.

Curvature measured over a distance of 220m, equivalent to about a third of the length of an average hillslope, reveals the abrupt changes associated with the channel floor and incised channels. Profile curvature shows irregular convexity in the footslope area, whilst plan curvature shows consistently convex crests and several concave depressions that appear to drain into the network, but which are not channelized (Figure 5.29).

Profile curvature over a shorter distance (49m, about half the average width of valley bottoms) clearly shows convex banks adjoining concave incised channels on each side of the valley bottom (Figure 5.30a). Planform curvature over this distance distinguishes small gullies that flow into the main stem and the concave downstream shape of the valley floor (Figure 5.30b).

'Long-range' gradient calculated over a distance of 220m shows very flat crests and valley bottoms, with a relatively steep area bordering the broad valley bottom (Figure 5.31). These steep banks are even more clearly shown in the 'local' gradient, calculated over 49m. The 'local' gradient also reveals depressed pans scattered throughout the landscape.

This is an extremely flat area. Other than the morphology associated with the valley floor, changes in gradient and curvature are both small and gradual.

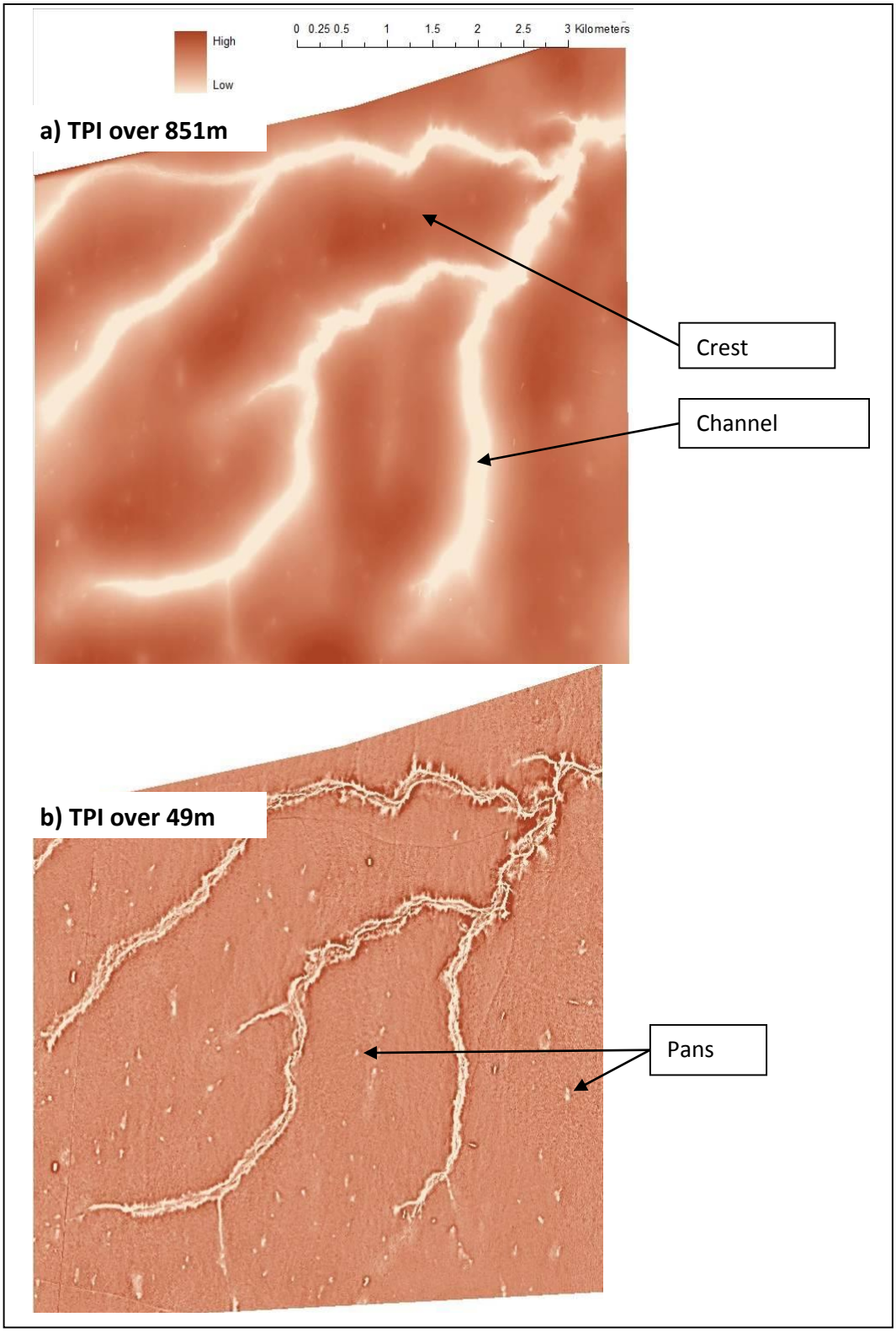


Figure 5.28: TPI calculated over 851m and 49m within the Nhlowa basalt study area.

a) TPI calculated over 851m clearly distinguishes between crest and channel regions.

b) The same measure calculated over 49m shows fine detail of scattered pans and channels in the valley bottom.

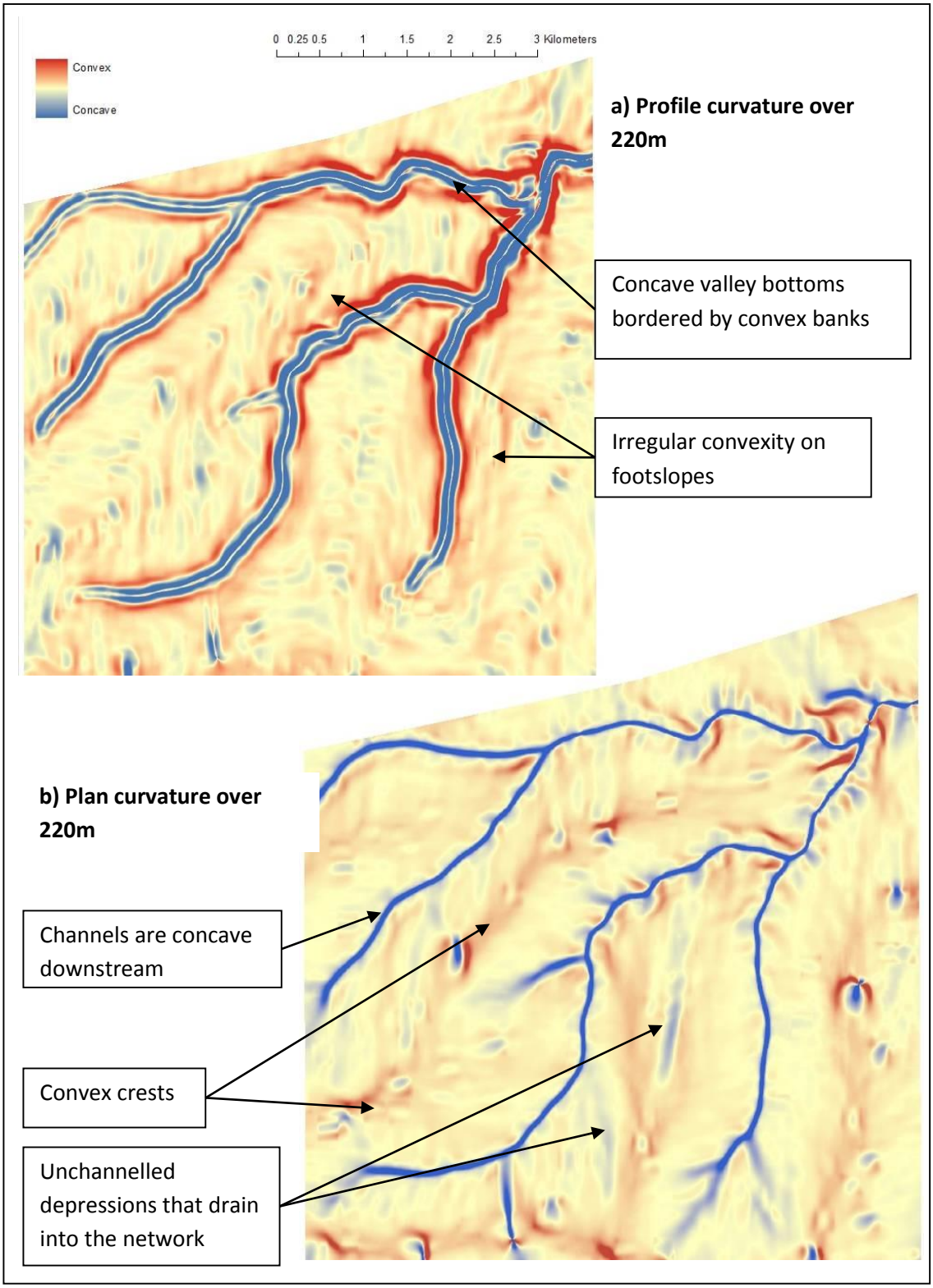


Figure 5.29: Curvature in the Nhlowa basalt study area.

a) Measured over 220m, profile curvature shows abrupt changes associated with valley bottoms. Profile curvature shows irregular convexity in the footslope area.
b) Plan curvature shows the downstream concavity of channels and convex crests. Several unchannelled depressions that appear to drain into the network are also revealed.

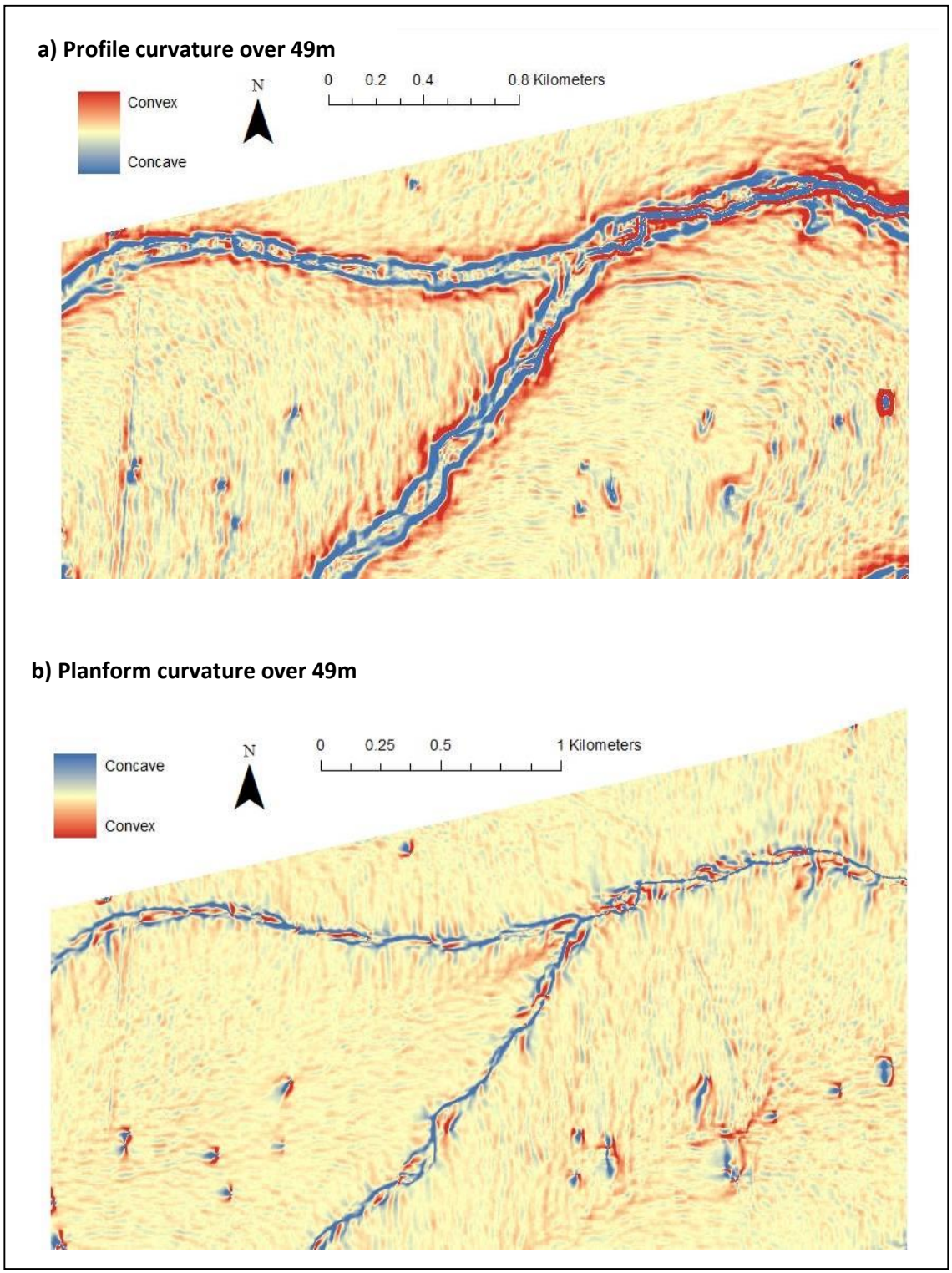


Figure 5.30: Curvature over 49m in channels on the Nhlowa basalt study area.

Whilst profile curvature measured over 49m reveals the incised channels and banks of the valley bottom, planform curvature distinguishes gullies that flow into the main stem.

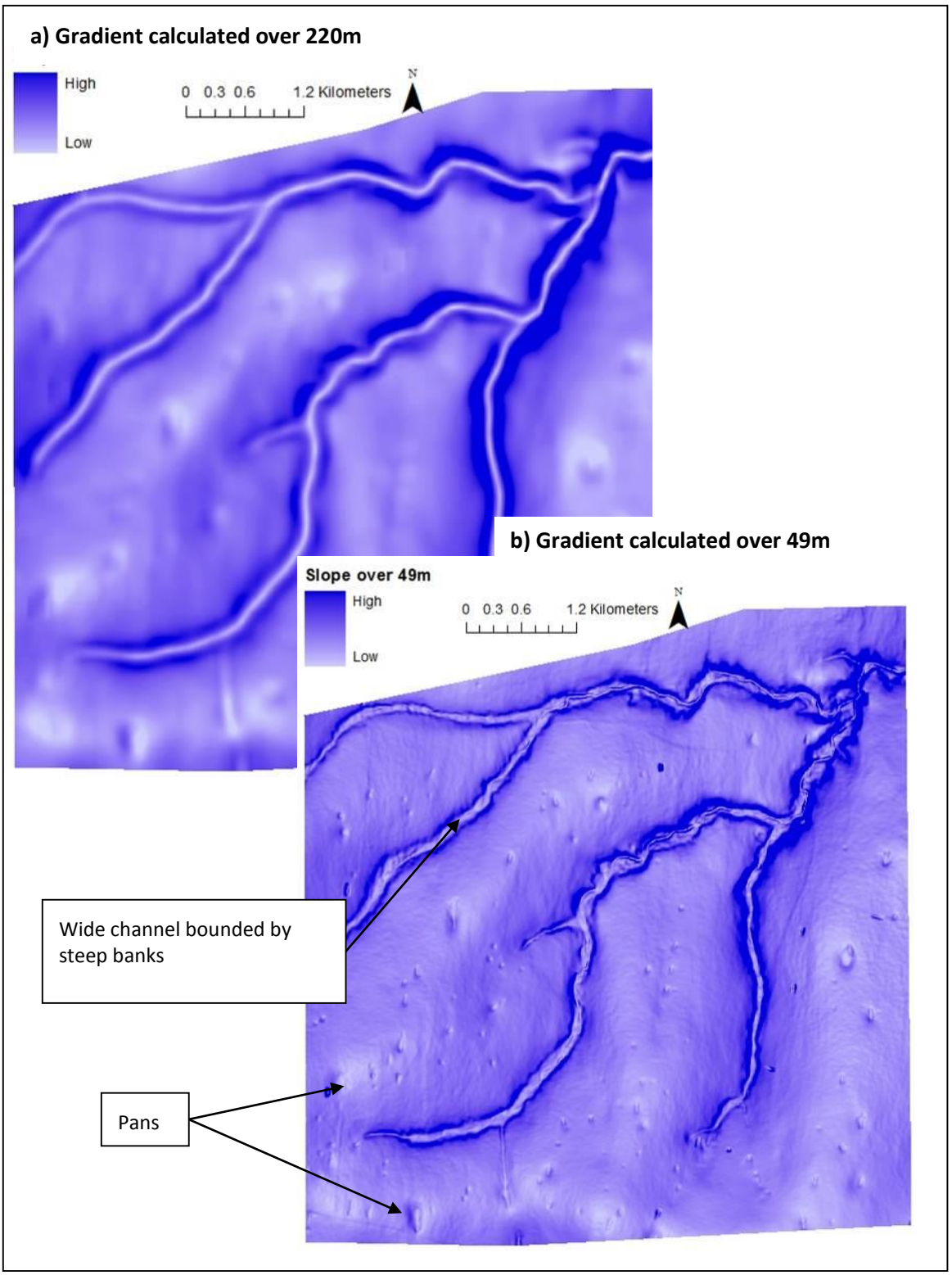


Figure 5.31: Gradient calculated over 220m and 49m in the Nhlowa basalt study area.

a) Calculated over 220m, gradient shows broad differences between the crests and the valley bottoms. b) Gradient calculated over 49m clearly shows the relatively steep banks that bound valley bottoms, as well as the depressed pans scattered throughout the landscape.

Whilst valley bottoms are well defined, the small and gradual variations in topography in this area make it difficult to separate footslope areas from crests and valley bottoms. In particular, it is not clear how far upslope the relatively steep, convex footslopes described in the *a priori* archetypes should extend. Furthermore, there are no obvious vegetation patterns to help guide this decision.

A fuzzy classification was therefore used, separating areas above the valley bottom into three classes, based on a combination of TPI and 'long range gradient'. Small depressions (pans) were also identified separately.

The classes used to define terrain units in the Nhlowa basalt study area were thus (Table 5.2):

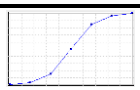
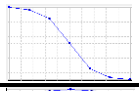
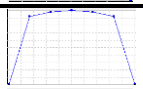
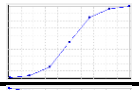
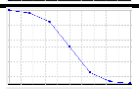
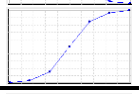
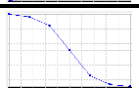
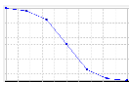
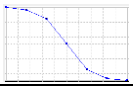
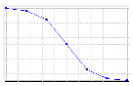
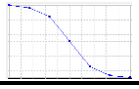
- ***Crests***: high in the landscape and very flat
- ***Midslopes***: steeper 'long-range' gradient than crests, and medium-high in the landscape
- ***Footslopes:*** steeper 'long-range' gradient than midslopes, and medium-low in the landscape
- ***Valley bottoms:*** Very low in landscape and flat
- ***Channels***: Very low in landscape and highly concave curvature over 49m
- ***Pans:*** on crests or midslopes and mean TPI <= -0.1

The fuzzy classification used to define terrain units in this classification recognises that classes blend into each other, particularly in areas such as the Nhlowa basalt study site, where changes are very subtle and gradual.

Although crests, midslopes, footslopes and channel floors are progressively lower in the landscape, there is considerable overlap between the classes. Although both crests and valley bottoms are flat, crests can have slightly steeper gradients than channel floors. Similarly, midslopes can be less steep than footslopes.

When these conditions are combined, the minimum class value applies. For example, a high TPI value of 1.4 (both crest and midslope membership values = 100) and a moderate gradient of 1.0 degrees (crest membership value = 50, midslope = 100) would yield a combined crest membership value of 50 and a higher midslope value of 100, so that image object would be mapped as a midslope.

Table 5.2: Rule set used for the fuzzy classification of terrain units in the Nhlowa basalt study area.

Class	Variable	Membership function curve	Minimum value	Maximum value	Comments
Crest AND (Min value of all functions)	Mean TPI (851m)		0.5	1.0	High in the landscape
	Mean 'long range' gradient (220m)		0.7	1.5	Flat
Midslope AND	Mean TPI (851m)		-2	2	Lower
	Mean 'long range' gradient		0	0.7	Steeper
Footslopes AND	Mean TPI (851m)		-1	-0.8	Lower still
	Mean 'long range' gradient		0.7	0.9	Steeper still
Channel Floor AND	Mean TPI (851m)		-3	-2	Very low in landscape
	Mean 'local' gradient (49m)		1	1.2	Flat locally...
	Mean 'long range' gradient (220m)		0.8	1	...and/or over 'long range'
Channels AND	Mean 'local' profile curvature (49m)		-0.0003	-0.0002	Locally concave (over 49m)
	Mean TPI (851m)		-3	-2	Very low in landscape

The final stage in producing a map of terrain units for the Nhlowa basalts was to smooth boundaries by applying a low-pass filter (majority value in neighbouring circle of 5 cell (25m) radius). Units that were smaller than the MMU (<1 ha) were not merged in this classification, in order to preserve the small pans.

The final classification shows a discontinuous incised channel lies within a larger channel, which is bounded by sloping banks (Figure 5.32). Boundaries between footslopes, midslopes and crests are somewhat arbitrary, since continuous gradual change is poorly represented in categorical maps.

Pans on the crests and midslopes sometimes form chains of ponds in the centre of concave depressions that appear to drain into the channel network. These features could be early stages in the development of a new channel. Other pans seem to be disconnected from the drainage network and probably result from local subsidence, enlarged by animal use as wallows.

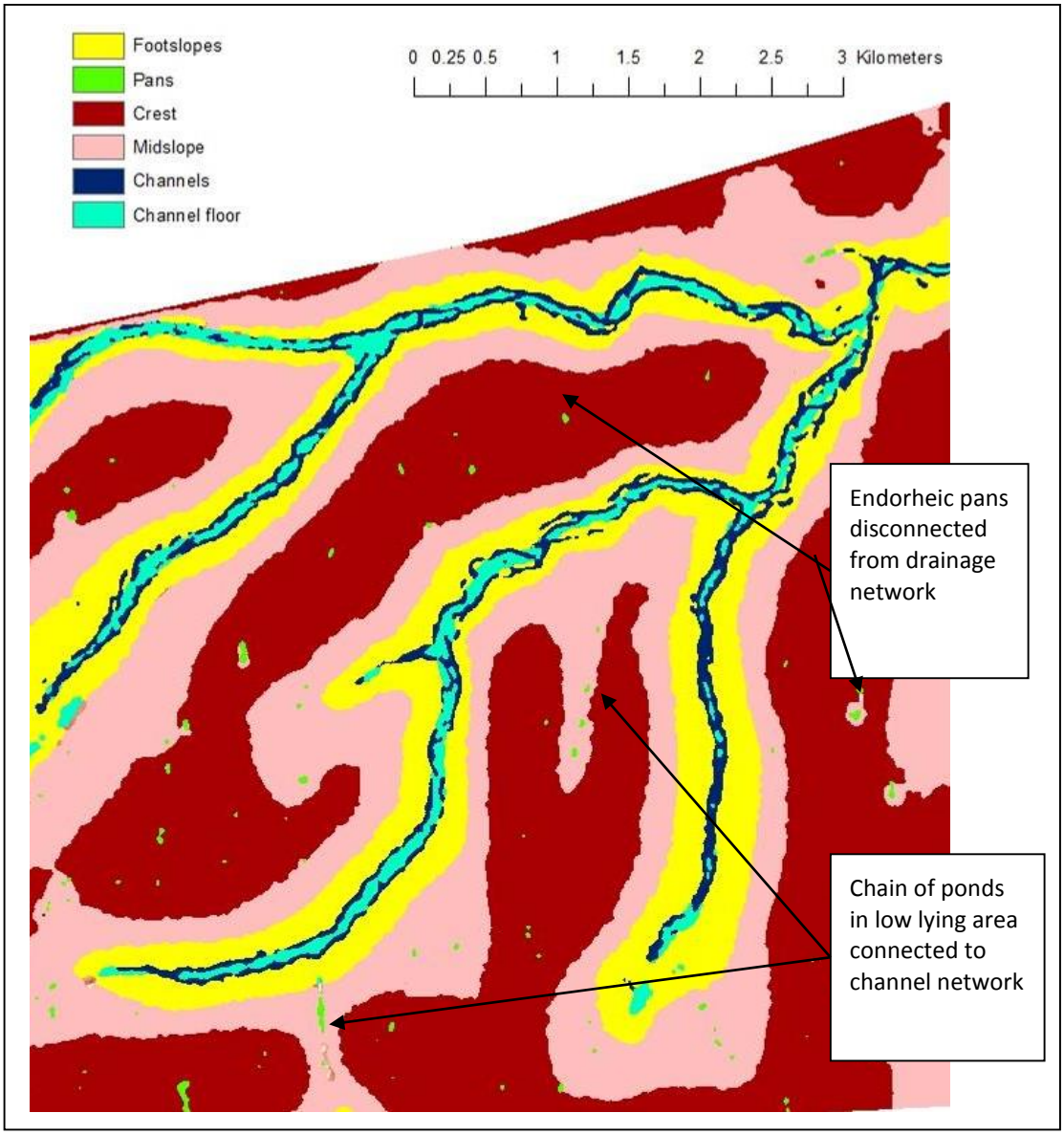


Figure 5.32: Terrain units in the Nhlowa basalt study area.

A discontinuous channel clings to the edges of a broad channel floor that is bounded by sloping banks. Pans on the crests and midslopes are sometimes chains of ponds that suggest the possible development of a new channel, but are also seen in positions where they appear to be disconnected from the drainage network.

5.4.5 STEP THREE: C) Relationships between vegetation and terrain units in the Nhlowa basalt study area

There is little difference in the vegetation associated with crests and midslopes, which are both dominated by open grassland (Figure 5.33). The proportion of woody cover increases on footslopes, declining again in inundated valley bottoms and channels. It is likely that when dry, valley bottoms are either bare or covered with grass. Overall, woody vegetation is sparse in all areas, with only a few lower-lying areas that have moderately dense cover, as described by Venter (1990) and in the *a priori* archetypes (Section 5.4.1 above).

Although no shrub cover and more tall trees are found on pans than on crests or midslopes, the small sample size means that these results are only indicative.

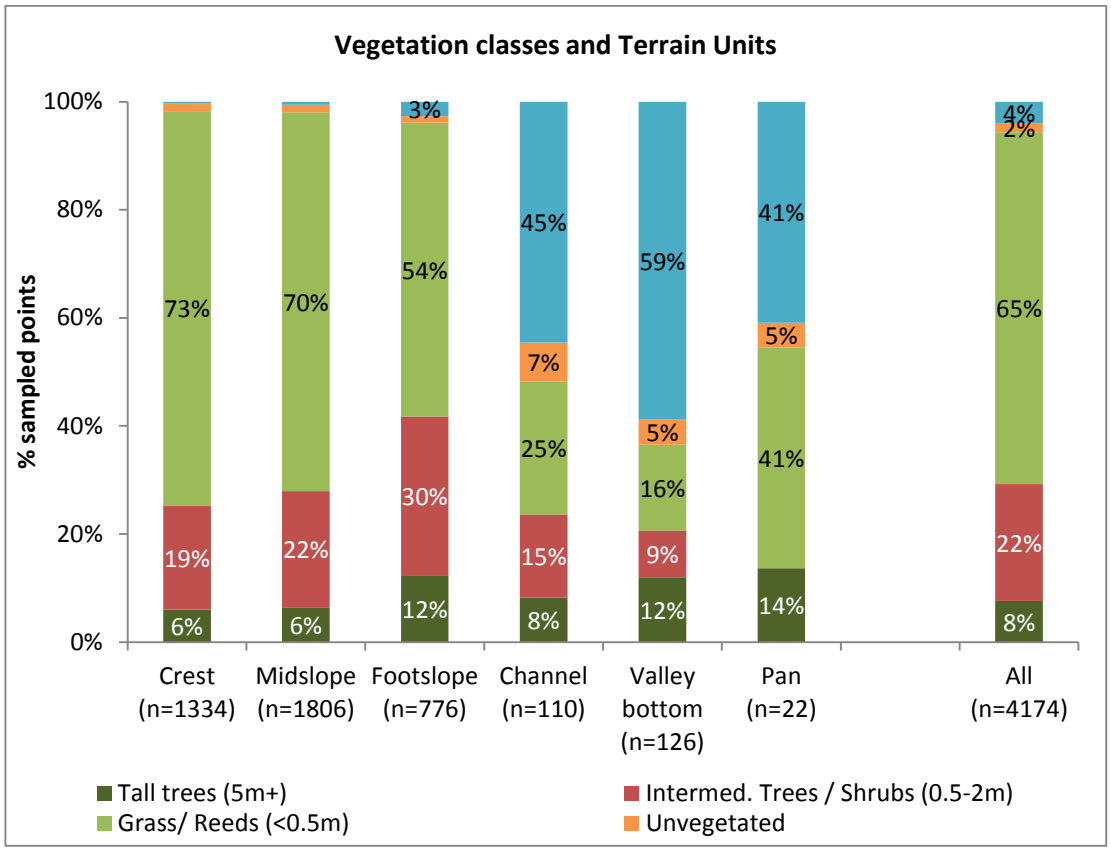


Figure 5.33: Relationships between vegetation and terrain units on the Nhlowa basalt study area. Vegetation associated with crests and midslopes are very similar, with a slight increase in intermediate and tall trees on footslopes. Results are based on points sampled at 100m intervals.

5.4.6 STEP THREE: D) Catenal elements in the Nhlowa basalt study area

Since there was no significant difference in the vegetation associated with midslopes and crests (Section 5.4.5), these units were merged, leaving three archetypes of catenal elements in the Nhlowa basalts: crests, footslopes and valley floors (Table 5.3). Whilst pans and channels could be mapped separately, they are generally small features that are more appropriately considered at a lower level in the landscape hierarchy. Pans and channels are therefore considered as microfeatures associated with crest and valley bottom catenal elements respectively.

In constructing the final map of catenal elements, the image was smoothed, over a 25m radius and generalised by eliminating units with areas less than the MMU of 1ha.

Table 5.3: Archetypes of catenal elements in the Nhlowa basalt study area.

	Crest	***Footslope***	***Valley floor***
Profile curvature	Planar/ convex	Convex	Concave/ planar
Gradient	Flat	Locally steep	Flat
Woody vegetation	Open grassland, sparse tall trees and shrubs	Open grassland, with clusters of tall trees and shrubs	Open grassland with some tall trees. Inundated in wet season
Microfeatures	Isolated pans		Incised channels, often discontinuous

The Nhlowa basalts are dominated by crests (Figure 5.34). The vegetation on these interfluves is heterogeneous and is likely to be influenced by patterns of subsurface water storage, fire and herbivory, rather than by the very slight topographical variations seen in this very flat landscape.

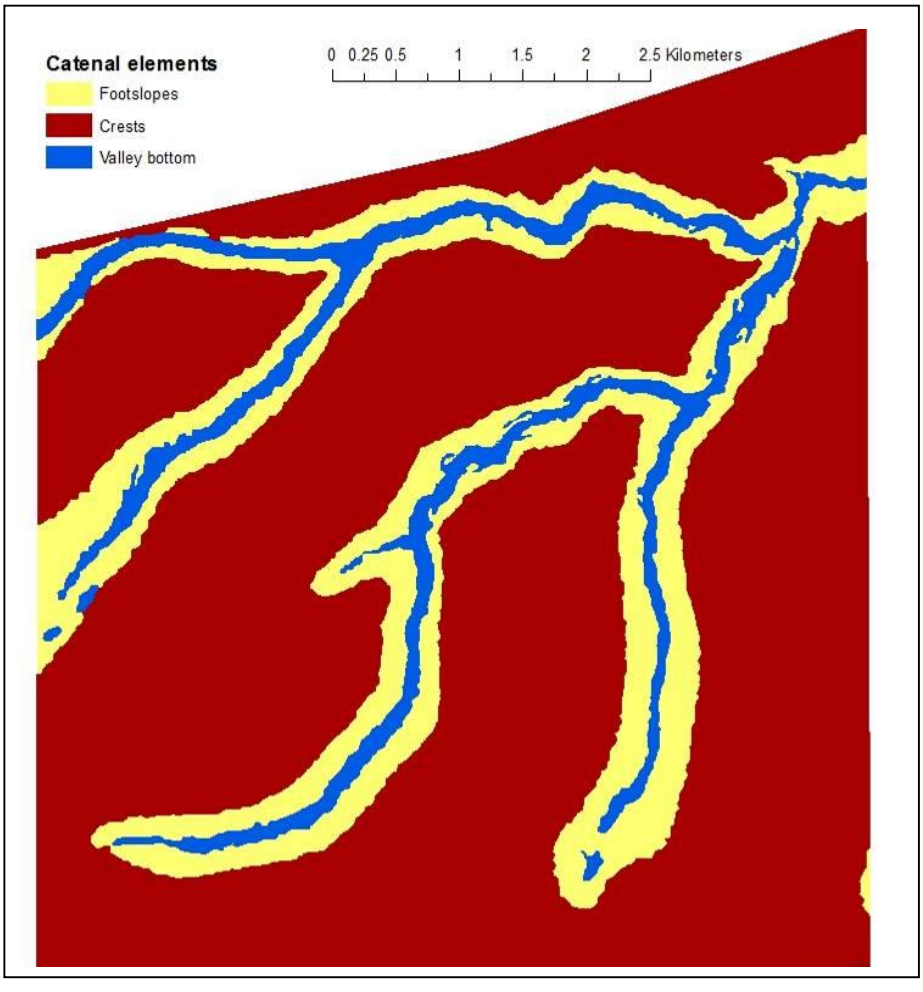


Figure 5.34: Catenal elements in the Nhlowa basalt study area.

This area is dominated by crests, which occupy some 80% of the study site. Whilst footslopes and valley bottoms are characterised by the presence of relatively tall trees and water, the vegetation on interfluves is heterogeneous and is likely to be influenced by patterns of subsurface water storage, fire and herbivory, as well as by the very slight topographical variations seen in this very flat landscape.

5.5 Discussion: Evaluation of the classifications and the approach used

5.5.1 How well do the archetypes describe each of the landscapes studied?

Conventional evaluations of classifications, involving groundtruthing to ascertain whether or not sampled areas have been assigned to the correct class, assume that the ontology underlying the classification is useful and that the classes themselves are 'correct'. However, the main aim of this classification has been to explore the feasibility of partitioning the landscape into ecohydrological units that provide similar settings for a wide range of ecological processes. I therefore start the evaluation of the classification by considering the extent to which the proposed archetypal elements actually describe the landscape.

N'waswitshaka granite study site

Over 80% of the study site was classified into classes that correspond to the archetypes that were defined *a priori* and modified as the classification was developed. This suggests that these conceptual models can be used to describe the vast majority of the area (Table 5.4).

Table 5.4: Percentage area of the N'waswitshaka granite study site occupied by each catenal element. Some 81% of the study area can be described in terms of the archetypal catenal elements that were proposed a priori or developed as the classification progressed (shown in bold below). However, two classes emerged that clearly do not correspond to the archetypes (shown in italics below).

	% Area	Area (ha)
Rel. woody crests	**30%**	**4 986**
Rel. grassy crests	*10%*	1 612
Koppies	**<0.5%**	**32**
Rel. grassy midslopes	**26%**	**4 380**
Rel. woody midslopes	*9%*	1 463
Rel. grassy floodplains	**2%**	**395**
Riparian trees	**18%**	**3 073**
Sodic sites	**1%**	**191**
Channels and banks (grassy/ bare/ water)	**4%**	**698**
ALL	100%	16 831

However, two classes clearly fall outside the mental models underlying previous descriptions of the study site, from which the *a priori* archetypes were developed:

- 'Relatively grassy crests', which occupy some 10% of the site and are mostly located in the north and west of the scene. A quarter of all crests in the study site are classified as 'grassy'.
- 'Relatively woody midslopes' (9% of the scene and a quarter of all midslopes) occur throughout the area.

- These anomalies can be treated as part of the inevitable local heterogeneity, just being identified as exceptions to the rule, noting that observations and experience from other sites falling within archetypal areas cannot be extrapolated to apply in these anomalous areas. Such anomalies are often associated with geological features such as fractures in the granite blocks or intrusive dolerite dykes (Figure 5.35).
- Alternatively, new archetypes can be developed, accompanied by new conceptual models that link the observed patterns to underlying generative processes. Various considerations influence whether or not each of the anomalies challenge the underlying ontology sufficiently to warrant the development of new archetypes or other changes to the classification scheme:
- Are they situated in transition zones, suggesting that class boundaries need to be refined and/or that the classification (and its representation in a map) needs to be fuzzier?
- Are they concentrated geographically, suggesting that new archetypes might be needed to better understand and manage a particular area? If so, is this area sufficiently large or important to warrant separate scientific assessment or management?
- Are the anomalies likely to affect connectivity within the CASS, changing hydrological flows in ways that are likely to significantly alter the character and behaviour of the CASS?
- Are repeated toposequences evident in these areas that are poorly described by the current archetypes?

Some 'grassy crests' and 'woody midslopes' occur in circumstances which are artefacts of the classification, rather than areas where the underlying archetypes and catenal model are unlikely to apply:

- Many areas that have been classified as 'crest', due to their high elevation relative to neighbouring areas, are relatively low lying spurs or mounds towering above the floodplain or river bed. Such areas are more appropriately classified as 'midslopes'.
- Differences in vegetation associated with crests and midslopes are very subtle, and are overlooked in the classification rules. For example, many 'woody midslopes' lie above 'grassy midslopes', and would be better classified as part of the 'woody crest' above.

In these instances, refinements to the classification rules could potentially remove the anomalies. However, in other areas, grassy crests defy the underlying catenal conceptualisation:

- There is no visible vegetation difference between crests and midslopes – both are equally grassy or woody.
- In a few areas, graduated toposequences are evident, with a wide transition zone between the relatively densely wooded crests and grassy midslopes. Since this zone is less densely wooded than the crest, it is classified as a relatively grassy crest.

In these areas, hydrological flows are likely to differ from those hypothesised for toposequences of archetypes; catenal elements (see Section 4.12.3). However, since these areas cover a very small proportion of the study area, I did not think it worth developing a new archetype.

Pending the revision to classification rules needed to resolve the first group of anomalies, I would therefore recommend that all CASSs containing grassy crests are flagged as areas where the archetypal relationships between catenal elements are unlikely to apply.

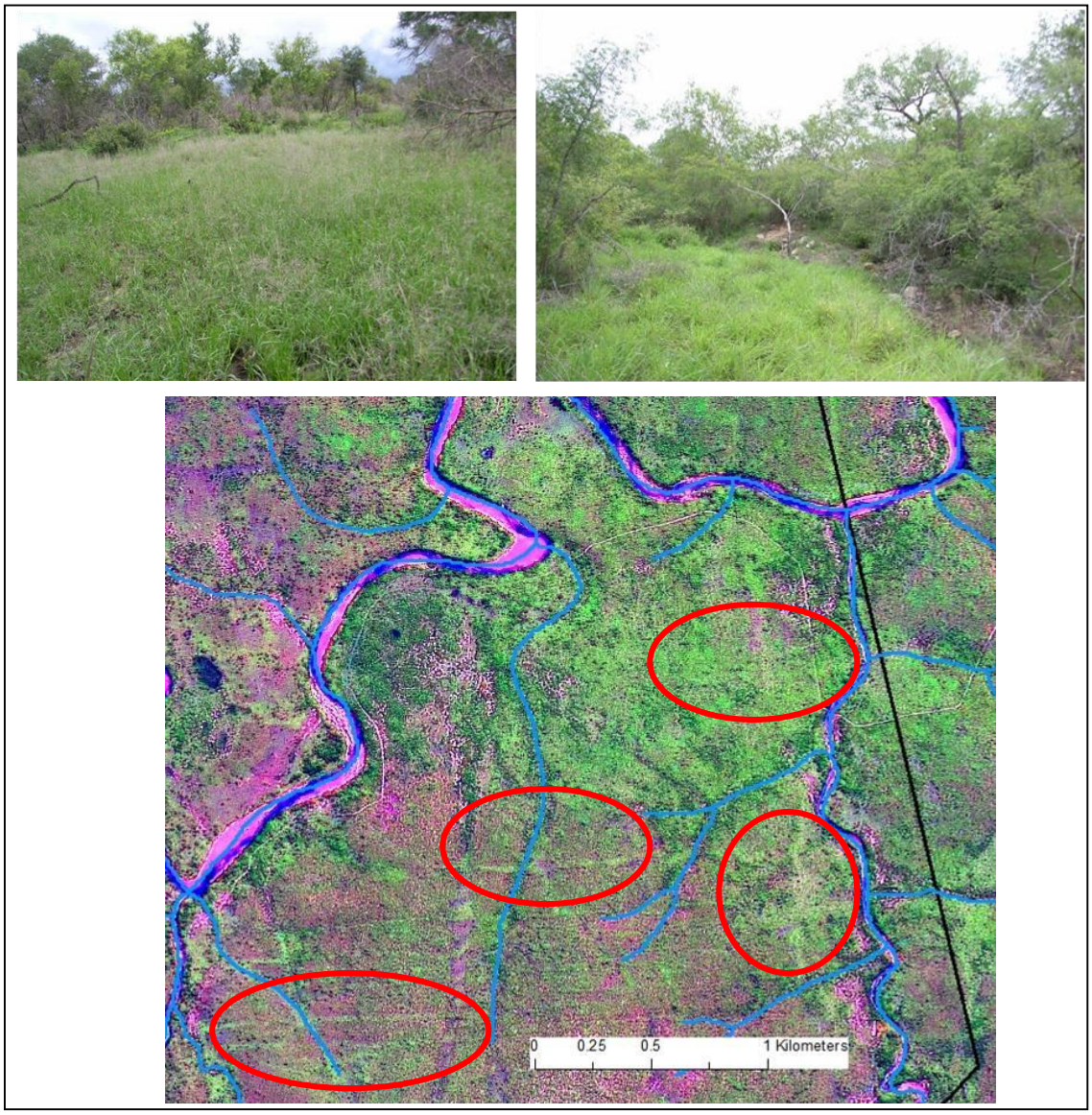


Figure 5.35: Vegetation changes associated with geological features such as joints/fractures in granite blocks or intrusive mafic dykes.

Geological features can disrupt the toposequences normally found on hillslopes. The photos show a grassy crest associated with a linear geological feature such as those seen on the SPOT5 image. The black line is the eastern boundary of the N'waswitshaka granite study site. Photos: CC Dec 2007, SPOT5 image (Red= SWIR band, Green =NIR band, Blue = Red band).

Nhlowa basalt study area

The entire Nhlowa basalt study site was classified into classes that corresponded to the *a priori* archetypes (Table 5.5). Most of the area consists of relatively homogenous crest, with random features such as pans and structured features such as chains of ponds in depressions, that do not qualify as channels. Vegetation patterns in these crestal areas are likely to be more influenced by factors such as fire and herbivory rather than by topography. This does not imply that toposequences are not relevant in this setting, merely that we need to adjust our perspective to accommodate the much larger catenal elements in this area compared to those seen in the N'waswitshaka granite site.

Table 5.5: Percentage area of the Nhlowa basalt study site occupied by each catenal element. The entire Nhlowa basalt study area can be described in terms of the a priori archetypal catenal.

	% Area	Area (ha)
Footslopes	14%	744
Crests	80%	4 122
Valley bottoms	5%	278
ALL	100%	5143

The boundaries of catenal elements are far less abrupt in this site than in the N'waswitshaka granites, with gradual transitions between the various elements that are not well represented in area-class maps.

5.5.2 How do these classifications improve on previous classifications?

Most semi-arid landscapes are characterised by toposequences of associated soils, vegetation and hydrology. Each catenal element in these sequences is structurally and functionally very different to its neighbours, such that averaging across elements is potentially very misleading. However, catenal elements are not usually mapped spatially explicitly (Hansen *et al.*, 2009). For example, in previous landscape classifications of KNP, broad areas are delineated that are distinguished from each other in terms of the toposequences of catenal elements they typically contain, but these toposequences are only described conceptually, rather than being explicitly mapped (e.g. Venter, 1990; Gertenbach, 1982). The same is true of the Land Survey of South Africa (MacVicar *et al.*, 1974) and, indeed, for local soil maps in most of Africa (Rossiter, 2008).

Mapping catenal elements explicitly reveals the extent to which soil-landscape models (conceived here as archetypal catenal elements and toposequences) actually apply at regional scales. For example, whereas the archetypal models applied throughout the Nhlowa basalt study area, in the N'waswitshaka granite study area there were many anomalies (Section 5.5.1). Understanding the extent of deviation from the archetypal model and the ability to map areas where these deviations allow us to better deal with local heterogeneity, both by assessing the extent of local variations and by signalling areas where extrapolations based on the archetypes may not apply. Furthermore, this approach allows new patterns to be observed, and, if warranted, new archetypes can be developed to describe and map these patterns. For

example, the new archetype for 'koppies' emerged during the analysis of the N'waswitshaka granite site, and new archetypes could also be developed to describe other common anomalies in this area, such as completely wooded or grassy slopes. The spatially explicit mapping of catenal elements also opens the possibilities of 'bottom-up' mapping of physiographic zones, by identifying those regions which contain similar sequences of catenal elements.

5.6 Reflections on the construction of the conceptualisations for the two study areas

Reflecting on the process of classification suggests some refinements to the meta-ontology of geographic ontologies proposed by Couclelis (2010, see Section 3.3, Table 3.1). Rather than a straightforward descent through the ontological levels, as Couclelis describes, I found that the construction of a geographic ontology for each of my study areas involved repeated iterations between each of the lower ontological levels (Figure 5.36).

Mapping catenal elements in each of these areas involved refining the level 5 conceptual entities defined in the abstract landscape hierarchy (Section 3.6.2) to apply in a particular landscape, developing local *a priori* archetypes that could be used to guide the rules used to identify, classify and map each catenal element. The interplay between the lower ontological levels that occurred during this process is reminiscent of the semiotic triangle that describes relationships between *conceptualisation* (thought), *representation* of that thought (e.g. in language, imagery or a map) and the *reality* (landscape) that is being thought about and represented in a map (Section 3.1.1, Figure 3.1).

Both the perception and representation of this reality are affected by scales of observation (Levin, 1992). In turn, reality also influences the selection of scales suited to its observation, since the spacing of ridges and valleys affects both our human perception of hillslopes (how much can be seen at a time) and the actual size of the catenal elements described by the local archetypes. Furthermore, the process of mapping archetypal landscape elements often leads to revision of the archetypes, since details are noticed that have been overlooked in initial qualitative assessments.

Thus the mapping and classification process involved constant interaction between the abstract conceptualisation and the landscape itself, mediated through the imagery and statistical analyses of mapped attributes. The important role played by the landscape itself in this approach to ecological mapping means that it is impossible to develop a standard approach to mapping catenal elements that will apply across all landscapes or all imagery. It also legitimises the representation, since the degree to which the landscape actually conforms to the analyst's conceptualisation can be assessed, themes to which I will return in the thesis discussion (Chapter 8).

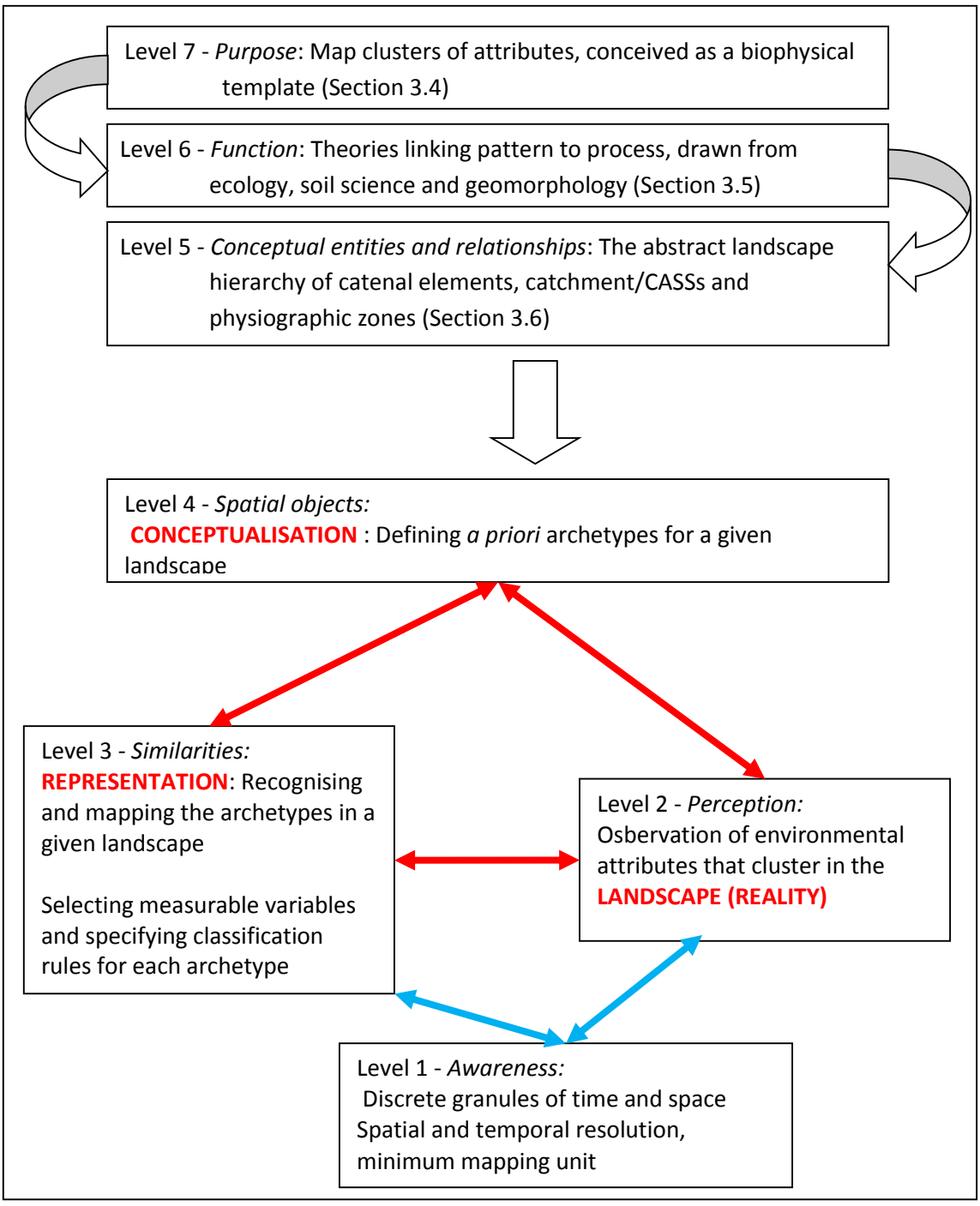


Figure 5.36: Relationships between levels in a geographic ontology.

When an abstract hierarchy is applied to a given landscape, the construction of a geographic ontology no longer follows a strict descent through the various levels of meaning, as suggested by Couclelis (2010). Instead, a semiotic triangle is constructed (shown in red), with iterative interplay between the CONCEPTUALISATION of a priori archetypes, the REPRESENTATION of this conceptualisation in a map and observation of REALITY (the landscape being mapped). The scale of observation both affects and is affected by the inherent grain of the landscape and the selection of mapping scales.

5.7 Summary

In this chapter I have applied the abstract conceptualisation for savanna landscapes at the lowest level of the hierarchy, developing *a priori* archetypes of catenal elements for two contrasting study areas. The archetypes were then used to inform a landscape classification, delineating catenal elements in each study area, revealing the extent to which each landscape conformed to the idealised archetypes. Whereas the proposed archetypes described the entire Nhlowa basalt area, about 20% of the area of the N'waswitshaka granite study area did not conform to the *a priori* archetypes. This approach to the explicit mapping of catenal elements allows the variability within an area to be assessed, identifying anomalous hillslopes that are unlikely to behave in the same way as the hillslopes that conform more precisely to conceptual models that describe typical soil-vegetation toposequences and the hillslope hydrology of the area.

In the following chapter, I apply the conceptualisation at the next highest hierarchical level, mapping the study areas in terms of catchments and CASSs and the toposequences of catenal elements that they contain.

CHAPTER 6: RESULTS PART TWO: CATCHMENTS AND CASS

In this chapter, landscapes are partitioned into catchments and CASSs. Assemblages of catenal elements found within catchments and CASSs of various sizes are considered. These assemblages are compared to idealised toposequences of catenal elements in the granite and basalt study sites. About half the CASSs in the N'waswitshaka granite study site conform to the archetype, with some geographical clusters of CASSs that differ from the archetype sufficiently to question the validity of extrapolating observations or experience from archetypal CASSs to these areas. Assemblages of catenal elements in the N'waswitshaka site change with network position, with toeslopes becoming more prominent as floodplains develop in higher-order CASSs. In the flatter landscapes of the Nhlowa basalts, assemblages of catenal elements are more uniform, conforming to the archetype and varying little with stream order. Challenges associated with identifying and analysing assemblages of landscape units are considered, together with benefits of conducting such analysis.

6.1 Introduction

Catenal elements are not arranged haphazardly, but are highly organised within catchments and CASSs (Contributing Areas to Stream Segments – see Section 3.4.2), forming toposequences that recur throughout the physiographic zones (Section 3.4.3). These assemblages of catenal elements contained within catchments may be connected to each other by hydrological flow paths that control patterns of water distribution across and through the catchment. Since water fluxes act as vectors for a wide range of materials (e.g. sediment, minerals and propagules), the patterns of these water movements influence a very wide range of ecological and geomorphological processes (e.g. Likens, 2001; Post *et al.*, 2007). Thus the partitioning of landscapes into a mosaic of catchments isolates structural-functional units that are relevant to many different disciplinary and management interests.

Both the composition and configuration of the catenal elements found within a catchment are important determinants of hydrological flow paths. The characteristics of the catenal elements determine the potential hydrological permeability of the boundaries between them, whilst their arrangement in space determines the patterns of connectivity. These patterns of hydrological connectivity have a temporal dimension as well as a spatial dimension, since the quantity and rate of water passing between catenal elements varies according to rainfall inputs and the degree of saturation of each element. Furthermore, the frequency and extent of connectivity also varies by depth: catenal elements are often hydrologically disconnected on the surface, but connected by throughflow in the vadose zone above the water table or by groundwater flow in even deeper bedrock zones.

In many landscapes, numerous ecological processes are spatially bounded within catchments. However, in areas of low-relief, catchment boundaries are often barely perceptible on the ground, such that adjoining crests or midslopes form continuous patches. Such notional topographic divides create no barrier for many ecological processes (e.g. predation, fire, and seed dispersal) and even the change in direction of surface and near-surface hydrological flow

paths can occur within a large transition area of hundreds of metres. However, even if crests are considered as a single patch, the distribution of resources for animals and plants is still dependent upon the broader-scale catchment-level hydrological, geomorphological and biological processes that generate and sustain a biophysical template with more or less predictable toposequences of catenal elements within a given physiographic zone.

Changes in morphology, vegetation and soils along the longitudinal course of a river are well documented. For example, headwater areas tend to have shorter, steeper hillslopes, with narrow, shallow streams in confined valleys that allow no room for wide floodplains, whilst areas further downstream tend to be characterised by longer, gentler hillslopes and wider, deeper rivers bordered by wide floodplains (Schumm, 1977; Montgomery & Buffington, 1997). These systematic changes in morphology have associated changes in soils, vegetation and the resources available to animals (Vannote *et al.*, 1980; Petts & Amoros, 1996). Thus, in an idealised system contained within a single physiographic zone, characteristic assemblages of catenal elements can be described for CASSs of each stream order. These idealised assemblages together form a set of *a priori* archetypes for a particular physiographic zone (Figure 6.1).

Conceptualising archetypal assemblages of catenal elements within the catchments and CASSs of a drainage network helps to solve the scale issues that have haunted the description of recurring landscape patterns (MacMillan & Shary, 2009), since the scale at which toposequences occur is determined by catchment/ CASS size. However, the size of mapped catchments and CASSs depends on the scale at which streams (or, in the case of ephemeral streams, evidence of drainage lines) are mapped, which in turn depends on the lowest order of streams that need to be mapped. The finer the scale at which streams are mapped, the more low-order streams and associated CASSs are delineated. At coarser scales only higher order catchments are seen and the CASSs of low order tributaries draining into the main stem are merged with high order CASSs (Figure 6.2).

It has already been shown (Section 5.2 Figure 5.2.2) that the streams shown on the 1:50 000 topographic map correspond well to hillslopes that show distinct toposequences of vegetation. Once this scale of observation is agreed, catchments can be considered as spatial entities that exist independently of the observer. Catchment and CASS boundaries are determined by landscape morphology, falling at the highest point between two streams. Catchment size and shape are not decided by the map producer, but are determined by the spacing of streams, a characteristic of the landscape itself that is related to patterns of landscape dissection. Although the precision with which these boundaries are mapped is affected by the resolution of the DEM used to delineate them, the location of the boundaries is observer-independent.

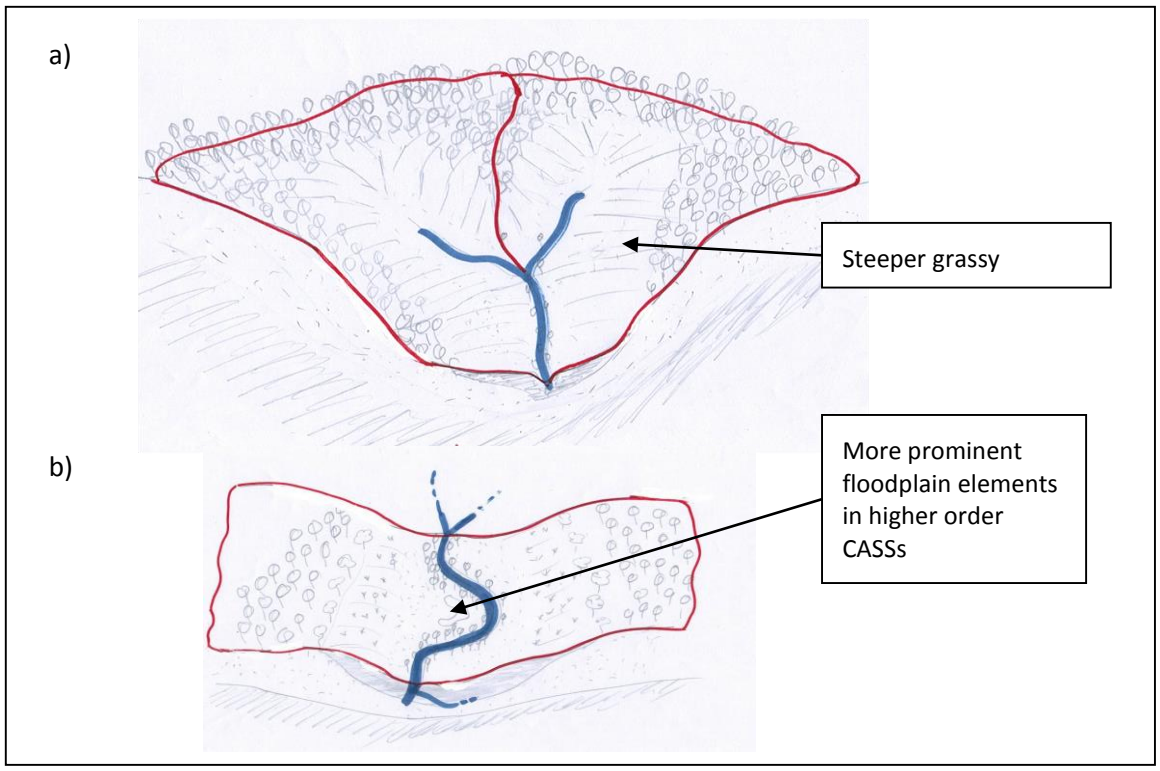


Figure 6.1: A suite of archetypal CASSs, each containing an assemblage of catenal elements that are characteristic of a hypothetical physiographic zone.

CASS boundaries are shown in red a) Headwater, low order CASSs may have steeper midslopes and less well developed toeslopes and floodplains than b) higher order CASSs.

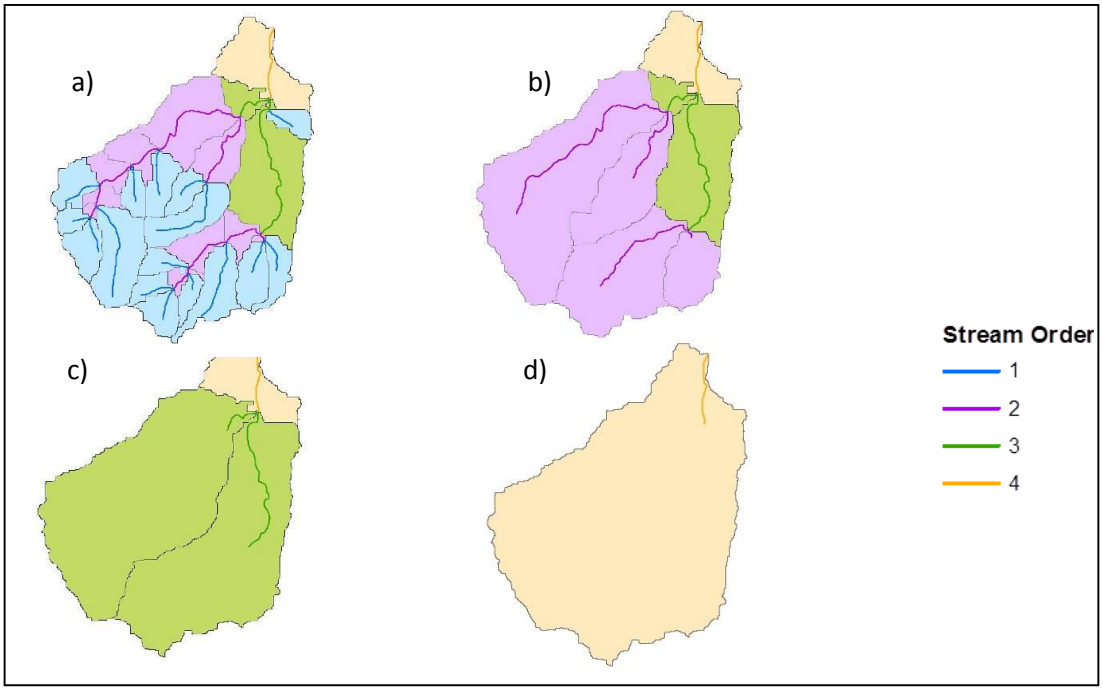


Figure 6.2 Steams and CASS delineated at various scales.

a) At the finest scale shown here, 1st order streams and CASSs are delineated. At progressively coarser scales (b-d), stream orders are lost and only higher order CASSs are delineated.

Any given landscape can be viewed at a particular scale either as a wall-to wall mosaic of CASSs or in terms of different order catchments that are spatially nested inside each other (i.e. a third-order catchment contains several 2nd order catchments, each of which contain many first order catchments, etc.) (see Section 3.4.2). It is therefore possible to conceive of catenal elements arranged within CASSs or within catchments of any stream order. It is also possible that patterns associated with catchments of different orders are superimposed upon each other, such that different catenal patterns are seen at the various scales of observation associated with each stream order (Figure 6.3).

The aim of this chapter is to demonstrate how catchments and CASSs can be described in ways that integrate terrestrial (patch) and aquatic (network) landscape perspectives. Specific objectives are to:

- Delineate catchments and CASSs within KNP.
- Describe repeating landscape patterns in different order catchments and CASSs in terms of archetypal assemblages (toposequences) of catenal elements in two contrasting study areas, considering:
    - any systematic variations in assemblages of catenal elements with network position, and
    - any patterns associated with different stream orders that are superimposed upon each other.
- Assess the variation around each suite of archetypes within each study area.
- Assess the usefulness and implications of considering landscape patterns as assemblages of catenal elements contained within catchments of different stream orders and in different network positions.

In the method section of this chapter, I describe how I delineated streams and catchments and CASSs in KNP. I then apply these boundaries to assemblages of catenal elements in my two study areas in the results section. Archetypal toposequences are developed for each area, before considering the extent of local variation around the archetype. Lastly, I discuss the challenges associated with describing repeating landscape patterns and the value of describing landscapes in this way.

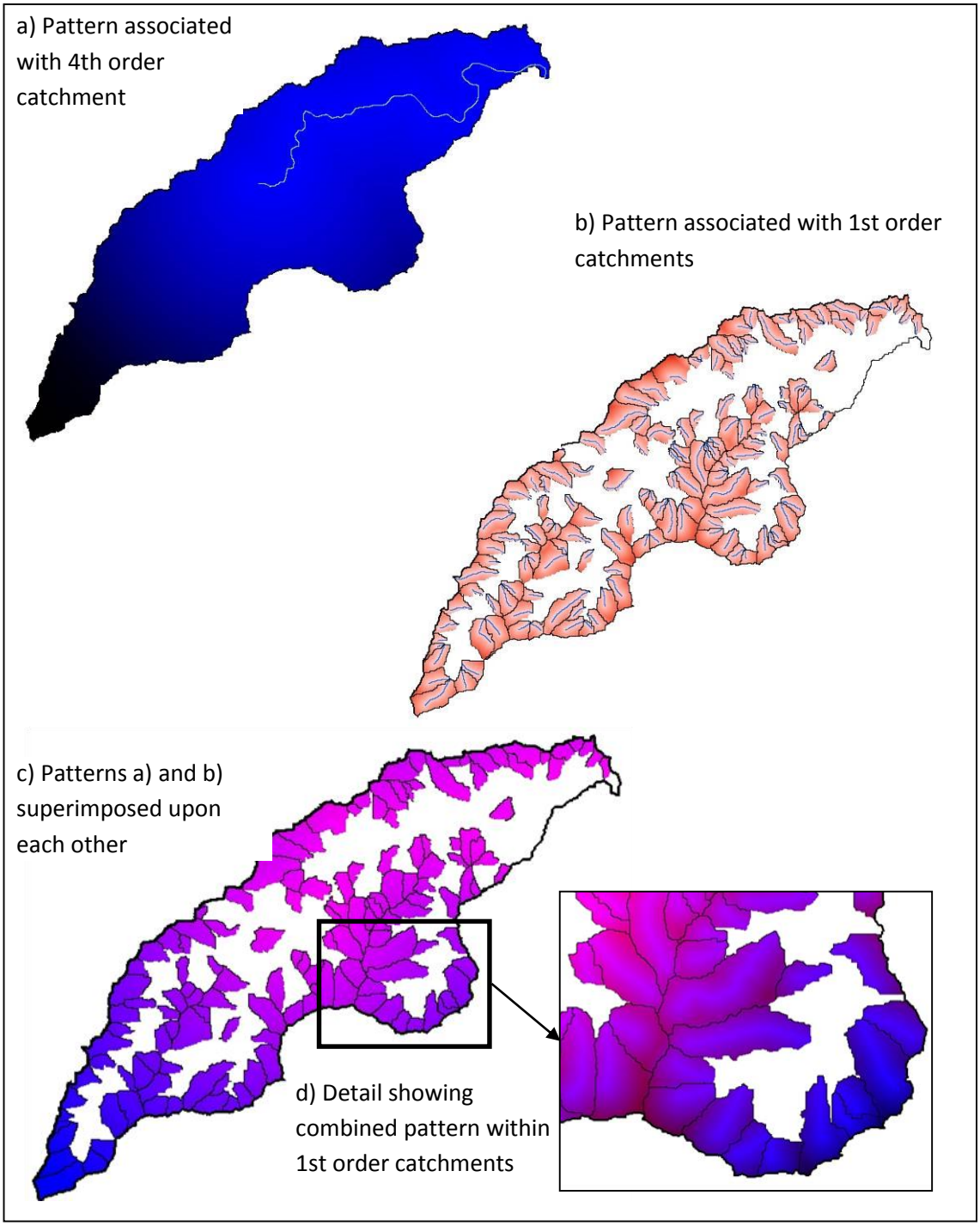


Figure 6.3: Patterns associated with different order catchments can be superimposed upon each other.

Since catchments associated with different stream orders are nested inside each other, it is theoretically possible that patterns in vegetation, soils, etc. associated with each stream order are superimposed upon each other.

a) Distance from a fourth order stream - a gradient along which soils and vegetation may change

b) Distance from first order streams - vegetation and soils may also vary along this gradient

c) and d) Superimposing a) on b), we see that the patterns associated with first order streams are modified by their position within the fourth order catchment. For example, the vegetation/soils found on first order crests near the centre of the basin differ to those found near the watershed of the fourth order catchment.

6.2 Method: Stream and catchment delineation

To delineate a stream network from which reach catchments and network variables such as stream order can be calculated, it is necessary to construct a hydrologically correct GIS layer of streams in which a connected drainage network flows in a downhill direction from source to outlet. The position of channels and the direction of downslope flow may either be constructed automatically from a DEM, or the channels denoted on an existing map may be converted into a hydrologically connected network.

Automatically delineating a stream network from a DEM usually involves either detecting changes in curvature to indicate channel position (Peuker and Douglas, 1975) or defining a threshold for the contributing area associated with channel initiation (Tarboton *et al.*, 1991). However, curvature-based approaches not only demand extremely high resolution DEMs to detect low order channels, they are also not suited to semi-arid or arid areas where incised channels may not exist along the entire length of a drainage line. Although the threshold approach to stream delineation is very widely used, there is no accepted method for determining thresholds for channel initiation. Furthermore, the use of a single threshold for stream delineation produces a network with a uniform drainage density, overlooking the variations in drainage density associated with different climatic and geological settings. In KNP, diverse geology and climate results in very different drainage densities in different areas of the park (Figure 6.4 and Figures 4.4, 4.12). As such it is inappropriate to apply a single threshold for the whole park. For example, using a 90m DEM and a 0.33km² threshold for the contributing area sufficient to initiate a stream resulted in a 32% underestimation of stream links in granite areas of the Sabie River basin and a 37% overestimation of links in basaltic areas, compared to streams shown on the 1:50 000 topographical map. Threshold-based approaches are also inappropriate in semi-arid landscapes such as those found in KNP, where many streams are ephemeral and low-order drainage lines are often discontinuous or unchannelised, such that there is no clear distinction between hillslope and channel processes.

Since the aim of this thesis is to link patterns of soil, vegetation and topography to patterns of water distribution, it is not relevant whether or not channelisation occurs in all drainage lines. The key task in stream delineation is to identify a network of longitudinally connected areas where water is concentrated in the landscape and to identify the hillslopes that drain into each portion of that network.

Areas where water is concentrated in the landscape are clearly visible in semi-arid landscapes, since they are associated with changes in the composition and structure of vegetation that are sometimes accompanied by changes in curvature (as seen in the delineation of catenal elements in Chapter 5). In preparing the 1:50 000 topographical maps covering KNP, changes in curvature and vegetation have been used by the South African NGI (National Geo-spatial Information) to delineate streams from high resolution aerial photography (Patrick Vorster, Chief Directorate National Geo-spatial Information, pers. comm.). For the purposes of this project it is therefore more appropriate to delineate a stream network based on this map, rather than to construct a network from a DEM. Furthermore, the results presented in Chapter 5 confirm that landscape grain is detected at this this scale, since vegetation patterns are

strongly associated with streams delineated at the 1:50 000 scale on the topographic map in both study areas.

However, the GIS layer produced by digitising the blue lines representing streams on 1:50 000 topological maps is not hydrologically correct, since streams have not always been digitised in the correct flow direction. Furthermore, tiny breaks in the lines mean that the network is not fully connected. To produce a hydrologically correct stream layer, stream locations were burnt into the 90m SRTM DEM by lowering the elevations of cells coinciding with the centre of streams shown on the topographical map. The procedures for stream delineation from a DEM were then modified to force flow along the burned-in flow paths and CASSs draining into each segment of these streams, and are then delineated (Box 6.1).

In practice, the scales at which streams and catchments are mapped are largely constrained by data availability. The finest resolution DEM currently available that covers the whole KNP is the 90m SRTM, equivalent to a cartographic scale of about 1:90 000. The minimum mapping unit (MMU) for catchments and CASSs is therefore 7.3ha (3x3 pixels) and smaller CASSs produced in the automated delineation process have been merged with neighbouring CASSs that drain to the same stream. The smallest stream length that is accurately mapped is 270m (3 pixels).

Maps of streams and CASSs for the KNP and the two study areas are presented in Figures 6.4 and 6.5.

Box 6.1: Procedure used for stream and catchment delineation in KNP.

DEM pre-processing	Identify depressions, appearing on a DEM grid as cells surrounded by pixels with the same or higher elevation. Fill depressions so that all surface water movement can be modelled as following along downwardly sloping flow paths that eventually enter a stream channel, using the ArcGIS hydrological tools (ESRI, 1999-2008).
Burn in streams from 1:50 000 topographical map	Resample the filled DEM to 10m resolution. Construct a grid raster (Stream cell =1, other cells =0) from the stream vector layer, snapped to the 10m DEM grid. The 10m resolution of this grid preserves tributaries and their junctions that are lost at the original 90m resolution of the DEM. Lower the elevation of stream cells by 750m, an arbitrary high value that ensures a trench is produced through the landscape.
Calculate flow directions	Fill pits on the new DEM. Assign slope function in ArcHydro (ESRI, 2004), lowering elevation where necessary to ensure streams run downhill. Calculate D8 flow directions for stream cells only.
Calculate contributing area for stream sources	Identify stream sources from the vector layer, using ET Geowizard node functions (Tchoukanski, 2010). Rasterise nodes at 10m resolution, snapping to the DEM layer (source cell =1, other cells =0). Calculate the area draining to these source points using the ArcGIS flow accumulation function weighted by the stream source cells.
Construct stream network, assign unique stream segment codes and identify downstream segments	Delineate streams using the ArcHydro stream delineation function with a threshold of 1 pixel on the flow accumulation and flow direction layers calculated in the previous steps (a procedure suggested by David Tarboton (pers. comm.)).
Delineate catchments	CASSs were delineated using an ArcHydro function that identifies the area draining into each stream segment, based on the previously calculated flow directions. CASS areas were then converted to polygons whose attributes include the unique codes of individual stream segments. Catchment boundaries for 2nd and higher order streams were constructed by dissolving the boundaries between all CASSs that eventually flow into each 2nd (or higher order) stream.
Generalise map	Streams and CASSs smaller than the MMUs (7.3ha (3x3 90m pixels) for CASSs and 270m (3 pixels for streams) were eliminated.

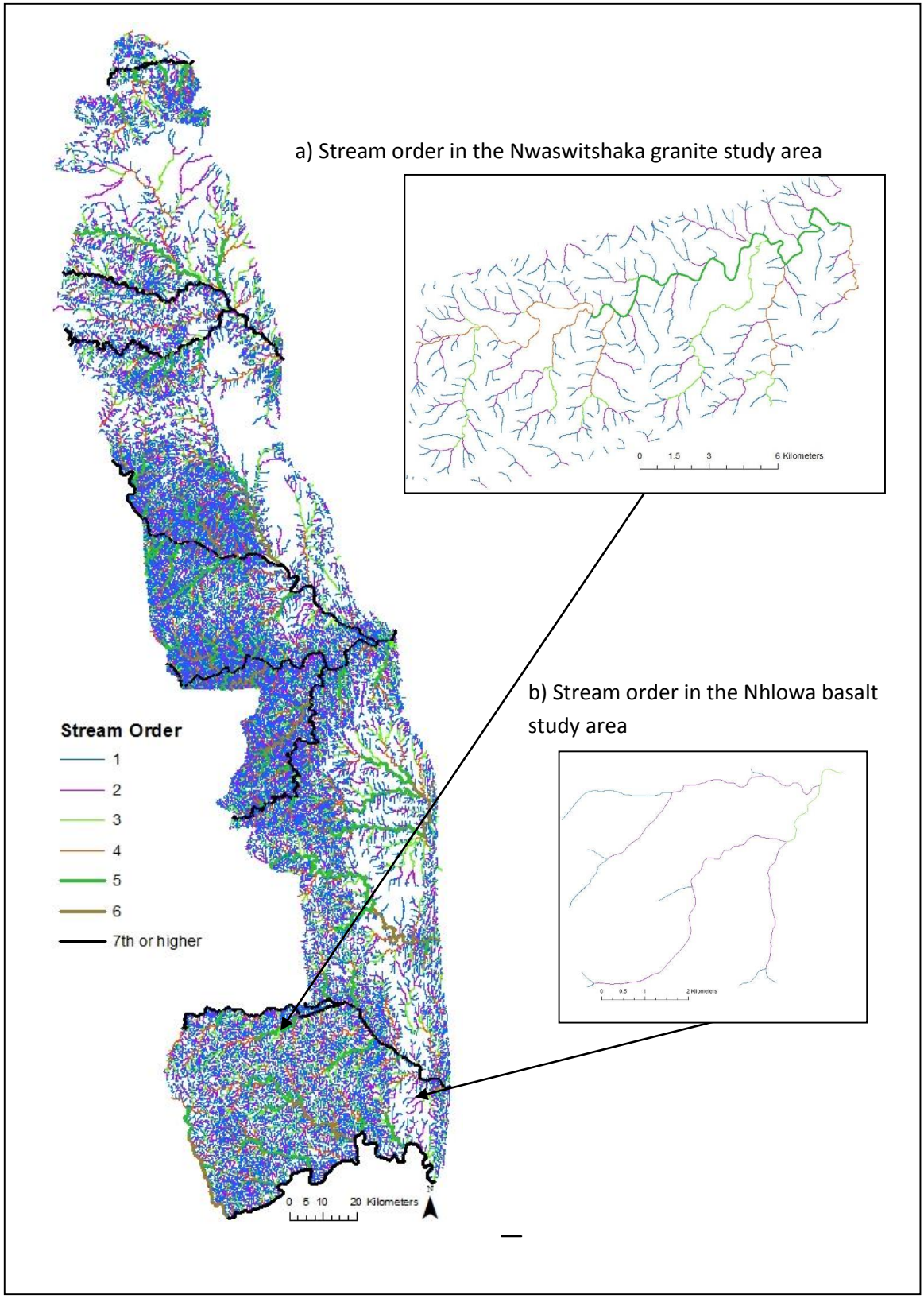


Figure 6.4: Steams in KNP, delineated from the 1: 50 000 topographical map and ordered using the Strahler-Horton method.

Insets show stream order in the two study areas.

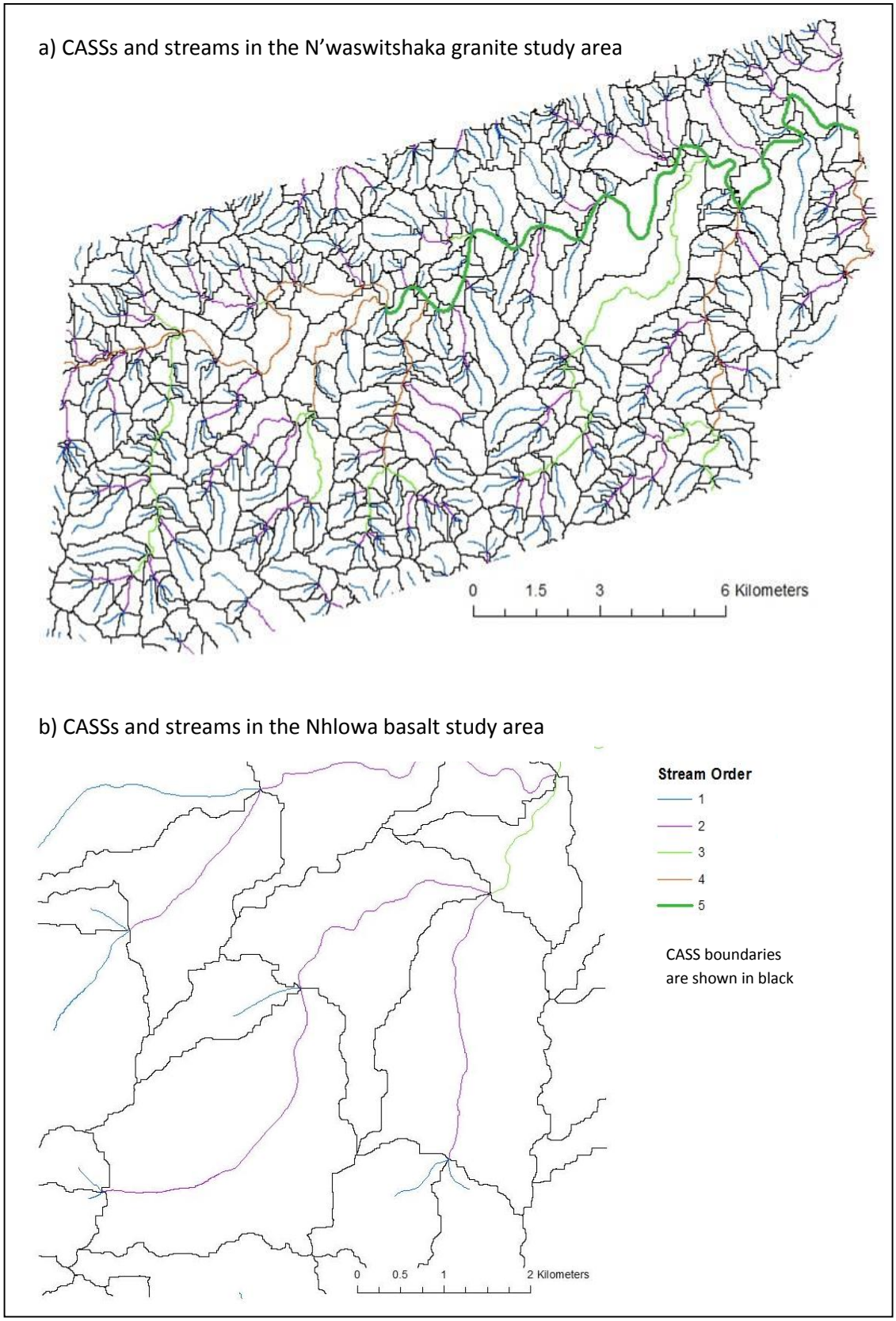


Figure 6.5: CASSs within the N'waswitshaka and Nhlowa study areas.

6.3 Results Part A: Assemblages of catenal elements within CASSs of the N'waswitshaka granite study area

6.3.1 Archetypal toposequences in the N'waswitshaka granite study area

Archetypal toposequences for the N'waswitshaka granite study site have been described in detail in Chapter 4 (Section 4.12.3), together with hypothesised hydrological processes and connectivities responsible for generating and sustaining the repeatedly observed patterns (Figure 6.6).

The original archetypal toposequences of the N'waswitshaka study area (Section 4.12.3) suggested that catchments would contain toposequences of:

- Crests that are relatively woody and slightly convex, with deep sandy soils
- Midslopes that are open and grassy, with a relatively steep gradient and clayey soils
- Flat toeslopes, which may be grassy floodplains, riparian forest or sparsely vegetated sodic sites
- Gravel bed channels with incised banks

It was suggested that as stream order increases, midslopes would tend to become less steep and toeslopes become more prominent.

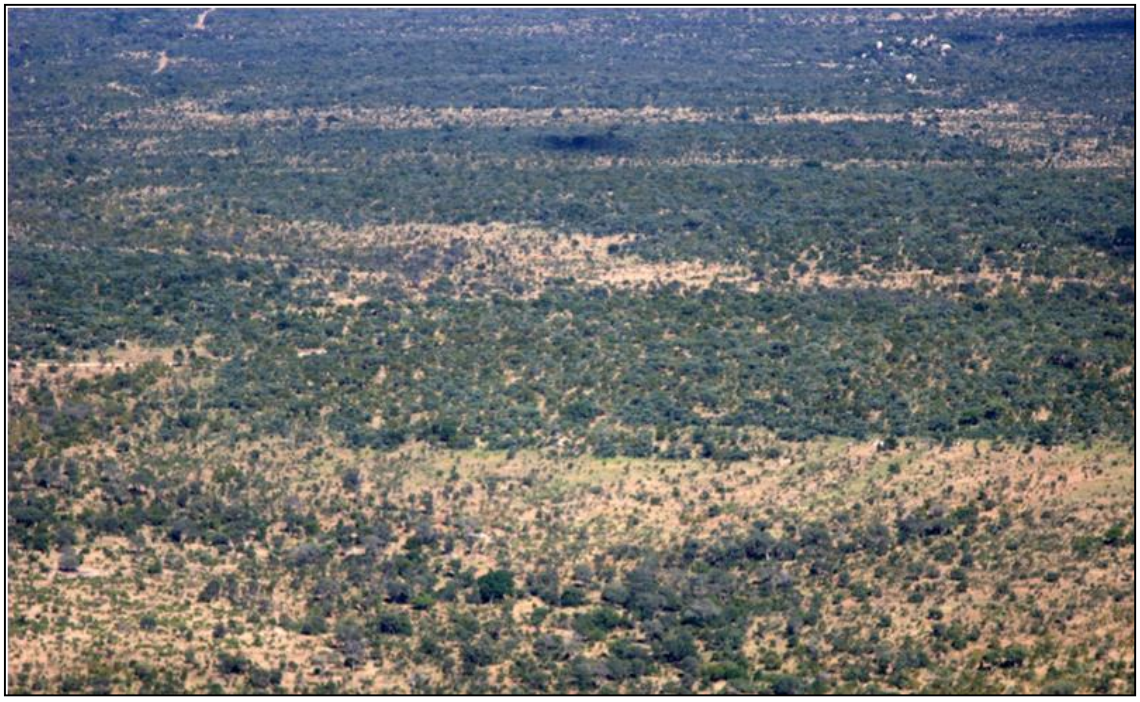


Figure 6.6: Repeating toposequences in the N'waswitshaka granites study area.
Woody crests, grassy midslopes and riparian trees form repeating patterns as far as the eye can see. Photo: KR April 09.

Although these *a priori* archetypes suggest the assemblages of catenal elements that are to be anticipated in the study area, they do not suggest the scale at which the patterns are best observed. In this section, I consider whether the archetypal patterns can be meaningfully associated with streams of all orders, or whether they are only seen at one particular scale. In a later section (6.3.4), I consider whether or not patterns associated with each stream order are superimposed upon each other.

By overlaying the map of catenal elements with the catchment boundaries associated with different stream orders, it is clear that the archetype only applies weakly to third and fourth order catchments (Figure 6.7). Although woody crests can be seen along the watersheds of both third and fourth order catchments, woody crests also occur within the centres of these catchments, with clear toposequences associated with lower order streams.

These same phenomena occur (albeit to a lesser extent) in second order catchments (Figure 6.8). However, first order catchments rarely contain crestal elements in the centre of the catchment and most contain the assemblages described by the *a priori* archetypes.

However, first order catchments do not cover the entire landscape, and some archetypal toposequences are clearly visible on hillslopes draining into higher order streams. Segmenting the landscape into CASSs (Figure 6.9) addresses both these issues, capturing most of the repeating assemblages visible in the scene. I therefore concentrated efforts to describe assemblages of catenal elements in terms of CASSs derived from the 1:50 000 topographical map.

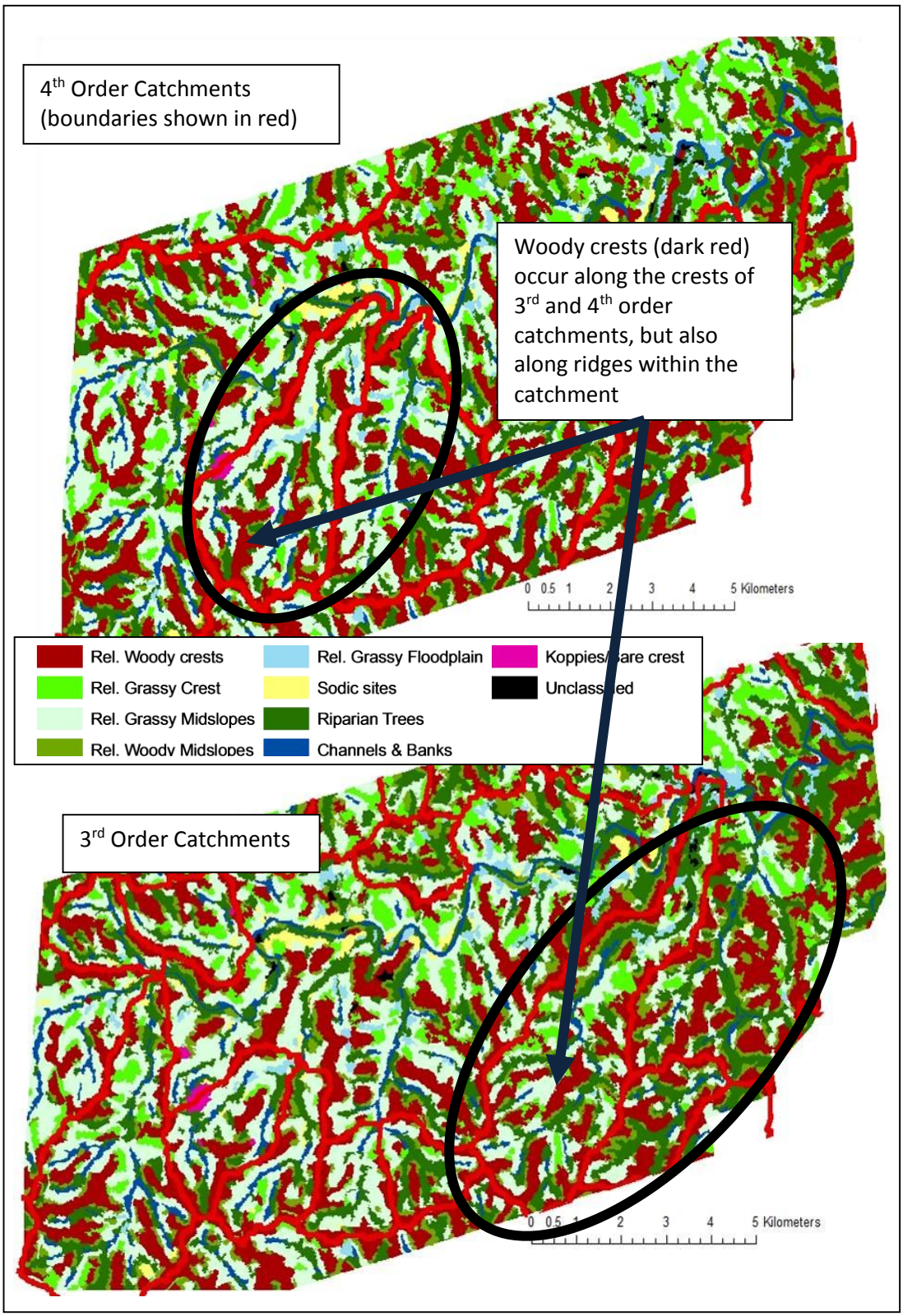


Figure 6.7: Catenal elements and high order catchments in the N'waswitshaka granite study area. Although woody crests can be seen along the watersheds of both third and fourth order catchments, repeating sequences of catenal elements can also be seen within these catchments, suggesting that the archetype applies better at a finer scale of observation.

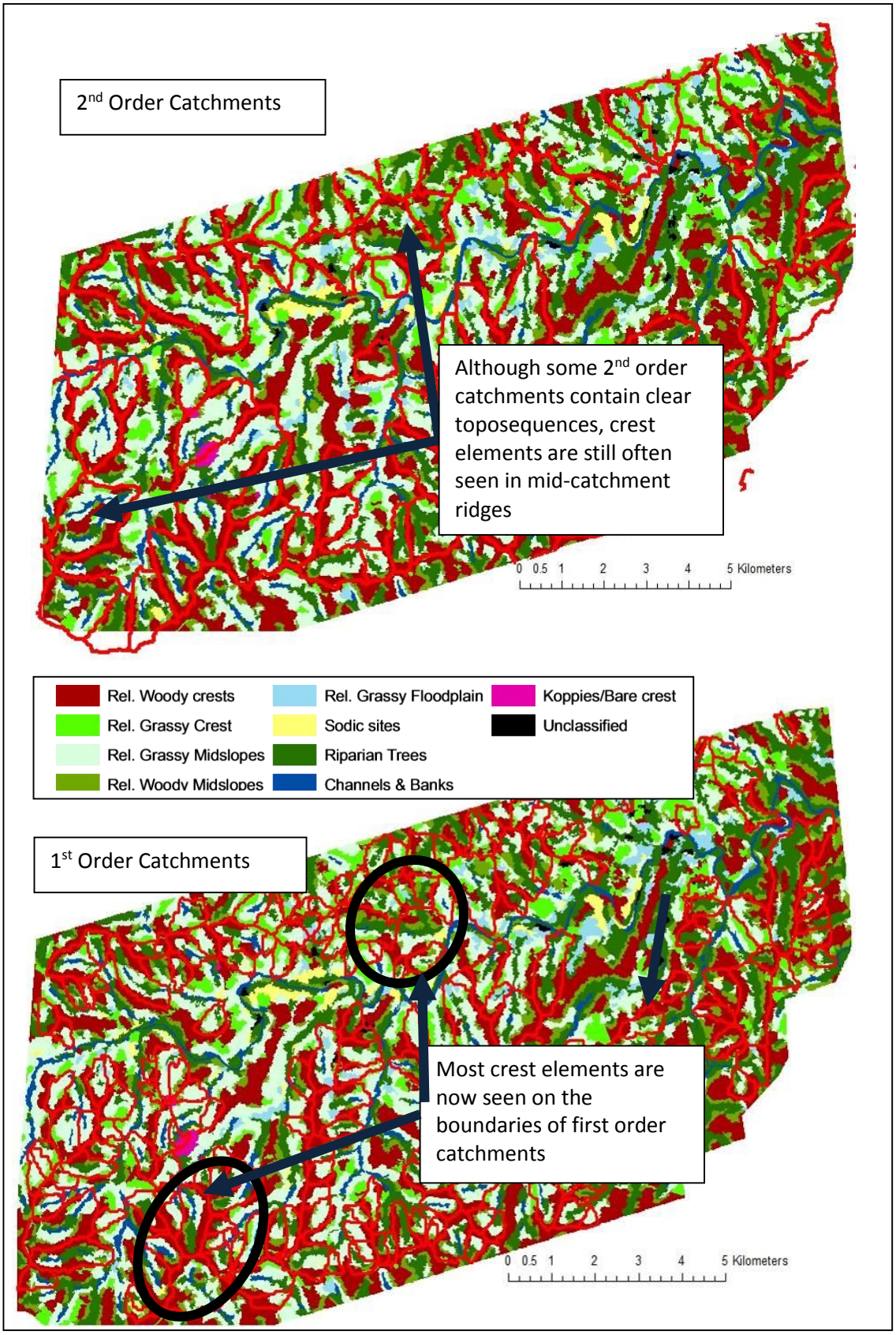


Figure 6.8: Catenal elements and low order catchments in the N'waswitshaka granite study area. Repeating assemblages of catenal elements are most clearly seen within first order catchments.

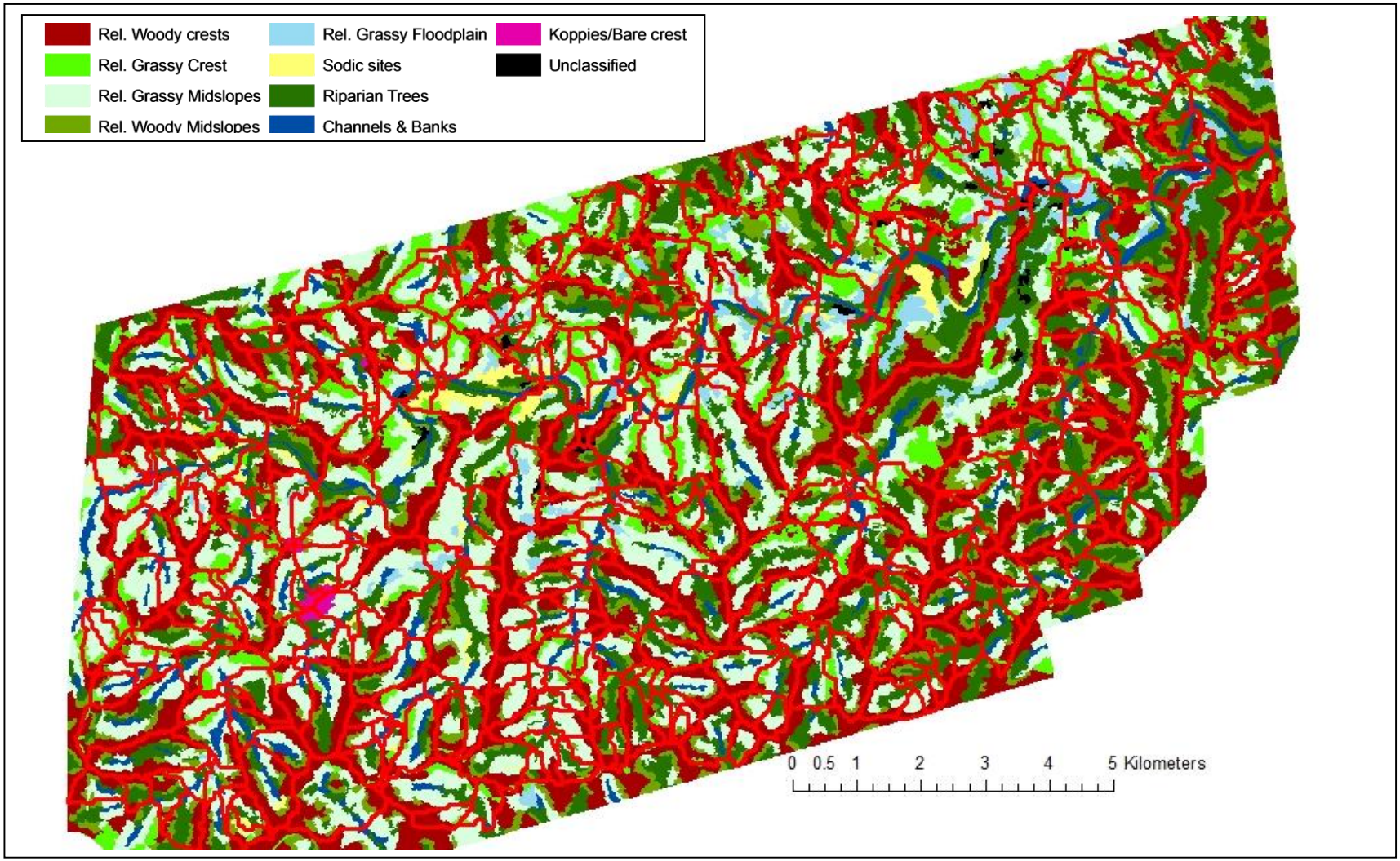


Figure 6.9: Catenal elements and CASSs in the N'waswitshaka granite study area.
Dividing the entire landscape into CASSs captures almost all catenal toposequences.

6.3.2 Assemblages of catenal elements in CASSs of the N'waswitshaka granite study area

Of the 428 CASSs completely contained within the N'waswitshaka granite study area, just over half drain into first order streams (Table 6.2). These CASSs also account for just over half the area of the study site, since there is little variation in the mean area of CASSs that drain into streams of different orders.

Table 6.2: CASS and stream order in the N'waswitshaka granite study area.

	Count	***Area***	***Mean area (ha)***
All CASS (completely contained within the study area)	428	14 705 (ha)	34.36
Stream Order	%	%	
1	51%	53%	35.58
2	24%	19%	27.45
3	10%	11%	38.25
4	9%	10%	37.23
5	7%	8%	40.52

Almost all CASSs show a similar downslope sequence of catenal elements: relatively woody crests above relatively grassy midslopes, with toeslopes, channels and banks in the valley bottoms (Figure 6.10). However, the composition of assemblages of catenal elements changes systematically along the longitudinal course of the river network. First order CASSs are dominated by crests and midslopes, with toeslopes and riparian elements occupying relatively little space. The areas occupied by toeslopes, channels and banks increases steadily as the CASS stream order increases, reflecting the widening of the channel and the development of floodplains as streams increase in size. The increased size of these fluvial elements generally comes at the expense of midslopes, since the area occupied by crests is similar within all CASSs of second order and above. However, the crests of 1st order CASSs are larger than those associated with higher order CASSs. On average they occupy 33% of the CASS, compared to only 21-37% of 2nd -5th order CASSs. Indeed, 60% of the areas of all crests occur within 1st order CASSs.

Thus the *a priori* archetype correctly described increasing toeslope prominence as steam order increases. This tendency clearly relates to the increasing space occupied by fluvial elements as streams increase in size. In low order catchments, there is neither space on the valley floor for floodplains to develop, nor is stream power or the amount of sediment carried in the channel sufficient to erode wide channels.

However, the 'local' gradient (over 15m) of midslopes is similar in CASSs of all stream orders, with no increase in the mean gradient as predicted by the archetypes (Table 6.3).

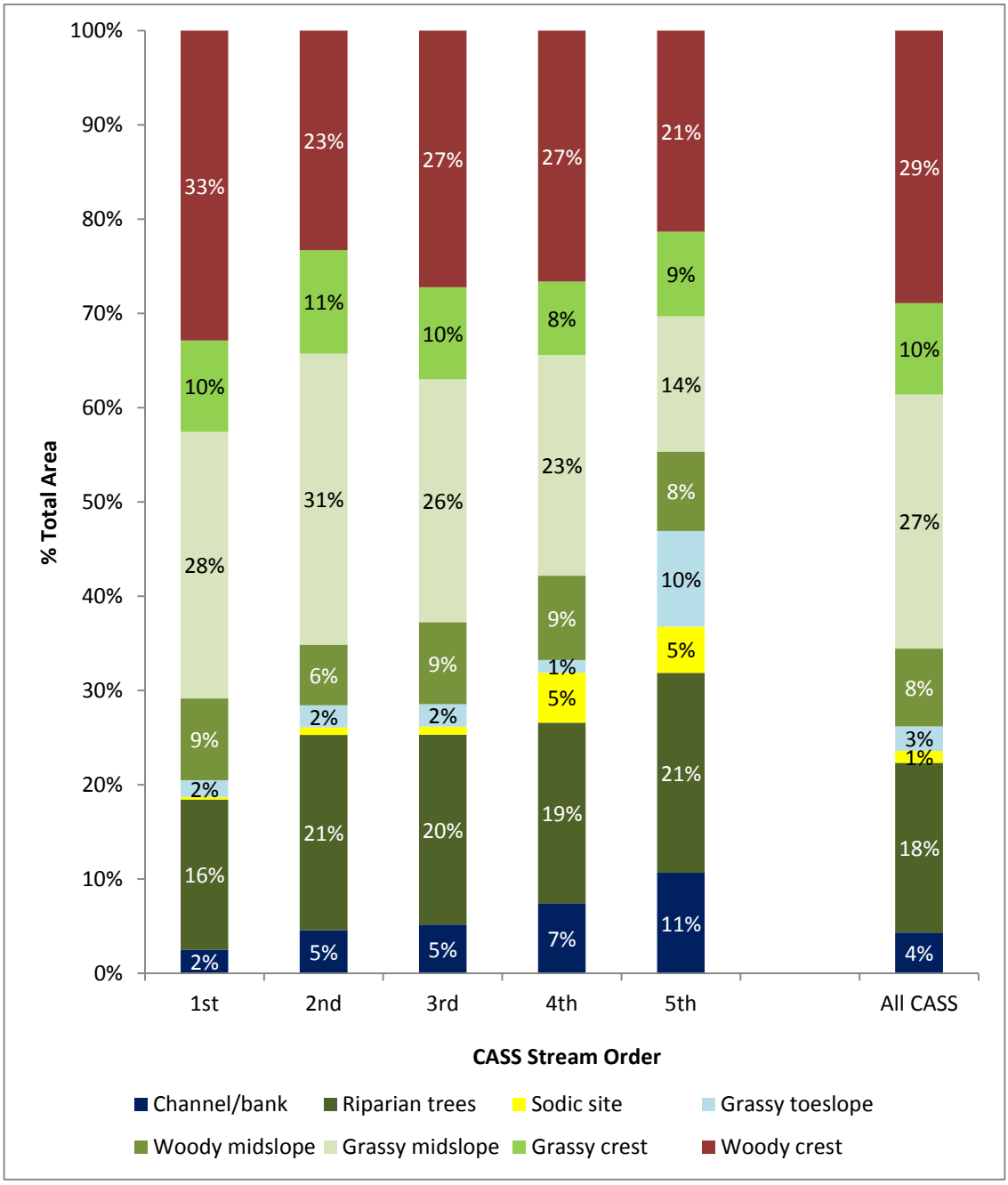


Figure 6.10: Total area of CASSs of each stream order occupied by different classes of catenal elements. The area occupied by riparian and floodplain elements (grassy toeslopes, sodic sites, riparian trees, channels and banks) increases steadily with stream order. The areal proportions of crests are very similar between all 2nd and higher order catchments.

Table 6.3: Mean gradient of midslopes in the N'waswitshaka granite study area.

	All CASSs	CASS Stream order 1	2	3	4	5
Mean gradient (deg over 15m)	3.45	3.44	3.50	3.51	3.67	3.08

6.3.3 *How well do the idealised archetypal assemblages describe the N'waswitshaka landscape?*

Many variations are to be expected around the central archetypal theme. It is important to understand the nature and extent of this variability to assess how well the idealised archetype actually applies in a given area and therefore how much confidence can be placed in spatial extrapolations based on the archetype. In particular, it is important to understand what local differences are likely to invalidate the model and hence to identify areas where the model does not apply at all.

When the map of catenal elements in the N'waswitshaka granite study area is overlaid with CASS boundaries (Figure 6.11), it is clear that many CASSs do indeed contain the archetypal assemblages of catenal elements. Statistical analysis also shows that almost all CASSs in the N'waswitshaka study area contain at least a small area of woody crests, grassy midslopes and riparian trees (Table 6.4).

The proportion of CASSs containing grassy floodplains and/or sodic sites increases with stream order, as suggested by the *a priori* archetypes. Lower order CASSs either lack flat toeslopes (floodplains) completely or they are too small to be mapped. Similarly, channels and banks are only seen in 69% of CASSs, since they are frequently too small to be mapped in lower order CASSs.

Table 6.4: Catenal elements and CASS stream order in the N'waswitshaka granite study area.

Proportion of CASSs containing at least one image object belonging to each class of catenal elements						
		Stream order				
	All CASSs	**1**	**2**	**3**	**4**	**5**
N (image objects)=	*428*	*217*	*103*	*41*	*38*	*29*
Woody crest	91%	97%	84%	90%	89%	72%
Grassy crest	75%	79%	61%	85%	71%	83%
Koppies	4%	5%	6%	0%	0%	0%
Grassy midslope	96%	97%	96%	100%	95%	86%
Woody midslope	74%	78%	66%	73%	84%	59%
Grassy toeslope	24%	19%	19%	17%	39%	72%
Sodic site	16%	9%	16%	12%	37%	41%
Riparian trees	93%	90%	95%	98%	97%	93%
Channel/banks	69%	54%	72%	93%	95%	97%

The idealised archetype for CASSs in the N'waswitshaka granite study area suggests that most crest areas should be relatively woody, whilst most midslope areas should be relatively grassy (Section 4.12.3). However, three quarters of all CASSs contain grassy crests and a similar proportion contains woody midslopes, with no clear trends by stream order (Table 6.4). A close examination of the map of catenal elements (Figure 5.19) also reveals that many CASSs contain assemblages of catenal elements that differ from those described by the *a priori* archetypes.

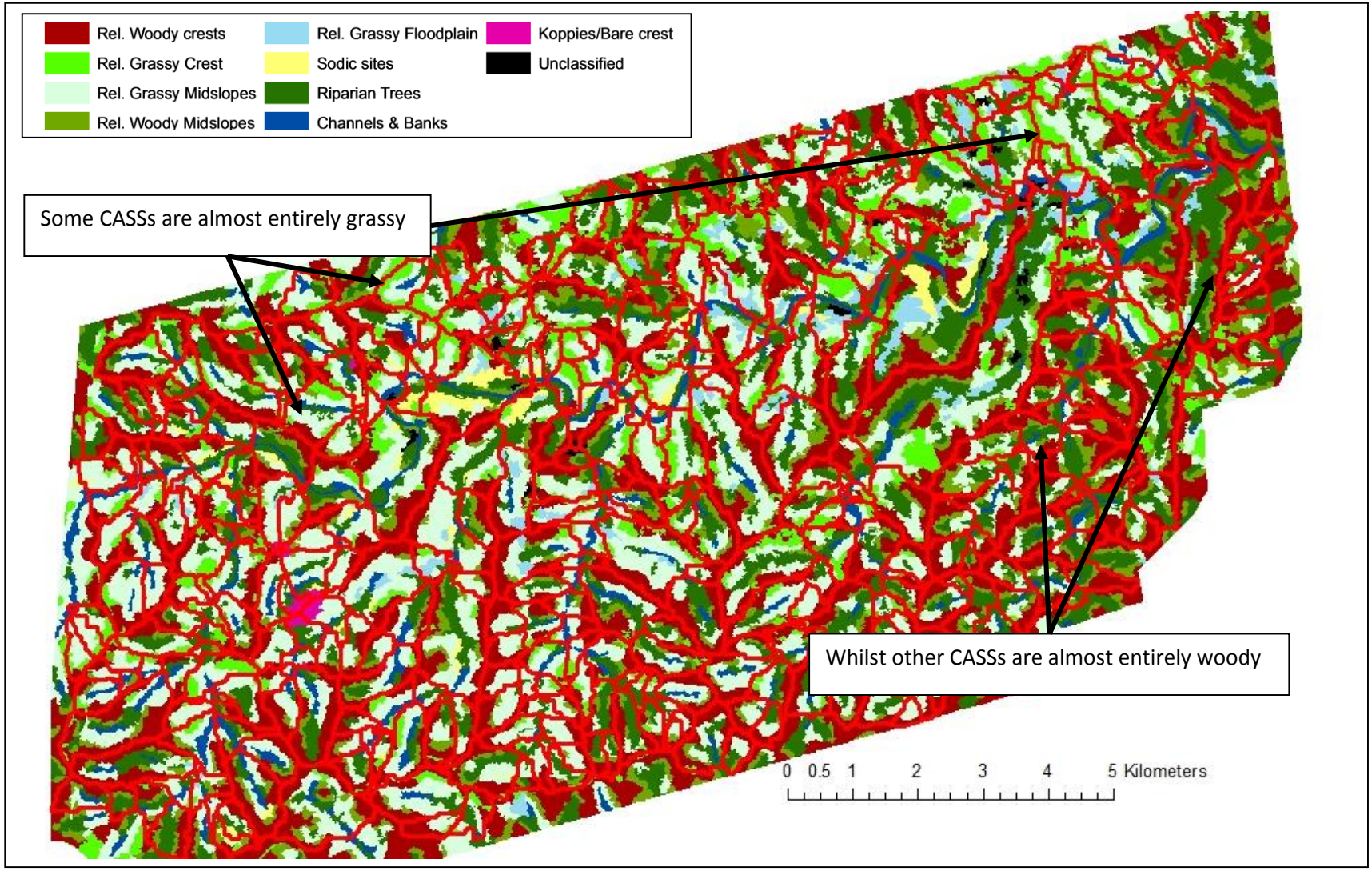


Figure 6.11: Catenal elements and CASSs in the N'waswitshaka granite study area.

The extent to which CASSs actually correspond to the archetypal ideal was examined by considering membership values to a class of "woody crests and grassy midslopes", defined by the minimum of:

a) % area of all crests in the CASS that are woody (membership =1 if 100% of the total crest area in the CASS is woody and 0 if there are no woody crests in the CASS at all) and
b) % area of all midslopes that are grassy (membership =1 if 100% of the total midslope area of the CASS is grassy and 0 if there are no grassy crests in the CASS).

Thus if all crests in the CASS are woody and 90% of all midslopes are grassy, a) =1 and b) = 0.9, so the combined overall membership value is 0.9.

Many CASSs match the archetype to a large extent: 46% (56% of the total area) have membership values to the idealised class larger than 0.6 (Table 6.5 and Figure 6.12). First order CASSs are most similar to the archetype, with 57% (62% of the total area of first order CASSs) having membership values over 0.6. Higher order CASSs tend to conform less well to the archetype: only 21% of fifth order CASSs (16% of their total area) have membership values over 0.6. Although relatively small proportions of the *number* of $3^{rd} - 4^{th}$ order CASSs are similar to the archetype (37-39%), much larger proportions of the *area* occupied by these CASSs are similar to the archetype (60-70%). This suggests that larger, high-order CASSs are more likely to conform to the idealised archetype than are smaller high-order CASSs.

Table 6.5: Degree of similarity to the 'woody crest & grassy midslope' archetype in the N'waswitshaka granite study area.

			Membership value to woody crests and grassy midslopes'						
ALL CASS		**Over 0.6**	**0-0.2**	**0.2-0.4**	**0.4-0.6**	**0.6-0.8**	**0.8-1.0**	**No crest / midslope**	**Kop-pies**
NUMBER (row %)									
ALL	*428*	**46%**	14%	15%	18%	30%	16%	5%	1%
Stream order									
1	217	**57%**	12%	13%	17%	35%	21%	1%	0%
2	103	**39%**	12%	15%	21%	23%	16%	11%	3%
3	41	**39%**	15%	20%	22%	34%	5%	5%	0%
4	38	**37%**	24%	18%	16%	29%	8%	5%	0%
5	29	**21%**	34%	17%	14%	14%	7%	14%	0%
AREA (row %)									
ALL	14 705ha	**56%**	9%	13%	21%	42%	15%	0%	1%
Stream order									
1	7 721ha	**62%**	6%	12%	19%	43%	19%	0%	0%
2	2 827ha	**44%**	13%	15%	26%	33%	13%	1%	4%
3	1 568ha	**70%**	5%	8%	17%	67%	3%	0%	0%
4	1 415ha	**60%**	10%	20%	10%	46%	14%	0%	0%
5	1 175ha	**16%**	26%	18%	40%	14%	2%	0%	0%

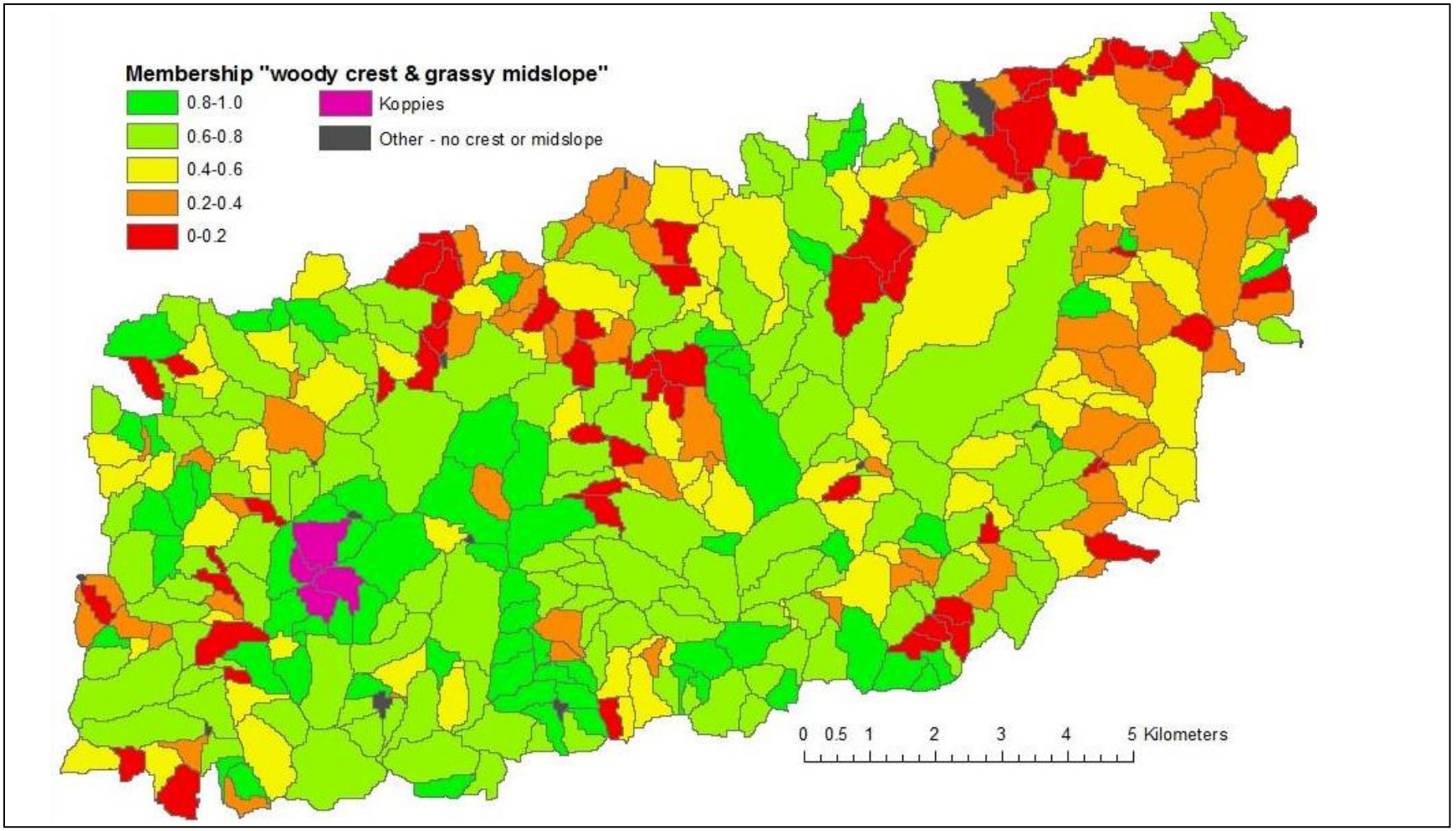


Figure 6.12: Degree of similarity to the "woody crest & grassy midslope" archetype in the N'waswitshaka granite study area.
Maximum class membership (1.0) means that all crest areas within the CASS are woody and that all midslope areas are grassy, whereas minimum class membership (0.0) means that all crests are grassy and midslopes are woody. Most mismatches to the archetype occur to the east and the centre-north of the scene.

Mismatches can be grouped into CASSs that either:

- Have little difference in cover between the crest and midslope, being either almost entirely woody or almost entirely grassy.
- Fall on floodplains, such that grassy crests are the lower part of ridges separating tributaries and woody crests are part of the riparian strip, lying on locally uneven ground (Figure 6.13).

CASSs that fall on floodplains occur throughout the scene, typically located in low-lying areas between tributary junctions. These small, high order CASSs tend not to have sufficient drainage area to develop their own channel, yet do not extend far enough away from the stream to contain the entire length of a high order hillslope and therefore lack crest elements. These areas could be considered as truncated CASSs, with channels and footslopes that are likely to behave in ways similar to the archetype, but without crestal elements. Since crests are relatively flat, with no sharp divides, midslopes in these truncated CASSs are likely to receive water from upslope, but from the crests of neighbouring CASSs rather than from crests within the same CASS.

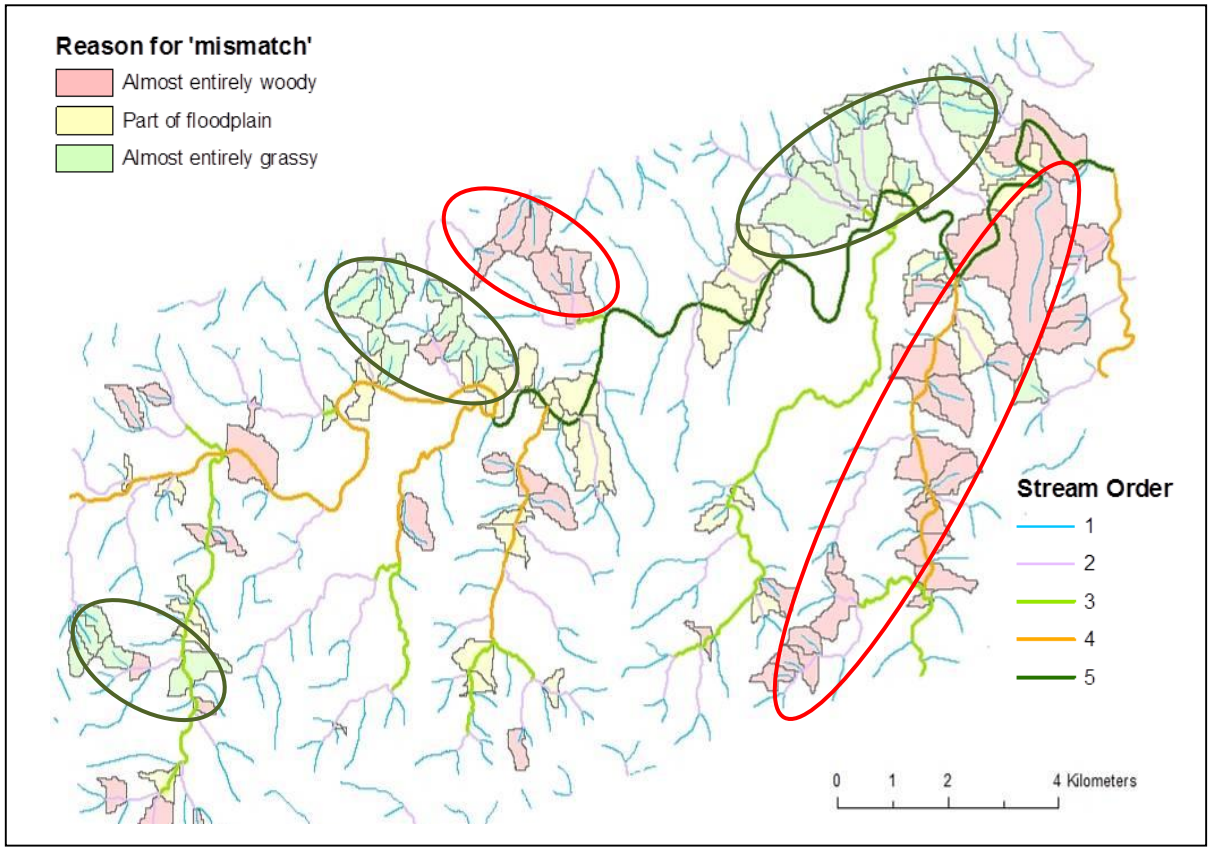


Figure 6.13: Reasons for mismatch with toposequence archetypes.

Mismatches due to CASSs being either almost entirely woody or entirely grassy tend to be grouped into distinct geographical areas, circled above. Mismatches due to low lying CASSs located almost entirely on a floodplain occur throughout the scene.

However, CASSs that are almost entirely woody or grassy are unlikely to conform to the archetype and probably lack the contrasting clay/sandy soils that are typical of catenas in this area. The CASSs tend to be geographically grouped, suggesting that they result from some local geological differences. However, these areas do not relate to any of the subdivisions of the study site made either by Venter (1990) or Gertenbach (1983) (see Section 4.4.2). These subtypes may warrant the development of a separate set of archetypes, depending on their perceived importance for management purposes and whether or not they occur elsewhere.

6.3.4 Are patterns associated with different order catchments superimposed upon each other?

Even if assemblages of catenal elements associated with higher stream orders are not readily observed (e.g. in Figure 6.7), it is still possible that such patterns are subtly superimposed upon the mosaic hitherto described. If, for example, distinct vegetation gradients existed from the channel to the divide of high order catchments, this pattern could be superimposed on the vegetation characteristics of CASSs within these catchments (Figure 6.3). For example, if woody cover increased from the lower slopes up to the divide in a high order catchment, then crests located high in the headwaters would be woodier than similar crests located at lower elevations, nearer to the main river.

I tested this proposition using a sample of points to compare vegetation cover in crestal and midslope positions within CASSs of the same stream order contained within progressively larger order catchments. For each point, I calculated:

- The *percentage cover over 0.5m high* found in a circle of 3.4m radius, a proxy for the density of woody cover. This metric was derived from the canopy height LiDAR data. Pixels with vegetation over 0.5m in height are coded 1, whilst others are coded as 0. Percentage woody cover is then calculated using a focal mean (the mean value of neighbouring pixels or part thereof falling within a circle with a radius of three cells (3.36m at the original LiDAR resolution of 1.12m)).
- *Hillslope position*. Points falling on crests were analysed separately from points falling on midslopes.
- *Distance* to the streams forming the main stem in first, second, third, fourth and fifth order catchments fully contained within each of the study areas.

Although there are some weak relationships between the density of woody cover and distance to the stream for some catchment orders, no strong relationships were found (all correlation coefficients were below 0.07 (Table 6.6)). There was no evidence of vegetation patterns in 2nd or higher order catchments superimposed on the patterns associated with first order catchments.

The fact that no patterns of woody cover are associated with position in high order catchments implies that the distribution of woody cover in this area is controlled primarily by hillslope position in relation to the nearest stream. This suggests that the density of woody vegetation is largely related to height above the local water table rather than to elevation *per se*.

Table 6.6: Relationships between canopy cover and distance to stream for terrain units in different order catchments within the N'waswitshaka granite study area.

Based on points regularly sampled at 100m intervals throughout the study area.

	1st order catchments	2nd order catchments	3rd order catchments	4th order catchments
n (catchments containing sampled points)	*237*	*178*	*7*	*2*
Points on crests				
Correlation coefficient of distance to stream vs. % canopy cover >0.5m high	*0.048*	0.068	0.017	-0.031
n (points)	*4 770*	*3 187*	*2 104*	*1 546*
Points on Midslopes				
Correlation coefficient of distance to stream vs. % canopy cover >0.5m high	0.015	-0.004	-0.059	-0.043
n (points)	*5596*	*4 324*	*2 743*	*2 179*

6.3.5 Summary: N'waswitshaka granite study area

Catenal assemblages similar to those described by *a priori* archetypes occupy over half the study area. As anticipated by the archetypes, low order CASSs lack the elements associated with floodplains that are found in higher order CASSs (i.e. grassy toeslopes and sodic sites).

Some of the mismatches between the toposequence predicted by the archetype and the classification of catenal elements are associated with CASSs located on floodplains, which often lack 'proper' crest elements. Other mismatches, where slopes are entirely 'grassy' or 'woody' are geographically clustered and may result from local geological features. The conceptual models of hydrological flows underlying the archetypes are unlikely to apply in these areas, and new archetypes may be required.

There is no evidence to suggest that patterns associated with different stream orders are superimposed upon each other. Instead, all toposequences appear to be related to the nearest stream, irrespective of its order.

6.4 Results Part B: Assemblages of catenal elements within CASSs of the Nhlowa basalt study area

6.4.1 Archetypal toposequences in the Nhlowa basalt study area

The original archetypal toposequences of the Nhlowa basalt study area have been described in detail above (Section 4.12.3). The idealised toposequence contains:

- **Crests**: Open, grassy and flat, with planar or concave curvature.
- **Footslopes**: Relatively steep, convex area bordering the valley bottom, with denser tree/shrub cover than on crests

- **Valley bottoms**: Flat, similar woody cover to midslopes, concave or planar with discontinuous channels and pans

Neither the structure not the functional hydrology is hypothesised to change within the 1st-3rd stream orders (Section 4.12.3 and Figure 4.20).

6.4.2 Assemblages of catenal elements in CASSs of the N'waswitshaka granite study area

The Nhlowa basalt study area contains only 10 entire CASSs, reflecting the low stream density in this location. However, by extending the area slightly to include some areas between mapped crests and catchment boundaries and by assuming that these areas are all 'crests', the coverage can be extended to include 14 entire CASSs (Figure 6.14). CASSs where part of the footslope or valley bottom lie outside the study area are excluded from this analysis.

Most of the area is occupied by 2nd order CASSs (Table 6.7). By comparison to these CASSs and their streams, 1st order CASSs are much smaller in area, with shorter streams. This landscape is structured quite differently to the N'waswitshaka granite site, where CASSs of different stream orders were very similar in size and 1st order CASSs accounted for over half the total area of the site.

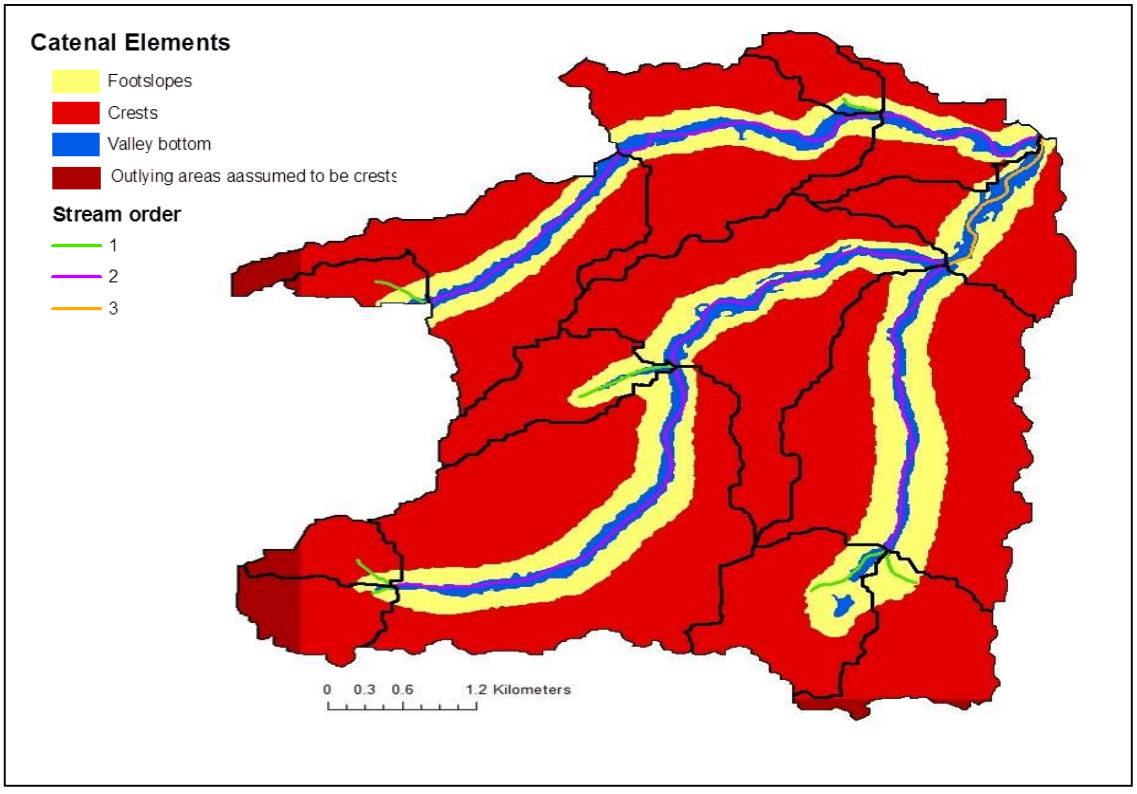


Figure 6.14 Nhlowa basalt study area extended slightly to include 14 entire catchments.

It is assumed that the small parts of first order CASSs shown in dark red consist of crests, similar to the areas shown in lighter red. Catenal elements are clearly related to channels rather than to catchment or CASS boundaries.

Table 6.7: CASS and stream order in the Nhlowa basalt study area.

	Count	% Total area	Mean area (ha)
All (entire) CASSs	14		226
Stream Order	No. (%)	%	
1	6 (43%)	22%	117
2	7 (50%)	72%	326
3	1 (7%)	5%	173

This landscape consists largely of large interfluves, which occupy some 74% of the total site (Table 6.8). The proportion of CASS area occupied by footslopes and valley bottoms increases slightly with stream order. In first-order CASSs, footslopes and valley bottoms occupy a lower proportion of the CASS area than in higher order CASSs, corresponding to their relatively short drainage lines.

Table 6.8: Percentage area occupied by each catenal element in the Nhlowa basalt study site.

		CASS Stream order			
	All CASSs	**1**	**2**	**3**	**Mean area (ha)**
Crest	74%	86%	71%	68%	168
Footslope	19%	12%	21%	19%	42
Valley bottom	7%	2%	8%	13%	15

There appears to be no systematic pattern of topography or vegetation on the large crests. Away from the channel, variations in vegetation (and, by inference, hydrology and soils) and the presence of pans do not appear to be related to either hillslope or network position (Figure 5.27 and 5.33). Instead, patterns of crestal vegetation appear to be randomly distributed, and are most likely to result from interactions between fire, herbivory, animal diggings and very local geological differences that make some areas more liable to subsidence. This suggests that there are no systematic differences in the water budget across these areas, which in turn suggests that the crests are hydrologically disconnected from the drainage lines. This supports the conceptual model underlying the archetypes, in which crests are characterised by vertical infiltration, with little or no lateral flow (Section 4.12.3 and Figure 4.18).

In the CASSs of all stream orders, the width of footslopes and the valley bottom is remarkably constant. Valley bottoms are generally about 100m wide, with footslopes for about 150m on each side of the valley bottom. This finding also supports the archetypal conceptual model, in which drainage lines occur in hollows formed by the subsidence of areas that are seasonally waterlogged. Erosion occurs mainly in the footslopes and valley bottoms, where subsurface water collects in the rainy season, moving laterally as the soils wet and dry, much like a giant sponge (Hansen *et al.*, 2009).

6.4.3 How well do the idealised archetypal assemblages describe the Nhlowa landscape?

The mapped catenal elements conform entirely to the *a priori* archetypes. With the exception of the more extensive crests and shorter channels associated with first order CASs, toposequences do not change with stream order, as predicted by the archetypes. However, it is anticipated that differences occur in higher-order CASSs lying outside the study area, where I have observed more permanent, deeper, incised channels with dense riparian forest.

6.4.4 Are patterns associated with different order catchments superimposed upon each other?

Given the flatness of this landscape and the way that footslopes and valley bottoms are tightly bound to the structure of the drainage network, there is no opportunity or patterns associated with different order streams to be superimposed upon each other.

6.4.5 Summary: Nhlowa basalts

This landscape is highly organised, with footslopes and valley bottoms of almost exactly the same width associated with every stream, no matter of what order. It is dominated by large crests, where vegetation is not organised systematically with distance to the channel, suggesting that that these areas are not hydrologically connected to the drainage lines. The findings support the archetypal toposequences for this area, based on a conceptual model of the development of similar features (dambos in East Africa) described by Hansen (2009).

6.5 Discussion

Although repeating patterns associated with toposequences have long been recognised in many landscapes, these patterns are usually described in terms of a single, two-dimensional hillslope transect that is deemed to be characteristic of a particular area (e.g. the land types/ system approach described in Section 2.6.1). The spatially explicit description of these patterns is fraught with challenges relating to appropriate scales of observation and local variability that have not yet been resolved (MacMillan & Shary, 2009).

Considering assemblages of catenal elements within the context of the stream network helps to address these scale issues by situating toposequences within CASSs, revealing the landscape grain. This approach allows scale-related decisions to be guided by the structure of the landscape itself, rather than being left entirely to the subjective judgement of the cartographer or the application of an arbitrarily selected standard scale applied to all landscapes.

However the description of assemblages of catenal elements is still challenging, particularly in a ‘naughty’ world (Kennedy, 1979), where elements vary in size and patterns are approximate. I experimented with various techniques before deciding to use a mixture of qualitative assessment (e.g. the grouping of anomalous assemblages in Figure 6.12), the presence/absence of various features (e.g. Table 6.4) and a class based on the percentage cover of various elements (e.g. Table 6.5 and Figure 6.13). I abandoned experiments with virtual transects, which proved to be very sensitive to the position at which they were drawn through a CASS. For example, drawing transects at right angles to the stream, half way along the stream

segment drained by the CASS meant that in many CASSs, no crest elements were picked up, since the transect stopped at a boundary lying atop a small midslope ridge between neighbouring tributaries.

New techniques for describing assemblages of elements are sorely needed, since partitioning landscapes in this way offers new insights into landscape structure that not only support land management and planning decisions, but can also generate new hypotheses about landscape function.

The description of catchment properties in terms of overall averages can be very misleading, overlooking potentially important diversity in catenal elements and the spatial and temporal connections between them. For example, granitic catchments in KNP are often described as having infertile soils, or poor forage (Scholes, 1990; Venter *et al.*, 2003), suggesting that they do not offer resources able to support large populations of herbivores. However, although these catchments do contain large tracts of poor grazing, they also contain smaller areas where highly nutritious grasses are found and which function as 'hot spots' to support large numbers of herbivores (Grant & Scholes, 2006). Similarly, riparian areas often provide key resources for plants and animals that would be completely overlooked if averages were applied evenly over the whole catchment (e.g. Naiman *et al.*, 1993). Since many of these hotspots are relatively small and are therefore only seen at very fine scales, they are not generally mapped over large areas. Identifying these areas as part of a toposequence and then mapping areas where these toposequences occur allows broad scale assessment of the spatial distribution of these areas that are often of key importance to land management and planning.

Identifying areas characterised by the same repeating toposequence also allows hydrological and other models to be partially distributed, improving performance considerably over lumped 'whole catchment' models, without the need to include cumbersome spatial detail on individual catenal elements. Such an approach is beginning to be adopted as part of the initiative to improve predictions of hydrological flows in ungauged basins (McDonnell & Woods, 2004; Wagener *et al.*, 2007; McDonnell *et al.*, 2007; Ali *et al.*, 2012; Hrachowitz *et al.*, 2013) and also underpins the recent adoption of research 'supersites' in KNP (Smit *et al.*, 2013a). The performance of such models would surely improve still more if areas where the archetype is less likely to apply are also identified.

The mapping process itself and the products it generates can provide new insights into geomorphic and ecological processes, generating hypotheses for future testing. For example, in the N'waswitshaka granite study area, vegetation patterns are largely dependent on elevation above the nearest stream, rather than on elevation *per se*. This suggests that controls on vegetation (and presumably soil) patterns are very local, probably relating to height above the water table and the frequency and extent of soil saturation and throughflow between catenal elements (as described by Renno *et al.*, 2008). This hypothesis can now be tested in the supersite catchments where extensive hydrological instrumentation has been installed. It can also be tested by more precise analysis of changes in vegetation related to height above the nearest stream (as in Baldeck *et al.*, 2014). In turn, these observations can be used to refine the archetypes of catenal elements and assemblages of elements and used to

inform more accurate maps and models of landscape evolution or likely future trajectories under various scenarios.

6.6 Conclusion

In this chapter, I have delineated streams and CASSs within KNP and used the results to situate assemblages of catenal elements in my two study areas within the context of the stream network. In both locations, catenal elements are highly organised by the stream network. However, in the N'waswitshaka granites, there is some variation from the archetypal 'norm'. Understanding the nature and extent of such variation is important in improving the performance of broad-scale extrapolations and models based on the behaviour of idealised archetypes.

The characterisation of catchments in terms of the assemblages of catenal elements that they contain also provides a way of describing the distinct landscape patterns that characterise each physiographic zone. Once these zones are delineated, it will then become possible to query the extent to which archetypes developed within a particular study area apply to the whole of the physiographic zone in which they are located. This consideration moves the focus away from particular study sites to a consideration of the different physiographic zones within the whole of the KNP, which is the subject of the next chapter of this thesis.

CHAPTER 7: RESULTS PART THREE: PHYSIOGRAPHIC ZONES

Physiographic zones are regions with distinct patterns of landscape dissection that can be considered as the imprint of historical interactions between geology, climate, relief and vegetation. After considering various approaches to mapping regional differences in contributing area-slope relationships and drainage density, an approach is developed that is based on the classification of low-order CASSs using just three key measures of catchment morphology: area, relief and mean gradient. ISOCLUSTER results are used to inform a fuzzy classification that distinguishes 8 archetypal patterns of landscape dissection. These classes are then intersected with the geological map to produce the final map of physiographic zones. This map is then evaluated by comparing it to Venter's (1990) classification. Implications of the differences between physiographic zones are then considered before some concluding remarks about the process of mapping physiographic zones.

7.1 Introduction

Physiographic zones are areas with distinct patterns of landscape dissection that contain repeating sequences of catenal elements within catchments. These sequences may change with catchment order, forming a suite of assemblages of catenal elements that are characteristic of the zone.

Patterns of landscape dissection impose constraints on the possible assemblages of catenal elements that can occur within a physiographic zone in at least two ways. Firstly, the potential energy available to move water across and through the surface of a landscape is limited by catchment relief and gradient. Secondly, patterns of landscape dissection often limit the physical space available for the development of distinct catenal elements. For example, a finely dissected physiographic zone with short steep slopes and narrow floodplains cannot support the same toposequences of morphology, vegetation and soils as a zone that has long hillslopes, little relief and wide floodplains. Thus the size and spacing of ridges and valleys sets boundary conditions for many geomorphological, hydrological, pedological and biological processes that operate within catchments. It is anticipated that these boundary conditions result in the spatial alignment of similarities in:

- Erosional processes, including weathering processes that result in soil formation as well as channel initiation and fluvial incision.
- Hydrological flows that control vegetation patterns as well as the movement of solutes and sediment across and through hillslopes and channels, and
- The resulting forms, such as landforms and channel and valley geometry.

Because of the constraints that landscape dissection imposes on lower levels of organisation and so many ecological processes, morphology is almost always included as a key variable in the development of land and river classifications, as well as ecoregion maps and regional-scale digital soil mapping (Section 2.6). For example, regional-scale terrain units form a key element in SOTER (World SOil and TERrain Digital Database), in which SOTER units are defined as "areas

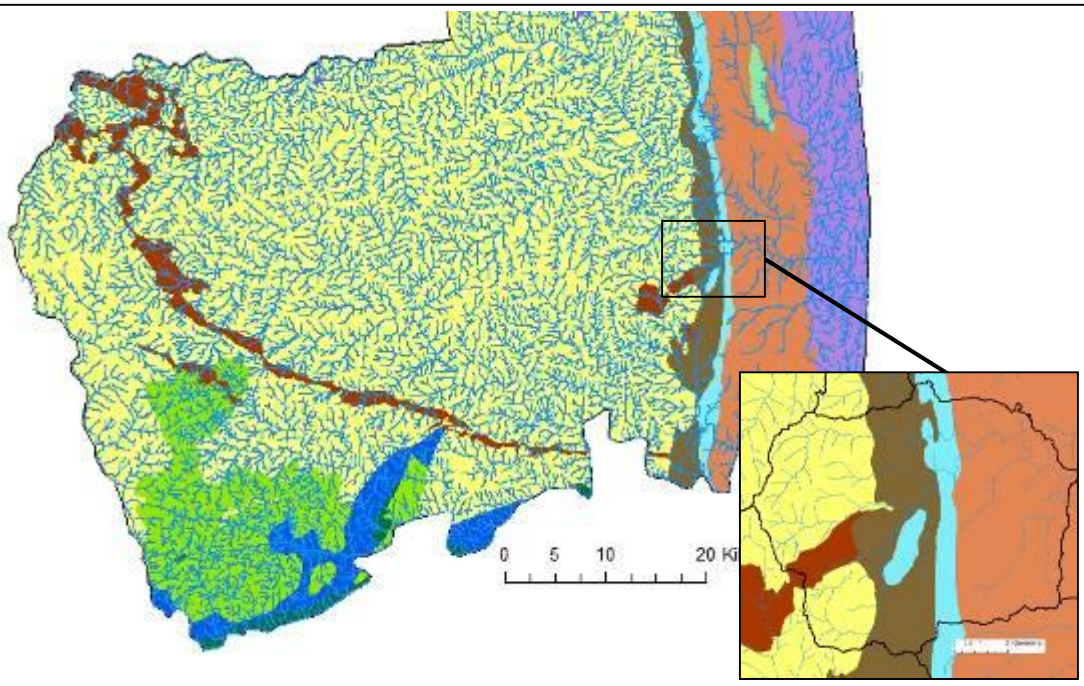
of land with a distinctive, often repetitive, pattern of landform, lithology, surface form, gradient, parent material, and soil" (van Engelen & Dijkshoorn, 2013 p. 9).

Regional similarities between catchment morphology have also been flagged as potential indicators of hydrological properties such as flood frequency, stream flow variability and subsurface or base flow responses to rainfall events, providing key inputs for projects around the initiative to improve Predictions in Unguaged Basins (PUB) (McDonnell & Woods, 2004; Wagener *et al.*, 2007; McDonnell *et al.*, 2007; Ali *et al.*, 2012).

Regional-scale patterns of landscape dissection (10s to 1000s km^2) have long been recognised and described worldwide at many scales and from many perspectives. Whereas some studies have emphasised hillslopes and relief, categorising landscapes in terms of descriptors such as mountains and plains (e.g. Hammond, 1964; Dikau, 1989; Dobos *et al.*, 2005), others have emphasised patterns in stream networks, focussing on drainage density (e.g. Horton, 1945; Tucker *et al.*, 2001), valley spacing (e.g. Wood & Snell, 1960; Perron *et al.*, 2009), channel head source area (Montgomery & Dietrich, 1989) or the arrangement of streams (e.g. Howard, 1967). All of these approaches are but various ways of describing the same patterns of landscape dissection and using them to distinguish between regions characterised by different morphology.

Patterns of landscape dissection result from a history of complex, reciprocal interactions between geology, climate and vegetation that have determined the relationship between the drivers and controls of erosional processes on the one hand, and the resistance of the earth's surface to these processes on the other hand (see Collins & Bras, 2010). Although the dominant processes of erosion vary between regions, as do the drivers and controls on these processes and the resistance offered by local substrates, these factors do not vary independently of each other in space. In the same way that the morphology, vegetation, hydrology and soils of catenal elements interact and co-evolve to form distinct complexes, a similar suite of factors interacts and co-evolves at regional scales to form distinct physiographic zones.

Although most of the factors that shape the surface of the earth are highly interdependent, forming a tangled causal thicket (Wimsatt, 1994), geology stands apart, since tectonic movements and rock formations are independent of surface vegetation, hydrology, soils, morphology and climate, at least at the decadal time scales that are the focus of this study (c.f. Schumm & Lichty, 1965). The close relationship between geology and stream density in KNP has already been illustrated (Figures 3.10 and 4.4). Looking at these relationships at a finer scale, it is clear that the spatial continuum of climate and vegetation is often quite rudely interrupted by geological variations. This phenomenon is clearly visible in the drainage patterns of southern KNP, where stream network patterns change abruptly with geology, even within the same catchment, disrupting the longitudinal sequences of different assemblages of catenal elements associated with different network positions (Figure 7.1).



Densities of streams shown on the 1:50 000 topographical map in the different geologies of southern KNP.

	Stream density (km/km²)	Area (km²)	Length of streams (km)
All KNP	1.86	19,006	35,308
Granophyre	0.86	198	171
Clarens sandstone	1.13	591	670
Basalt	1.22	5 783	7 051
Shale	1.59	478	762
Rhyolite	1.65	966	1 596
Gabbro	2.07	550	1 140
Granite	2.10	3 039	6 371
Biotite trondhjemite gneiss	2.24	107	239
Biotite gneiss	2.67	4 717	12 574

Figure 7.1: Stream density changes with geology in southern KNP.

Even within a single catchment, stream density changes dramatically with geology, disrupting the longitudinal sequences of different assemblages of catenal elements associated with different network positions. (Geology: Council for Geoscience 1986)

However, the description of morphological differences in ways that reliably distinguish between different physiographic zones is not straightforward and no standard approach to the detection of patterns of landscape dissection has yet been devised (Hengl & Reuter, 2009). Various techniques have been developed in attempts to characterise morphologies associated

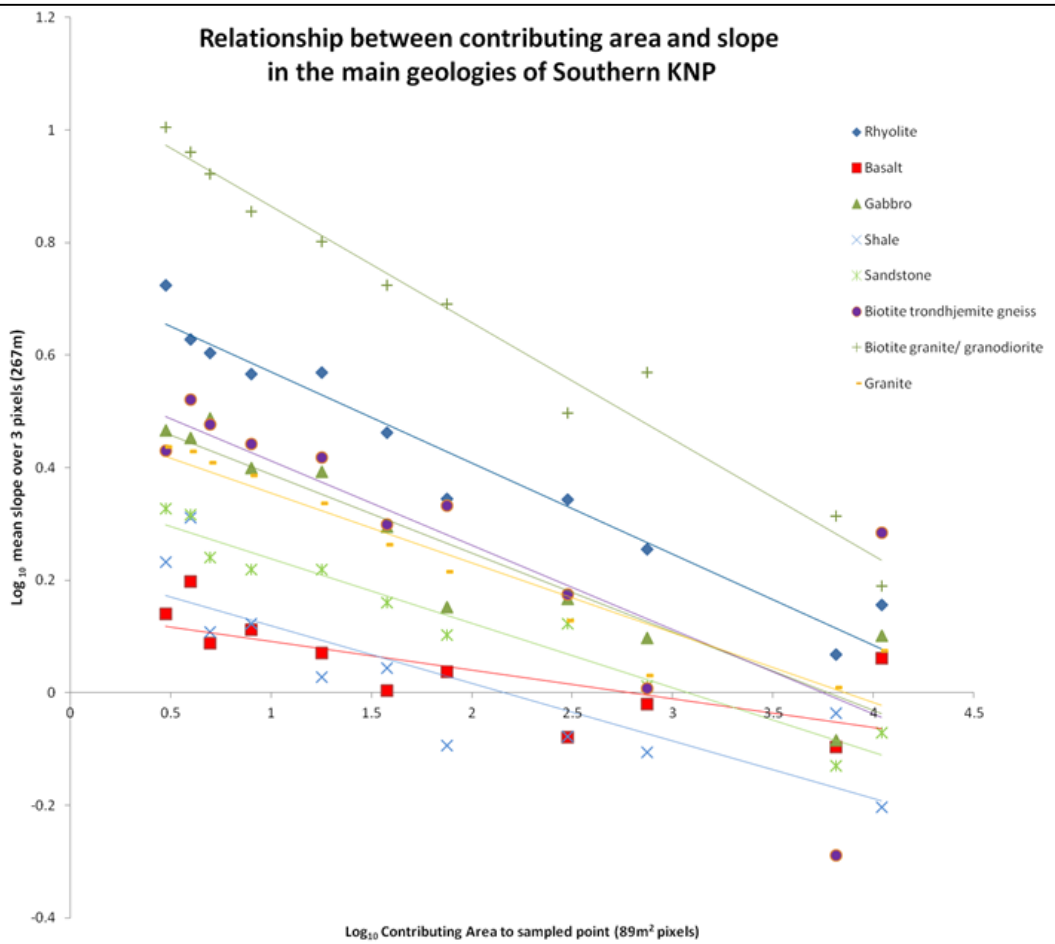
with different geologies including analyses of contributing area-slope curves and of drainage density *per se.*

Hancock (e.g. Hancock, 2005; Luo & Stepinski, 2008) used differences in the contributing area-slope relationship, cumulative area distribution and hypsometric curve to characterise morphologies associated with different geologies in the Northern Territories of Australia. I applied these techniques to try to distinguish between the various geologies found in southern KNP.

The contributing area slope relationship is the relationship between the contributing area draining through a point and the local gradient at that point, which is a morphological imprint of historical fluvial erosion processes (see Hack, 1957; Willgoose *et al.*, 1991; Montgomery & Foufoula-Georgiou, 1993). In southern KNP there are-strong relationships between the area drained and the local gradient that differ between geologies (Figure 7.2). However the relationships are not diagnostic, since several geologies have very similar curves. For example, despite clear differences in relief and vegetation (see Figure 4.7) granite and gabbro have curves with very similar slopes and intercepts, such that it would not be possible to separate these areas using contributing area-slope relationships alone.

Others have attempted to characterise different geologies in terms of stream density (e.g. Luo & Stepinski, 2008). However, not only is the description of stream density highly scale-dependent and challenging to summarise in a single metric (see Tucker *et al.*, 2001), but very different stream densities can occur on the same geology. Different climate regimes can generate very different stream densities on the same geology (contrast the low stream density on the northern granites of KNP compared to the southern granites in Figure 4.4), mainly as a result of changes in vegetation cover (Collins & Bras, 2010). History and morphological context can also lead to different drainage densities on the same geology. For example, a finely dissected region is associated with the passage of the Olifants River across the otherwise coarsely dissected basaltic plains in KNP (Figure 7.3). Here, the volcanic emergence of the Lebombo Mountains in the Karoo era has forced the Olifants River to cut down through the pre-existing surface to a new base level (Venter, 1990), creating a dense network of streams that has quite different morphology to that seen on the otherwise similar basalts to the north and south of the river.

Thus although geology and landscape dissection patterns are intimately related to each other, there is not a one-to-one correspondence between them. This means that both need to be considered in the definition of physiographic zones.



Geology	R^2	Slope of regression line (-ve slope indicates concavity of landscape)	Intercept (indicates steepness of landscape)	n=
Biotite granite/ granodiorite	0.97	-0.21	1.07	1 304
Rhyolite	0.95	-0.16	0.73	1 259
Biotite trondhjemite gneiss	0.63	-0.15	0.56	397
Gabbro	0.88	-0.14	0.53	575
Granite	0.92	-0.12	0.48	10 355
Sandstone	0.95	-0.11	0.35	197
Shale	0.71	-0.10	0.22	378
Basalt	0.52	-0.05	0.14	1 448

Figure 7.2: Contributing area-slope relationships associated with the main geologies of southern KNP.

The relationship between contributing area and slope (gradient) is closely related to geology. However, some geologies are very similar, for example granite, gabbro and biotite trondhjemite gneiss.
These analyses are based on a sample of regularly spaced points 160m apart (1 in 4 pixels n= 15 913). It includes all geologies with > 197 sampled points. The contributing area to each point was calculated on filled SRTM DEM. Areas < 3 pixels (267m) were excluded from the analysis.

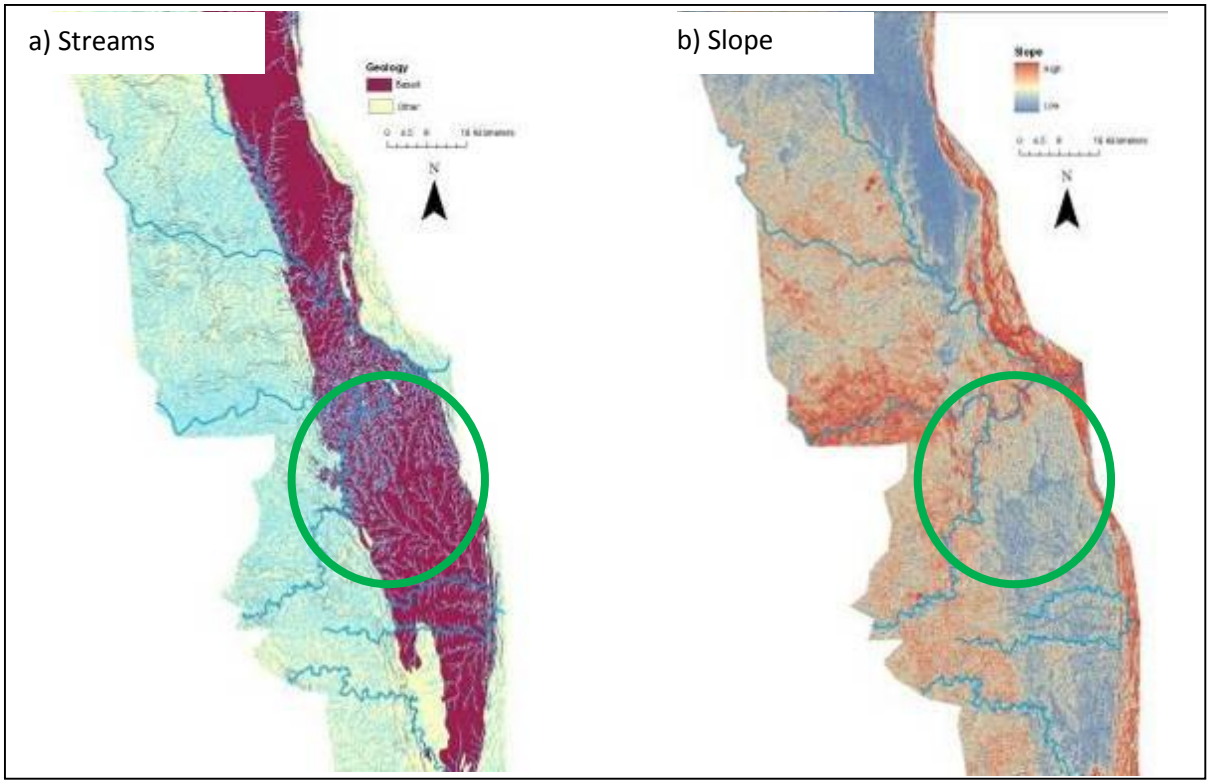


Figure7.3: High stream density and steep gradients associated with quaternary erosion by the Olifants River.

The area traversed by the Olifants River is far more finely dissected than the surrounding basaltic areas, which show the flat plains and low stream density normally associated with this geology.

In this chapter, I aim to develop a method of delineating physiographic zones that combines geology and morphological differences, delineating areas with distinct catchment morphologies that are likely to contain very different assemblages of catenal elements. Specific objectives are to:

- Describe archetypal physiographic zones in KNP
- Produce a map of these physiographic zones
- Assess the validity of this map, and
- Explore lessons learned in the process of delineating physiographic zones.

After outlining the general approach to mapping physiographic zones, I then step through the preparation of a map of physiographic zones for KNP. This map is then evaluated by comparing it to Venter's (1990) classification. Implications of the differences between physiographic zones are then considered before some concluding remarks about the process of mapping physiographic zones.

7.2 Method: Mapping physiographic zones

7.2.1 General approach

Either a 'top-down' or a 'bottom-up approach' could be used to identify different physiographic zones. A 'bottom-up' approach involves characterising catchments in terms of the composition and structure of the catenal elements they contain and then distinguishing regions that have distinct assemblages of these low-level elements. However, we currently lack the fine scale DEMs that are needed to fully characterise small-scale elements throughout KNP, so I have adopted a 'top-down' approach in which physiographic zones are delineated in terms of differences in landscape dissection and geology.

Unlike catenal elements and catchments (or CASSs), physiographic zones are not discrete ecological or spatial objects. Instead, they are merely geographical areas that contain more or less similar catchments. Therefore they cannot be defined either in terms of an *a priori* mental model (like catenal elements) or in terms of a physical boundary (like catchments and CASSs). Instead, they are essentially geostatistical constructs that describe spatial autocorrelations between morphological and geological attributes.

My approach to constructing these geostatistical clusters involved:

STEP 1. Selecting scales of observation

STEP 2. Selecting variables that efficiently describe patterns of landscape dissection

STEP 3. Undertaking cluster analysis to reveal patterns of landscape dissection in KNP and considering various solutions in the light of known geological differences and Venter's (1990) descriptions of clusters based on vegetation and soil differences as well as morphological factors.

STEP 4. Generalising these clusters into a smaller number of geographically coherent classes, defined in terms of morphological variables and then fuzzily classifying low-order CASSs according to their similarity to each of these class archetypes.

STEP 5. Intersecting the resulting map of landscape dissection classes with the geological map and then smoothing and generalising the product to create the final map of physiographic zones.

7.2.2 STEP ONE: Selecting a scale of observation

Hillslopes and channels, together with their toposequences of catenal elements can be delineated at many scales (Section 6.1, Figure 6.2). It therefore follows that assemblages of these slopes can also be delineated at many scales. For example, it is possible to describe valley-ridge spacing both at fine scales in relation to first order streams and at the coarse scales associated with high order streams. The horizontal spacing of major ridges and valleys is sometimes referred to as 'topographic grain' (Wood & Snell, 1960; Pike, 1988; Pike *et al.*, 1989). Relative relief (aka TPI), calculated within nested circles increases with circle size and then levels off at a kernel size that captures the relief of the largest valleys in the scene. This provides a measure of the topographic grain. Other related techniques for calculating topographic grain include the use of Fourier and wavelet transformations and texture-based segmentations (e.g. Moran & Bui, 2002; Lucieer *et al.*, 2005).

The use of different window sizes (or wavelet transformations) to derive multiscale terrain attributes is a tactic that has been employed by many researchers (e.g. Gallant & Dowling, 2003; Fisher *et al.*, 2004; Schmidt & Hewitt, 2004). However, this approach assumes that the same window size(s) capture similar features in all landscapes. This is patently untrue, since first order streams in a landscape with a coarse grain (low stream density and large CASSs) may well be similarly spaced to third or fourth order valleys in finely dissected landscapes.

An alternative approach is to use catchments or CASSs, rather than pixels, as the basic spatial entity for the classification of morphological patterns. This approach not only neatly sidesteps many of the issues associated with scale selection, but also provides an ecologically meaningful unit upon which the classification is built. Although several authors have hinted at this possibility, thus far, none have developed the proposals (Dehn *et al.*, 2001; MacMillan & Shary, 2009).

Defining morphological patterns in terms of CASSs or catchments not only makes sense as a way of identifying topographic grain, it is also congruent with my aim of defining physiographic zones as areas containing characteristic recurring assemblages of catenal elements within catchments found in a particular network position. This means that landscape dissection needs to be described in terms of morphological similarities between catchments of the same order, or at least of the order associated with the recurring patterns that distinguish between different zones.

In my study areas, patterns of vegetation were linked to catenal elements defined in terms of first order catchments and higher order CASSs derived from 1: 50 000 topographical maps. To describe physiographic zones, I therefore need to examine similarities between CASSs associated with the same 1:50 000 streams.

Most variation is expected to occur within low order CASSs, reflecting different processes of stream initiation that result in variations of area and relief within channel head zones (Montgomery & Dietrich, 1989). By comparison, the morphology of high order CASSs is likely to be very similar across several physiographic zones, with large, relatively flat channels and floodplains bounded by relatively gentle gradients. I therefore focussed on morphological differences in low (first and second) order CASSs. Since these CASSs occupy 76% of the entire KNP, they are representative of wide areas.

7.2.3 STEP TWO: Variable selection

Although there are many different metrics that can be used to describe hillslope and network morphology (Mayr & Palmer, 2006), most of these measurements are highly correlated. Indeed, most methods of delineating physiographic zones ultimately select just three or four variables that describe the key dimensions of landscape texture:

- The *horizontal* spacing of channels and ridges (landscape wavelength)
  e.g. Drainage density (e.g. Horton, 1945; Tucker *et al.*, 2001) and source area (Montgomery & Dietrich, 1989)

- *Vertical* relief (landscape amplitude) e.g. Local relief (Macmillan *et al.*, 2000), topographic grain (Wood & Snell, 1960; Pike *et al.*, 1989), TPI (Weiss, 2001) and relief intensity (Iwahashi & Pike, 2007)
- *Gradient* (the typical relationship between the horizontal and vertical dimensions) e.g. Mean catchment gradient (e.g. Hammond, 1964; Dikau, 1989; Dobos *et al.*, 2005), which can be measured over various distances (Wood & Snell, 1960; Pike *et al.*, 1989), and
- *Elevation* (this variable is sometimes omitted when considering flat areas or small extents where altitudinal influences on ecological processes are negligible).

Other possibilities include:

- *Network branching pattern* (Howard 1967). However, metrics that represent these patterns are difficult to specify, particularly given the amount of local variation generally present. Emerging techniques that describe network topography may prove useful in the future (e.g. Lashermes & Foufoula-Georgiou 2007; Zanardo *et al.* 2013).The *shape* and *aspect* of low order catchments generally change within a river basin, such that these metrics are not generally spatially correlated and so are unsuited to the detection of regional patterns.
- *Curvature* metrics are most useful at finer, hillslope scales or for identifying particular landforms (e.g. alluvial fans). Although curvature has been widely used at regional scales (e.g. Iwahashi & Pike, 2007), this has been to identify ridges and watersheds. However, by using CASSs as the basic unit of analysis, this function becomes redundant.

I used the *area*, maximum vertical *relief* and the *mean gradient* (maximum gradient in a 3 x 3 cell of the 90m SRTM DEM) of all 1st and 2nd order CASSs in KNP to differentiate zones with different degrees of landscape dissection. Elevation was not used as this metric is highly correlated with relief and gradient in the mainly very flat landscapes of KNP.

7.2.4 STEP THREE: Cluster analysis

Clusters of CASSs with distinct morphology were detected by:

- Measuring the *area*, maximum vertical *relief* and the *mean gradient* (maximum gradient in a 3 x 3 cell of the 90m SRTM DEM) of all 1st and 2nd order CASSs in KNP.
- Detecting spatial clusters of these attributes using ISOCLUSTER in ArcGIS, which is an iterative self-organising clustering procedure (ESRI, 1999-2008). The maximum number of clusters is specified in advance. The procedure starts with arbitarily assigned means for each potential cluster. All cells are then assigned to their closest cluster. New cluster means are then assigned in an attempt to minimise dispersion within each cluster and to maximise the separation between clusters. The process is then repeated many times to derive the optimum solution (I used 100 iterations). After the clusters become stable, results are checked to ensure clusters are of similar size and are well separated from each other, merging neighbouring clusters if necessary.
  Although this is a pixel-based method, all pixels within each CASS were assigned the

same values, such that the results effectively classify entire catchments. Since larger catchments contain more pixels, the results are effectively area-weighted, so that a class may contain fewer larger CASSs or more smaller CASSs. All metrics were transformed (using natural logarithms), normalised and standardised to satisfy the assumptions of this method. CASSs consisting of less than three $90m^2$ pixels (approximately 2.4ha.) were excluded.

- Solutions were calculated for 6, 8, 10, 12 and 16 clusters.

The various cluster solutions all reflected similar patterns that are closely associated with geological differences (Figures 7.4 and 7.5):

A. Contrast between large, low relief CASSs in the basalts and smaller, steeper CASSs in the western granites
B. Very small, high relief CASSs where the Olifants River enters KNP
C. High relief, small and steeply sloping CASSs near Berg-en-Dal in the extreme south west

In addition,

D. A gradual transition is evident across the south of the park, between Skukuza and Lower Sabie, described in slightly different ways by the various clustering solutions.

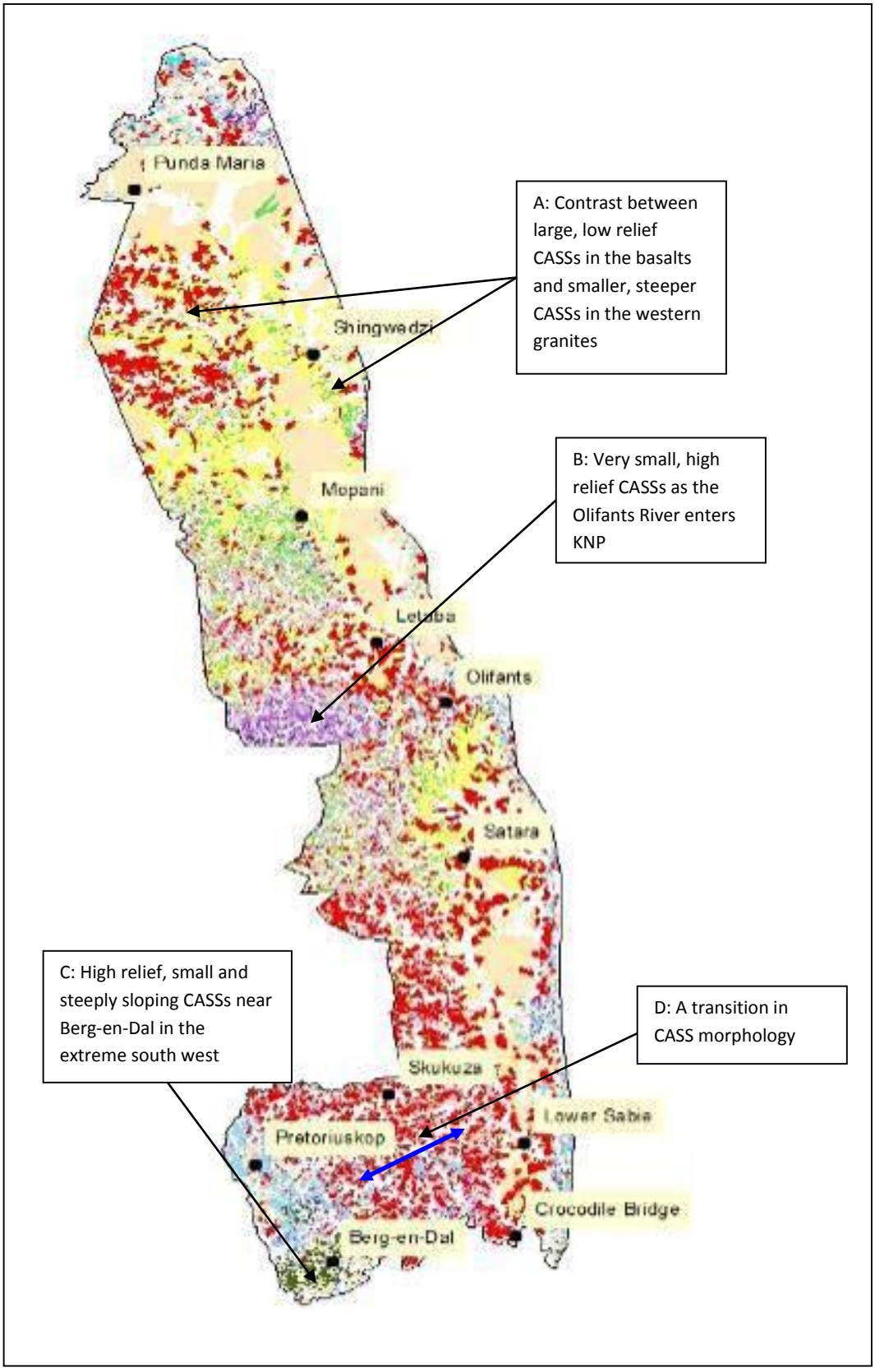


Figure 7.4: Common themes shared between all cluster solutions.

The close relationship between geology and patterns of landscape dissection results in common themes across all the cluster solutions (see Figure 7.5).

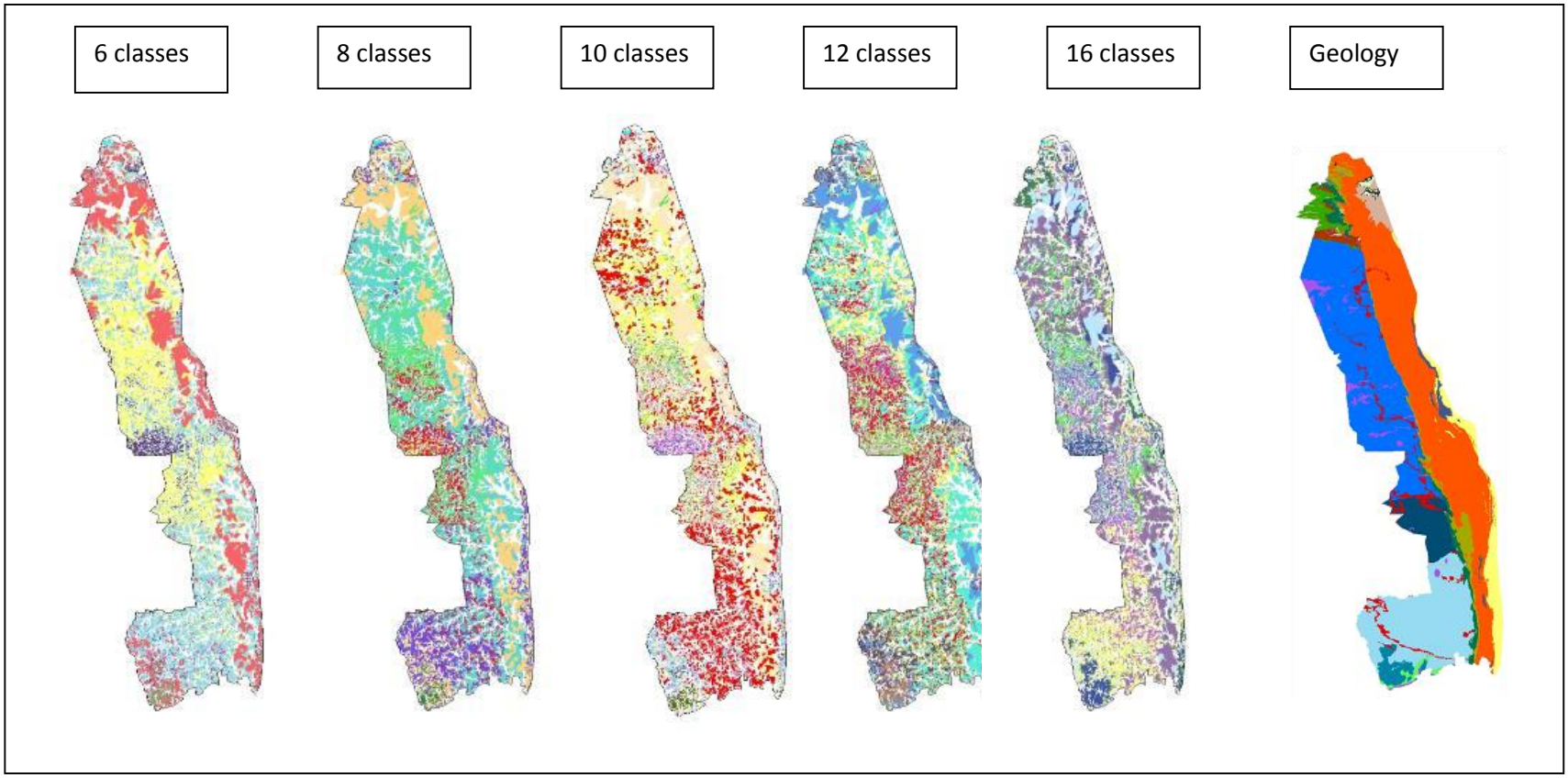


Figure 7.5: ISOCLUSTER solutions with various numbers of classes of first and second order CASSs.

Geological differences are reflected in all the cluster solutions for landscape dissection. The 10-cluster solution offers a good compromise between over generalising differences that may turn out to be important and introducing detail that may be spurious, particularly in the already complex north of the park.

The 10-class solution not only shows many of the geological differences in KNP, but also corresponds well with Venter's (1990) land classification, which also takes into account soil and vegetation differences (Figure 7.6). However, several of Venter's lower-level land types (green outlines in Figure 7.6) emerge at the same level as land systems (black outlines in Figure 7.6), most of which follow major geological boundaries.

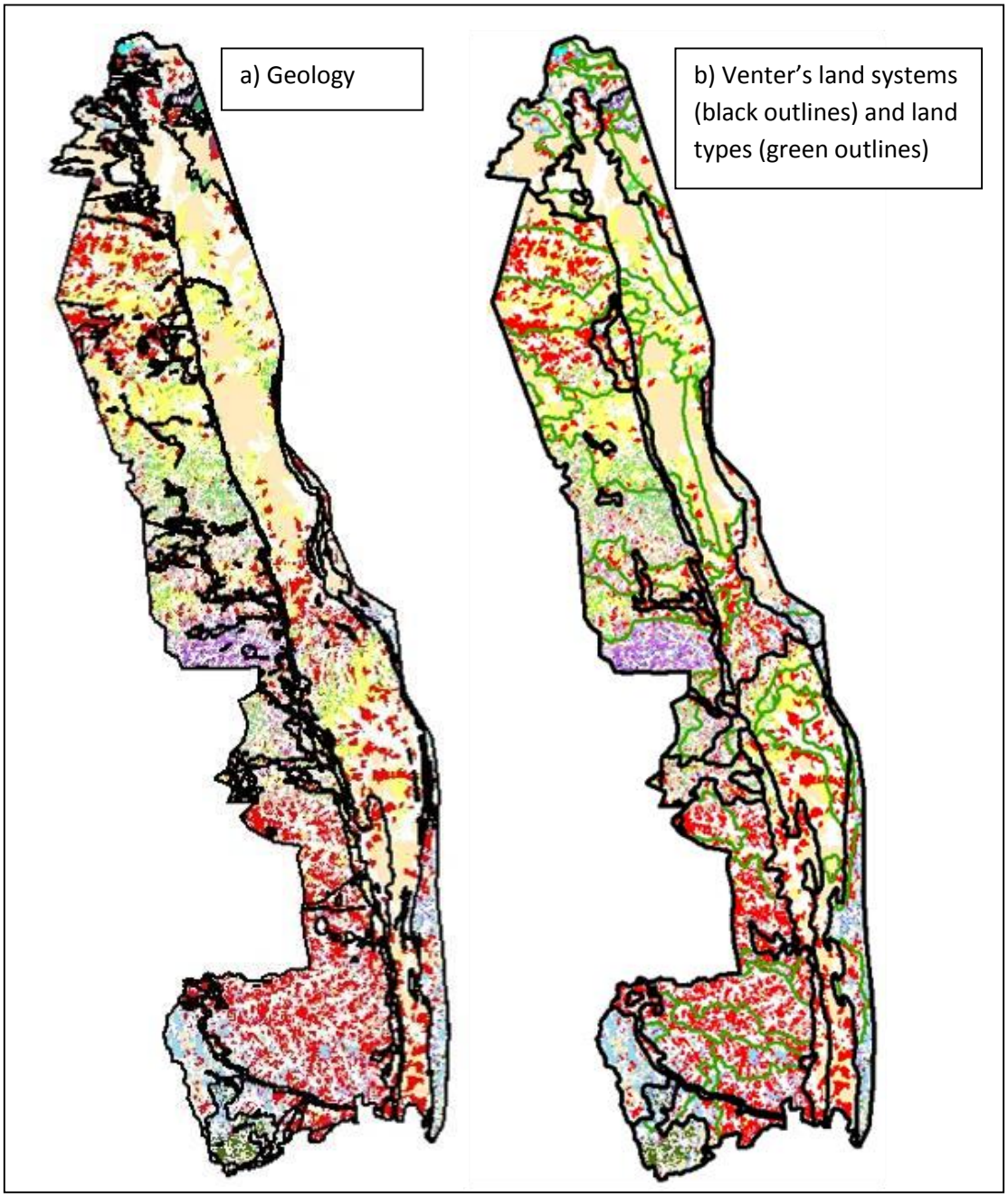


Figure 7.6: Geological and Venter's (1990) land classification boundaries superimposed upon 10-classes of landscape dissection in KNP.

Many (though not all) of the regions with distinct patterns of landscape dissection correspond to either a) geological zones and/or b) Venter's Land systems (black boundaries) and Land types (green boundaries).

7.2.5 STEP FOUR: Archetypes for classes of landscape dissection

The regions identified in the cluster solutions often consist of a mixture of two or three classes (see Figure 7.7).

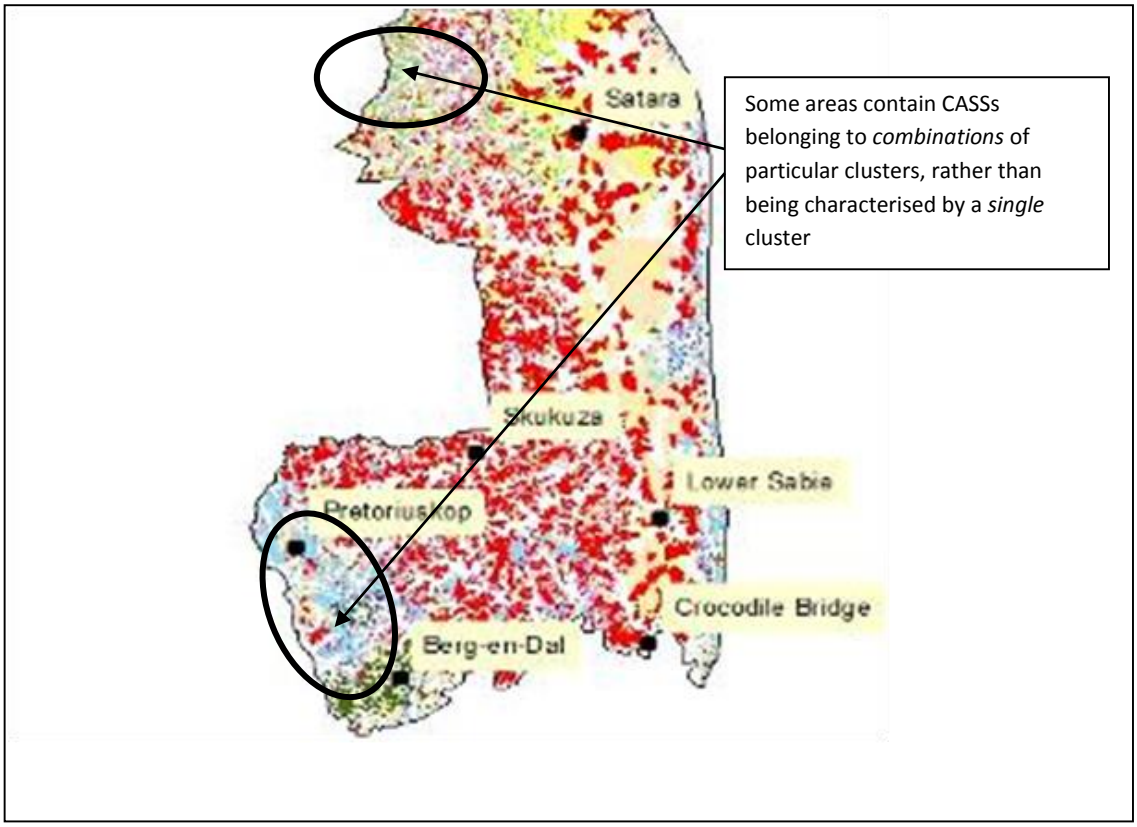
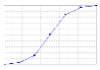
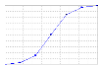
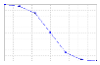
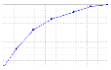
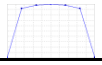
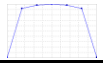


Figure 7.7: Combinations of landscape dissection clusters characterise some areas in KNP.
Some areas are characterised by a particular combination of landscape dissection clusters, rather than CASSs that have just been assigned to a single cluster.

To better describe regions with mixed classes of landscape dissection, I developed archetypes for eight geographical regions, based on the properties of the classes or combinations of classes shown in the cluster solutions (Table 7.1).

Table 7.1: Rule set defining regional classes of landscape dissection in KNP.

Characteristics of clusters of 1st and 2nd order CASSs were used to guide the development of the rule set. Values for area, elevation range and gradient are ln transformed, normalised and standardised on a scale of 1:1000 to make for easy comparison.

Zone	*ISO*	***Area***			***Relief***			***Mean Gradient***		
	CLUSTERS	*Shape*	*Low*	*High*	*Shape*	*Low*	*High*	*Shape*	*Low*	*High*
1	7,8,9		500	570		550	800		570	700
2	7,6,10		300	650		500	800		500	780
3	5,4		440	640		450	640		430	560
4	4,2		300	550		300	600		375	600
5	6,8		300	450		430	700		500	750
6	3,10		470	700		440	860		340	780
7	3		470	620		440	540		350	450
8	3,5		470	640		440	640		340	560

A fuzzy classification was then undertaken in eCognition (Trimble, 1995), segmenting the three layers (CASS area, relief and mean gradient) into image objects equivalent to 1st and 2nd order CASSs. This resulted in a classification which was much more regionally homogenous than that produced using the unsupervised ISOCLUSTER procedure (Figure 7.8a). The map was then further smoothed by applying a circular focal majority filter with a neighbourhood of 5 cells (equivalent to 445m radius at 89m resolution) and then eliminating zones under 1km^2 by merging them with those neighbours with which they shared the longest border (Figure 7.8b). This procedure effectively extrapolated the findings over the areas occupied by higher-order CASSs that were not included in the analysis.

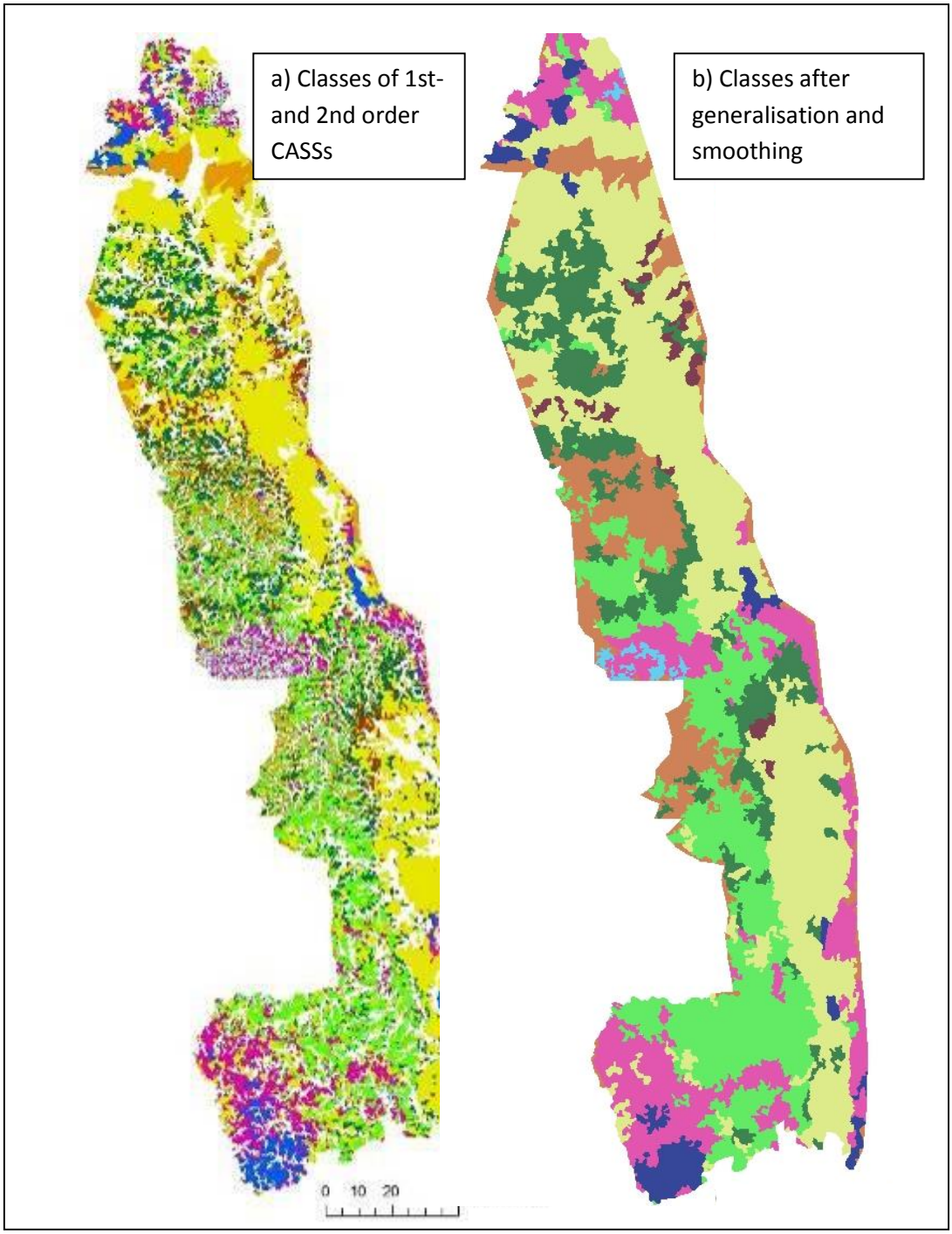


Figure 7.8: Landscape dissection patterns in KNP.

The fuzzy classification of 1st-2nd order CASSs (a) is simplified in b) by applying a majority filter and then eliminating all polygons <1km^2. This extends the classification to incorporate higher order CASSs.

7.2.6 STEP FIVE: Incorporating geological boundaries

Although transitions between the morphologically based classes of landscape dissection often reflect geological boundaries, some ecologically important boundaries are not clearly distinguished. Some geologies show very similar patterns of landscape dissection, but their different mineral composition results in their supporting very different vegetation and soils.

For example, both shale and basalt have similar patterns of landscape dissection, in that they are very flat and have relatively low drainage density (Figure 7.9), but their soils and vegetation differ greatly. Whilst shale has relatively shallow soils, that are often duplex with high sodium content, and supports dense woody cover, basalt soils are generally much deeper, supporting dense grass, but relatively few trees (Venter 1990). These differences suggest that catchments and catenal elements on the two substrates are likely to have very different water budgets and should therefore be considered as belonging to two separate physiographic zones.

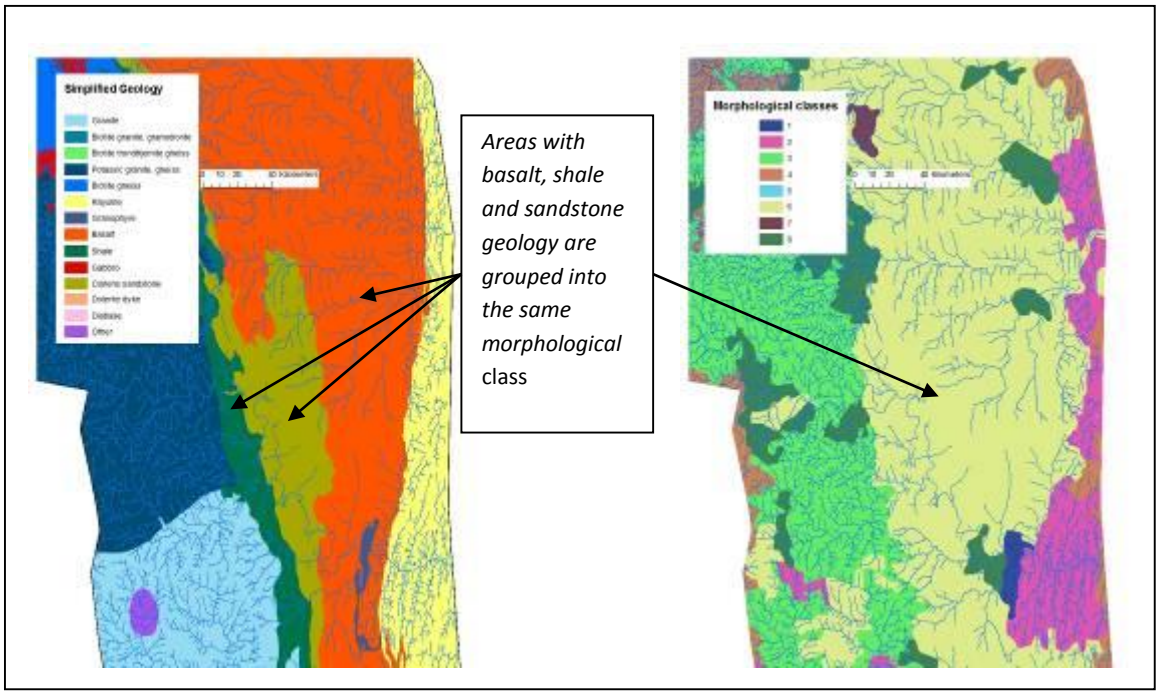


Figure7.9: Morphological similarity between shale, sandstone and basalt geologies.

Furthermore, geological variation does not respect catchment boundaries, since geological differences are not controlled by surface processes. This means that some small or narrow patches that are both morphologically and geologically distinct from their neighbours are not clearly shown in the resulting map. For example, the gabbro strip across southern KNP is represented only by a few relatively flat patches (pale green in Figure 7.10a).

To derive the physiographic zones of KNP I therefore overlaid the map of landscape dissection classes with a simplified geological map (derived from a 1: 250 000 map produced by the Council for Geosciences, Figure 7.10b). This procedure generated a total of 87 separate classes, many of which occupy very small areas (Figure 7.10c). I then consolidated these classes by merging classes occupying less than 150km^2 across the whole park with their most similar neighbours, reducing the number of classes to 27 (Figure 7.11). Classes occupying less than 150km^2 across the whole park have been merged with their most similar neighbours to produce 27 physiographic zones.

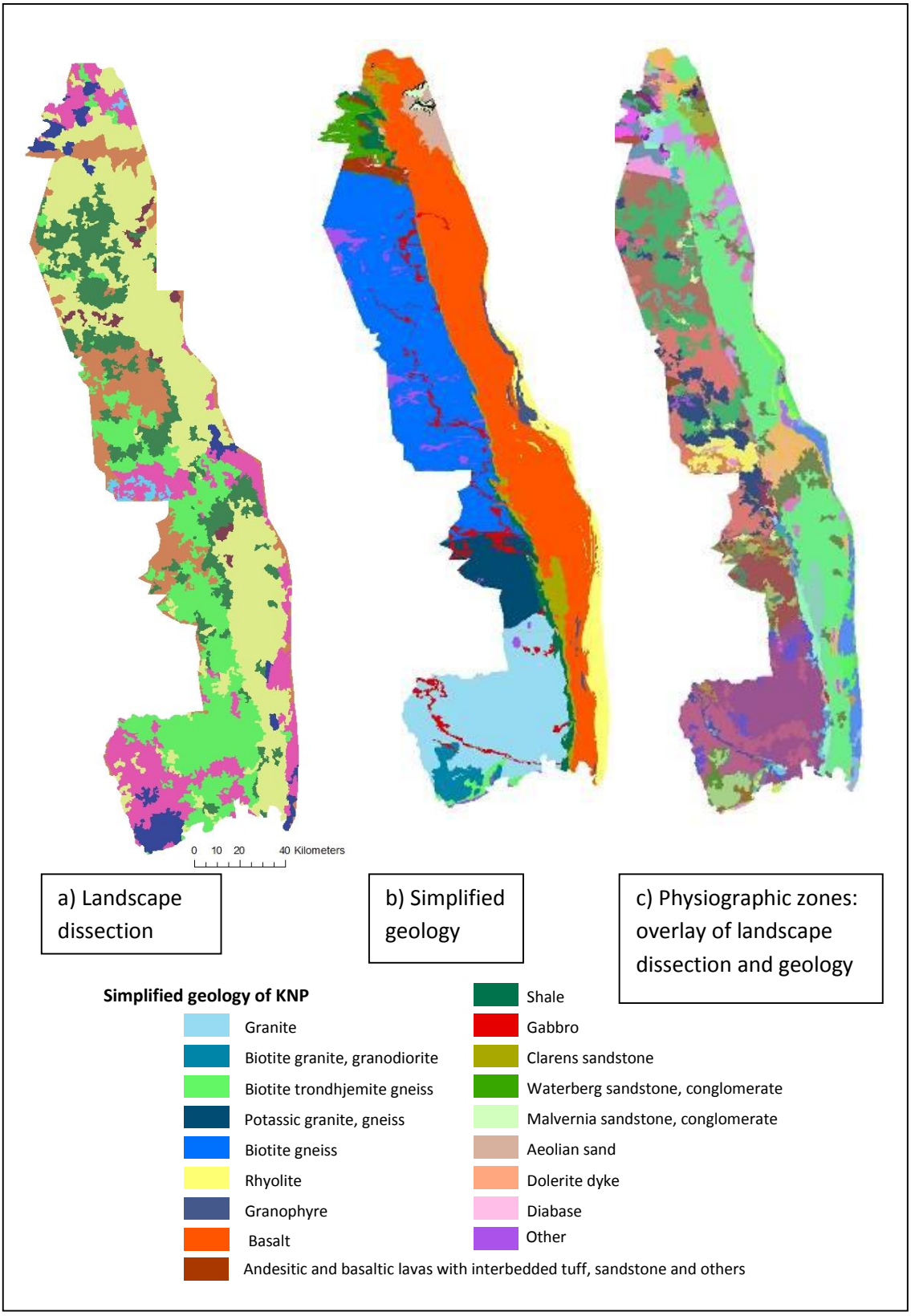
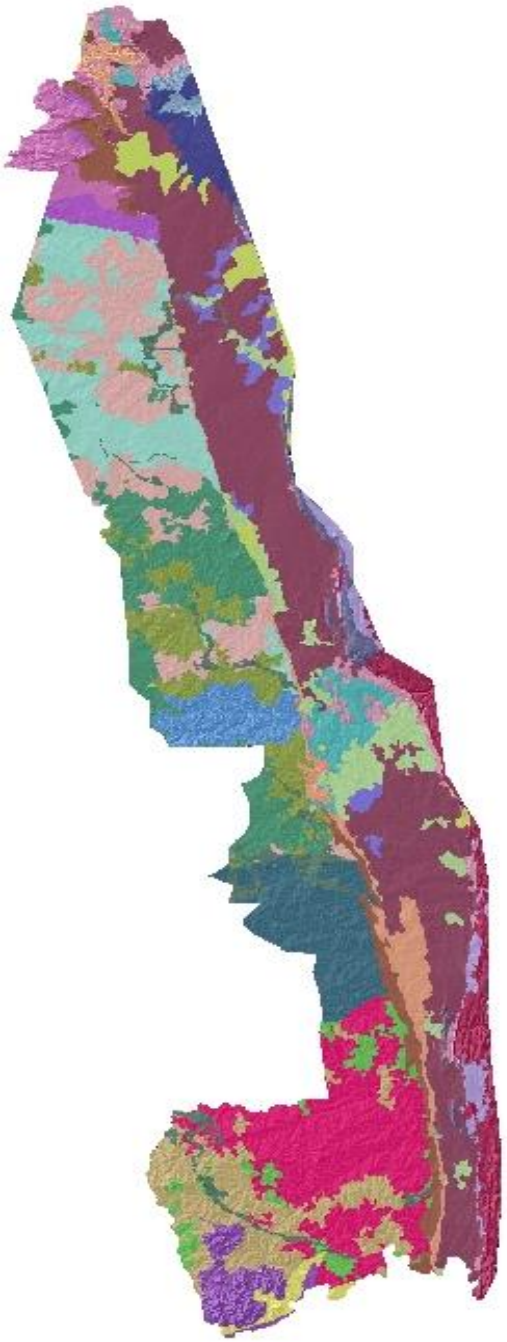


Figure 7.10: Zones of landscape dissection overlaid on geology.

a) Morphological classes of landscape dissection, b) simplified geology derived by combining similar geologies shown in the 1:1250 000 geological map and c) the result of overlaying a) and b), producing 87 separate classes, many of which occupy very small areas.

7.3 Results: Physiographic zones of KNP

The final map of physiographic zones in KNP consists of 27 classes (Figure 7.11). Some 30% of the total area of the park is occupied by the 2 largest classes, which lie in the eastern basalts and the granites around Skukuza, and within which my two study sites were located.



ZONE	Area KNP		1st and 2nd order CASSs		
	%	ha	Mean slope (deg)	Mean relief (m)	Mean area (ha)
	2%	469	1.7	21	29
	2%	358	8.1	89	21
	3%	496	1.5	26	69
	1%	210	4.2	80	77
	3%	571	2.6	34	59
	1%	269	2.1	31	132
	2%	395	4.9	90	114
	5%	874	1.7	18	23
	4%	674	4.1	48	32
	1%	248	2.1	41	81
	2%	329	1.8	20	24
	2%	321	1.5	21	87
	2%	384	3.1	37	27
	21%	3 971	1.1	27	173
	3%	611	1.2	15	29
	1%	230	0.7	10	36
	4%	798	1.9	17	17
	7%	1 246	1.6	12	12
	2%	443	3.3	22	9
	6%	1 176	1.1	20	90
	8%	1 427	1.3	16	31
	1%	204	1.7	36	153
	9%	1 769	2.0	24	30
	5%	1 005	2.8	37	34
	2%	311	1.9	36	76
	0%	79	4.0	26	10
	1%	118	3.7	60	39
ALL	100%	18 986	2.3	25	34

Figure7.11: Physiographic zones in KNP.

Physiographic zones are overlaid on hillshading derived from 90m SRTM DEM to show differences in relief associated with each zone.

7.4 Discussion

7.4.1 Evaluation of the map

Ideally, the classification of physiographic zones should be validated by examining the extent to which assemblages of catenal elements do indeed vary more between the different zones identified than within each zone. However, such validation can only be undertaken when finer-resolution DEM data become available that permit mapping of catenal elements in all areas of the park.

The validity of the map is supported in broad terms by its congruence with previous classifications of KNP, such as Venter's (1990) land systems (Figure 7.12 and Section 4.4.8), which is the most thorough and most used classification, and which is also based on principles similar to those used in this thesis. Unsurprisingly, agreement is strongest in areas with distinct geology and/or morphology, bounded by abrupt borders, such as the high relief area near Berg-en-Dal composed of biotite granite and granodiorite or the finely dissected area around the eastern end of the Olifants River (B and C in Figure 7.4) as well as the eastern rhyolites and the broad divisions of the geologically complex north. However, there are some major areas of disagreement, notably:

- Treatment of the gradual change in morphology across the south of the park
- Northern and central granites
- Sandstone and shale
- Basalt north and south

The gradual change in morphology across the south of the park

The various cluster solutions (Figure 7.6) all seem to hint at a gradual change in morphology across the southern area of the park along a broadly southwest to northeast axis. It is therefore likely that the differences between Venter's classification and the physiographic zones delineated in this area result from somewhat arbitrary partitioning across a gradual transition in both classifications (Figure 7.13). Venter describes the transition in terms of subtle changes in soils and vegetation from the upland areas of the divide between the Sabie and Crocodile basins (Napi and Randspruit) to the lowland areas bordering the Sabie River (Skukuza), with Renosterkoppies as a transition zone on either side of the Sabie River. The transition is also likely to be related to the rainfall gradient, with higher rainfall occurring in the higher relief areas to the west, slowing decreasing in a north westerly direction (Figure 4.5).

These discrepancies highlight the deficiencies of categorical maps in portraying gradual spatial transitions. All boundaries are portrayed as equally abrupt, whether or not this is actually the case.

Northern and central granites

Although the broad pattern of physiographic zones is reflected in Venter's land types, there are some discrepancies. Venter's distinctions between related land types in the north-central granites are merged into a composite of two physiographic zones (Figure 7.13). However, Venter's finer distinctions are lost in the south-central area.

Sandstone and shale

Venter groups the narrow central strips of shale and sandstone, which are depicted as separate physiographic zones.

Basalt north and south

Venter subdivides basalts more finely than the physiographic zones, including a north-south distinction based on the presence/absence of olivine.

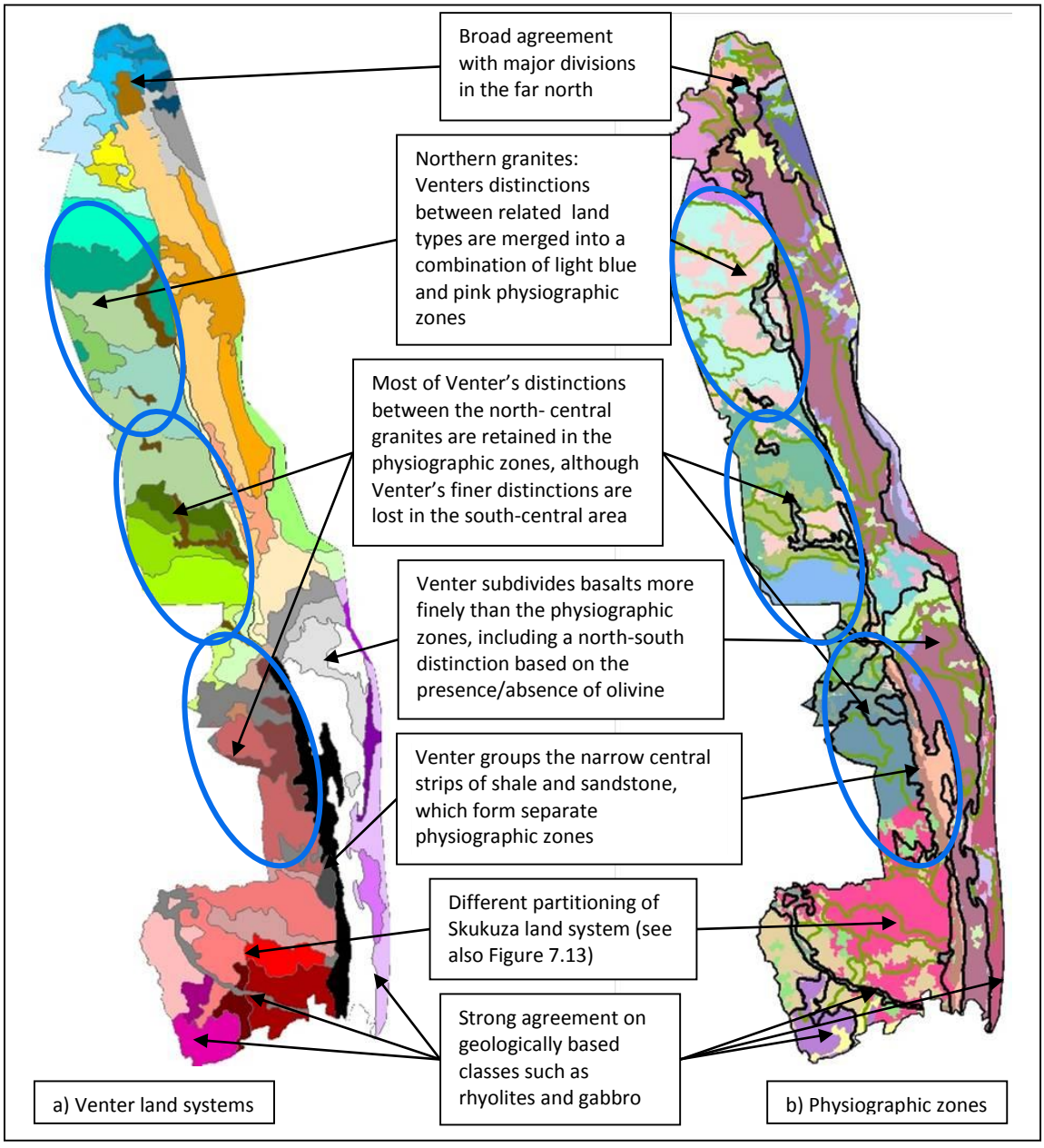


Figure 7.12: Comparison between physiographic zones and Venter's land systems (1990). Overall, there is strong agreement between the two classifications, with some differences in emphasis.

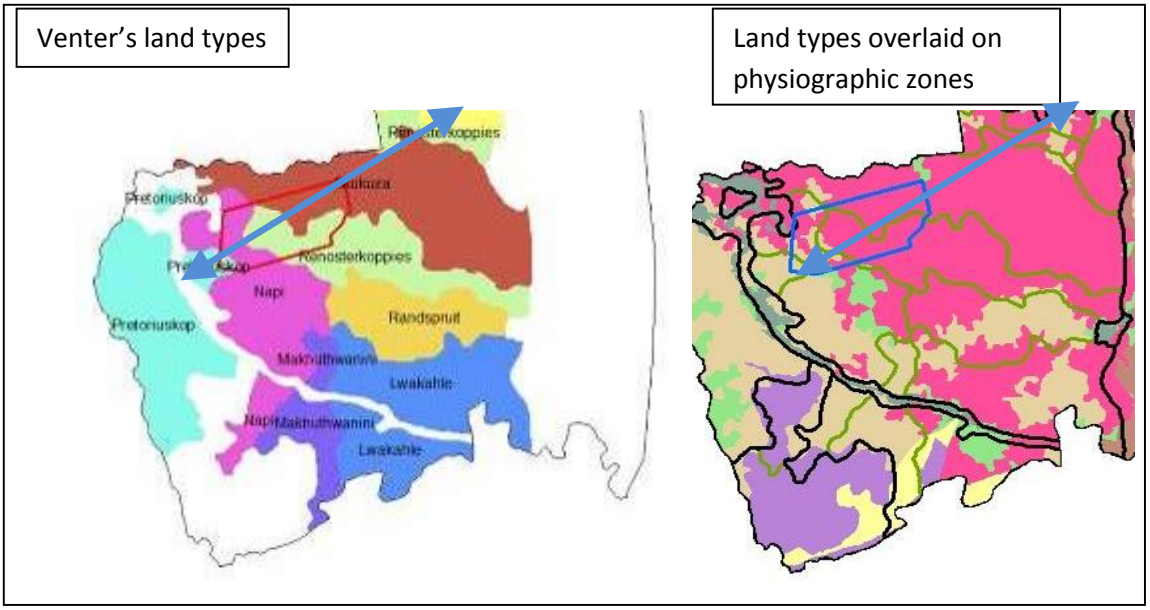


Figure 7.13: Comparison between physiographic zones and Venter's land types in KNP southern granites. Areas between Skukuza and Pretoriuskop are partitioned differently in the two classifications. This is likely to be because of a subtle southeast-northwest transition (blue arrow) that is somewhat arbitrarily divided in both classifications. The N'waswitshaka study site lies across the transition.

Apart from qualitative comparisons with the previous classifications, the extent to which differences in CASS assemblages of catenal elements are captured by physiographic zones can only be evaluated against detailed maps of these elements. So far, such maps only exist for the two study sites described in this thesis. The N'waswitshaka study site lies in the transition zone (Figure 7.13), which helps to explain the differences seen in the catenal assemblages of this area (Sections 5.5.1 and 6.3.3). It is likely that the assemblages that contain woody midslopes and grassy crests are associated with subtle regional variations of the Skukuza land type that are poorly described in both classifications. More precise mapping of these variations can only be achieved through mapping catenal elements over a much larger area.

By contrast, the Nhlowa study site is clearly positioned within a basaltic zone that is unambiguously described in both classifications. It is therefore reasonable to assume that the assemblages described for the study site are repeated throughout the surrounding physiographic zone.

7.4.2 Implications of the differences between physiographic zones

The regional trends in CASS morphology that are described in maps of physiographic zones are the integrated result of historical interactions and feedbacks between climate, geology, relief and vegetation, integrating fluvial and hillslope processes (e.g. Tucker & Bras, 1998; Collins & Bras, 2010; Coblentz *et al.*, 2014). The integrated effects of these processes continue to shape the landscape and to provide a template that constrains a wide range of ecological processes. For example, the length, gradient and curvature of hillslopes affects the direction and intensity of hydrological flows that ultimately shape the landscape through weathering and erosion processes and support various types of vegetation. The spacing of streams and hillslopes affects hydrological fluxes and flood regimes (e.g. Robinson *et al.*, 1995; Pallard *et al.*, 2009) as

well as the distance animals have to travel to find water. Given the importance of riparian systems to biodiversity (e.g. Naiman *et al.*, 1993), stream density has a large impact on regional biodiversity. Since streams are natural fire breaks, stream density also has a large impact on the spread of fire.

Variations in the morphology and geology of physiographic zones therefore have profound effects on many ecological processes, such that these processes are likely to vary significantly between different physiographic zones. Each physiographic zone is also likely to face a distinct set of threats to system integrity, with different levels of sensitivity to environmental or climate change. This means that it is desirable for each physiographic zone to have its own management strategy, with monitoring and research in place to learn about the particular nuances of each system. The recently adopted fire management policy in KNP is a step in this direction. The park has been divided into five Large Fire Management Units (LFMUs) according to historic fire return periods, geological substrate and mean annual rainfall (Smit *et al.*, 2013). These units represent areas in which fire both behaves differently and has different ecological effects, with distinct fire management and ecological objectives in each LFMU (van Wilgen *et al.*, 2014). These units have strikingly broad similarities to physiographic zones (Figure 7.14), reflecting the fact that both zonations are based upon differences in geology, climate and vegetation that affect a wide range of ecological processes.

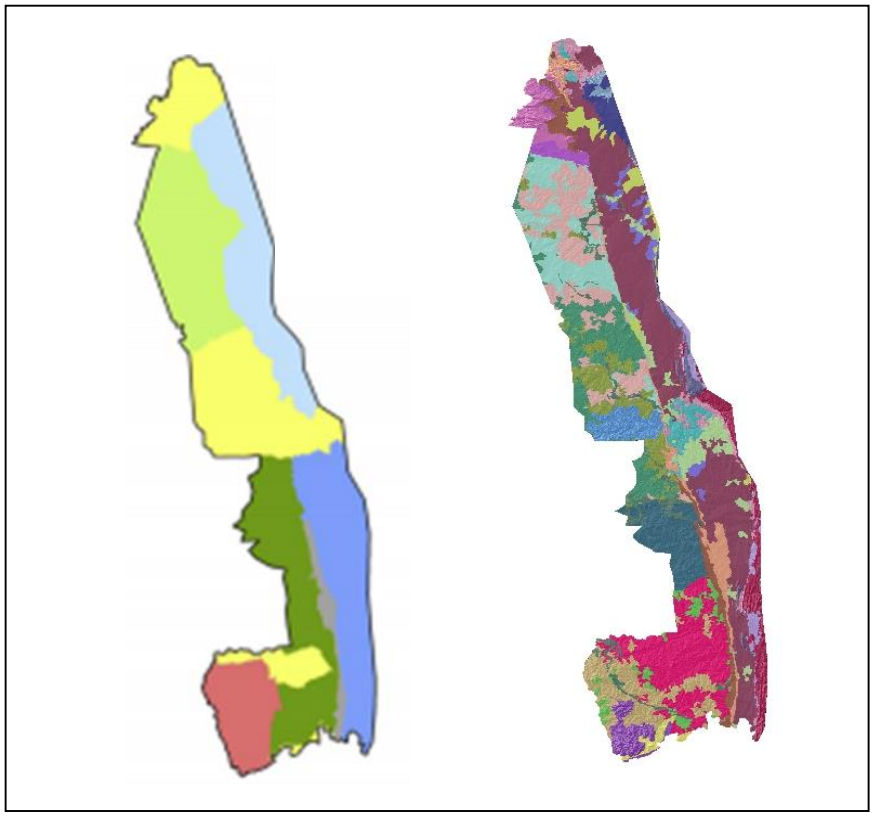


Figure 7.14: Broad similarities between Large Fire Management Units and physiographic zones in KNP. The broad similarities between the recently adopted LFMUs in KNP and physiographic zones reflect a common basis in geological, vegetation and morphological variation within the park. (SANParks GIS, 2010)

7.5 Concluding remarks

Like the mapping of catenal elements (Chapter 5) and of assemblages of these elements in CASSs and catchments (Chapter 6), the mapping of physiographic zones has involved extensive iterations between conceptualisation, representation and observation of the landscape itself, the semiotic triangle embedded in the lower levels of the Couclelis description of geographical ontologies (see Figure 5.36). Although many decisions have depended on the choices made (and justified) by the cartographer, opportunities for the landscape itself to have a 'voice' have been maximised. For example, rather than using an arbitrarily spaced grid to define basic spatial objects (as happens in pixel based classifications), maps of landscape dissection patterns were based on the fuzzy classification of CASSs. The size and shape of the basic spatial objects were therefore determined by the landscape itself rather than by a cartographic decision.

Completing the application of my conceptualisation of savanna landscapes to the landscapes of KNP, I am struck by the symmetry of the landscape hierarchy and the theoretical convergence of top-down and bottom-up perspectives and procedures: in the same way that catenal elements nest within CASSs and catchments, generating emergent catchment-level characteristics and behaviour, so to do CASSs nest within physiographic zones, generating emergent regional characteristics and behaviour.

CHAPTER 8: DISCUSSION AND CLOSING COMMENTS

8.1 Introduction

Landscape classifications that describe patterns of co-varying and interacting biotic and abiotic ecosystem components are widely used for applications at regional, national and global scales that range from conservation to food security (Bailey, 2009a). Such classifications demand cross-disciplinary perspectives that integrate many system components. Integrated perspectives are also demanded within earth sciences, where approaches are converging to create new fields that dissolve traditional boundaries (e.g. ecohydrology (Rodriguez-Iturbe, 2000), biogeomorphology (Stallins, 2006) and hydropedology (Bouma, 2006)).

As shown in Chapter 2, the classical approach to integrated descriptions and maps conceives landscape units as structural-functional units that contain more or less discrete and static ecosystems, with interactions between system components that are regular and predictable(e.g. Bailey, 1983; Sayre, 2005). The emphasis is on similarities and universal principles, with many local differences in space or time being regarded merely as background noise or as irrelevant and ignorable complications. This conceptualisation of the world is very useful, since it provides a rationale for the transfer of knowledge and experience from sample or reference sites to other sites in the same class, allowing spatial models to be constructed and likely responses to management interventions or environmental change to be foresighted and mapped (e.g. Ferree & Anderson, 2013).

However, this classical approach is seriously challenged by insights from complexity theory (e.g. Urry, 2005) and from the American school of landscape ecology (e.g. Turner *et al.*, 2001):

- *There are multiple valid perspectives on ecosystems and landscapes*
    - Ecological classification of landscapes involve imposing subjective boundaries on inherently open ecological systems (Schneider & Kay, 1994), such that these classifications are always contestable (McMahon *et al.*, 2004; Omernik, 2004).
    - Perceived landscape patterns change with the scale of observation (Levin, 1992) or if different combinations of defining variables are used (Buyantuyev & Wu, 2007). Scales and variables therefore need to be chosen for a specific purpose: general purpose classifications designed to inform integrated approaches to landscape management and planning cannot be defended (Section 2.3.5).
- *Heterogeneity is important and is obscured by generalisation*
    - Landscape heterogeneity is valuable in its own right, since it generates biodiversity and system resilience (e.g. Turner & Chapin, 2005).
    - Local contingencies affect system responses, creating surprising outcomes: Each landscape is potentially unique (Phillips, 2007).
- *System dynamics and long-term system trajectories cannot be ignored*
    - Static snapshots are inadequate representations of systems that are in constant flux.

    - Disturbance regimes often hold ecological systems far from equilibrium (Turner *et al.*, 1993).
    - Imprints of history often influence contemporary processes and future trajectories (Cadenasso *et al.*, 2006).
    - Observed changes (or lack of change) depend on the time scales of analysis (Perry, 2002)
- *Different factors drive and control ecological systems in different contexts*
    - Different ecological processes shape landscape character and behaviour in different climatic and geological settings (e.g. Schmidt & Dikau, 1999; Omernik, 2004).
    - The configuration of landscape mosaics (patch arrangement and connectivity) also affects ecological processes (e.g. Turner *et al.*, 2001).
    - Standardised classification schemes that use the same scales and variables over wide areas are inappropriate (Omernik, 2004).
- *Ecological systems are complex systems that are inherently unpredictable*
    - Multiple non-linear interactions, with lags, thresholds and sensitivity to initial conditions generate 'causal thickets', such that the processes responsible for observed patterns defy mechanistic modelling and are inherently unpredictable (Wimsatt, 1994, 2007).

We therefore have a situation in which managers, policymakers and scientists are all demanding integrated approaches to land classification, but the very possibility of an integrated, multi-disciplinary approach is denied by some landscape ecologists.

However, ecosystem behaviour is neither chaotic nor random, so that regularities in time and space can be observed in most landscapes (e.g. Kay & Schneider, 1994; Wimsatt, 1994). In water-limited landscapes, such as the savannas of KNP, clusters of co-varying abiotic and biotic attributes have been observed and described for decades, at least (e.g. Milne, 1935). In this thesis I have developed a conceptualisation of savanna landscapes that describes these patterns and which is designed to serve the needs of scientists, managers and policymakers, whilst addressing the challenges posed by our improved understanding of system complexity and dynamics and our appreciation of the importance and value of local heterogeneity. The conceptualisation embeds toposequences of catenal elements within the highly organised structure of drainage networks. In turn, the structure of these networks is recognised as varying between different geological and climatic settings. This conceptualisation provides a framework that not only unites terrestrial and riverine perspectives, but provides a platform for the integration of many other perspectives and applications.

Alongside this conceptualisation I have also articulated an approach to implement this way of thinking, which is based around the fuzzy comparison of generalised archetypes to particular landscapes (Section 3.8 and Table 3.2). The conceptualisation and the way of applying it through archetypes present a radical departure from the classical way of viewing landscapes, as this approach:

- Uses a skeletal hierarchy to describe features found in all landscapes
    - Guides choice of scales and variables to describe features and patterns in particular landscapes
    - Does not use standardised, pre-determined scales, attributes and approaches, but lets the landscape 'talk', using concepts such as topographic grain
    - Is adaptable, providing a platform for integrating/ adding/ storing knowledge
- Employs fuzzy logic to describe a fuzzy world (Zadeh, 2008)
    - Archetypes are used to navigate between general concepts and particular instances and between general principles and local processes
    - Graded class membership is applied
    - Reframes analytical lenses to reveal differences as well as similarities

Given that we now recognise that there are many valid ways of partitioning and classifying landscapes, it is no easy task to win consensus around a single conceptualisation. To inform integrated study and management, a shared conceptualisation has to be seen as credible, relevant and legitimate by all parties involved (Cash *et al.*, 2003). In practical terms, it should be viewed as a work in progress that is continuously open to reappraisal, testing and refinement. In this concluding chapter I review the narratives that I have constructed to demonstrate the credibility, relevance and legitimacy of the new conceptualisation developed in this thesis.

Both credibility and legitimacy are conferred upon the new conceptualisation by the theories and practices in which it is grounded. I therefore start this discussion by reviewing the foundations of the new approach in previous conceptualisations, considering the contributions made by each of the various perspectives that have been woven together to create this new way of looking at savanna landscapes. Next, I demonstrate the completeness and internal coherence of the conceptualisation by means of a systematic review in terms of Couclelis's meta-ontology of geographic information (Couclelis, 2010). Particular attention is paid to the ways in which credibility is built and how the challenges of complexity, dynamics and heterogeneity are addressed at each level. Whereas the upper levels of Couclelis's meta-ontology are concerned with abstract conceptualisation, lower levels entail the application of the conceptualisation to a specific landscape through the construction of local archetypes and their representation in maps. I therefore review the way in which the conceptualisation was used to map KNP landscapes at three hierarchical levels of organisation: catenal elements, CASSs /catchments and physiographic zones. In this section, I focus on issues of credibility raised by tensions between the need for flexibility and adaptation on the one hand, and the need for rigorous and systematic definitions on the other hand.

I then turn from reviewing the conceptualisation *per se* to reviewing the implementation of the conceptualisation as a framework for classifications of KNP landscapes. These classifications were not undertaken to deliver a product, but to understand how the new conceptualisation and approach to classification would play out, to learn lessons, gain insights and indicate areas for improvement and further research. I therefore consider how well the classification described the landscape: Was the landscape decomposable into the units suggested by the

hierarchy? To what extent do landscape patterns actually correspond to the archetypes suggested by the hierarchy? I also consider how the implementation dealt with the challenge of constructing generalisations, whilst recognising system complexity and retaining information about local heterogeneity.

I turn next to a discussion of themes that have emerged from the thesis, considering firstly the ways in which classifications based on this conceptualisation are informed by the landscape itself, rather than being imposed by standardised schemes or totally subjective assessments. In particular, I discuss the concept of landscape grain, which describes the scale intrinsic to a particular landscape, considering implications for both ecological science and management. I next discuss the various ways in which my conceptualisation uses fuzzy reasoning and classification (Zadeh, 1973, 2008) to describe landscapes that are themselves inherently fuzzy, continuing to reflect on how this approach also relieves the tension between fragmented reductionist generalisations that ignore important and detailed accounts of local heterogeneity that are difficult to apply elsewhere.

This discussion is followed by an assessment of the limitations of my approach, identifying areas that need further development. I frame this in relation to future directions for scientific research and management applications based on this conceptualisation. In conclusion, I reflect on how this project has come full circle, ending up with new ways of legitimising very old ideas.

8.2 What has been learned from existing landscape conceptualisations?

The European school of landscape ecology provides a vision of a holistic approach to the identification, mapping and interpretation of ecosystems that recognises the interconnectedness of ecological systems, integrating many different system drivers, controls and responses (e.g. Neef, 1967; Zonneveld, 1989; Naveh, 2000; Bastian & Steinhart, 2002). A similar vision underlies the production of ecoregion maps, for which there is a huge demand and range of applications (e.g. Bailey, 1983; Omernik, 1987; Loveland & Merchant, 2004; McMahon *et al.*, 2004; Sayre *et al.*, 2009; Olson *et al.*, 2012). However, both these approaches are framed within realist perspectives that assume that landscape patches are self-evident - or at least that a panel of experts can reach a consensus on boundaries. Relying on end-user faith in expert perception, these approaches fail to deliver convincing narratives that justify their adoption in the face of multiple competing conceptualisations.

By contrast, disciplinary-based approaches that focus on one of the key system components tend to be grounded in theory and conceptual models that explicitly link observed patterns to formative processes. By making such links explicit, these conceptualisations provide rationales that support end-user demands for spatial and temporal extrapolations: reasons are given why locations are grouped into a certain class and why class members are expected to exhibit similar characteristics and behaviour. For example, the soil-landscape model used by soil surveyors to link soil distributions to more easily observable features such as topography and vegetation is grounded in Jenny's (1941) soil-forming factors (Section 2.6.1). Geomorphological river classifications are based on widely accepted principles and mental models that link form

and process in many different contexts and at different scales. (e.g. Frissell *et al.*, 1986; Rosgen, 1994; Bohn & Kershner, 2002; Rogers & O'Keefe, 2003; Brierley & Fryirs, 2005; Thorp *et al.*, 2006; Beechie & Imaki, 2014). Furthermore, these classifications are framed within a hierarchy that decomposes river systems into readily identifiable, process-based units at several scales, and which has gained widespread consensus amongst the community of river scientists (Section 2.7.2).

Hierarchy theory shows that decomposing landscapes into spatial units at various organisational levels offers a way of tackling issues of scale and attribute selection by specifying the different types of entity that are visible within different scale domains. Furthermore, the theory also provides a way of reconciling reductionalist and holistic perspectives by suggesting that mechanistic interactions at lower levels of organisation can play out in many different ways, but that these outcomes are contextually constrained by both vertical location within a particular setting and horizontal neighbourhood relationships, including configuration and connectivity (Section 2.2.3).

However, hierarchy theory offers only a framework, making no suggestions as to how the entities should be defined. Indeed, American landscape ecologists argue that there can be no definitive way of partitioning landscapes, since ecosystems are inherently open, so that all landscape conceptualisations and hierarchical frameworks can only be designed with a particular purpose in mind, selecting and defining entities, scales and attributes in light of our knowledge about a particular organism or process of interest (e.g. Levin, 1992).

Somewhat counter-intuitively, it emerges that disciplinary-based approaches offer integrated conceptual models that can populate the hierarchy, describing the ways in which landscapes are self-organised into distinct spatial entities at various scales. Once the toposequences described by soil scientists are placed within the context of the systems described in geomorphological river classifications, the structure of landscapes becomes clearer. Situating hillslopes in the context of the stream network they drain into integrates the network perspective of aquatic ecologists and fluvial geomorphologists with the patch perspective of terrestrial ecologists and soil scientists (Section 3.4.3). Drawing on mental models from each of these disciplines, it becomes possible to define spatial entities that are bound by the structure of a given landscape. Rather than producing maps and classifications based on statistical correlations among a dealer's choice of environmental attributes and scales, it becomes possible to give the landscape itself a 'voice'. Inspecting images for repeating toposequences of vegetation patterns leads to the detection of the particular grain of a given landscape (see Sections 2.2.2, 3.7, 4.2, 5.2.2, 6.5 and 7.2.2). As soon as the scale at which streams and hillslopes are delineated is agreed, a landscape can be decomposed into catchments and then further partitioned into toposequences associated with the hillslopes of each catchment, including both vegetation patches on the hillslopes and the channel reach elements in the valley bottom. Furthermore, these patches can be placed within the context of a networked river system connected to hillslope flow paths, such that all patches are potentially connected to each other. The four-dimensional gradients that have been described in river systems (Ward, 1989; Petts & Amoros, 1996) can now be seen reflected in the character and dynamics

of each patch or CASS, which, when viewed together, form a dynamic mosaic. Thus patch, network and gradient perspectives are united in a conceptualisation that unites riverine and terrestrial perspectives.

Geomorphologists and soil scientists are adept at moving between general principles and local instances (Burt, 2005), offering valuable insights into strategies and techniques that facilitate interplay between empirical field observations and general principles and theory, allowing place based understandings to be constructed by careful adaptation of idealised mental models (Phillips, 2012; Brierley *et al.*, 2013; Wohl, 2013). General principles are treated as rules to be deviated from in almost every instance, with adjustments made to accommodate local differences. Whereas other scientific disciplines demand idealised precision and adherence to universal laws, these field-based scientists are comfortable in a world of approximations and uncertainty:

> *"The physicist Ernest Rutherford famously claimed that science is either physics or stamp collecting. Geomorphology is neither solely physics (universal) nor stamp collecting (site-specific case studies) because of the influence of contingency on geomorphic form and process, as well as the existence of consistent patterns of form and process." (Wohl, 2013 p. 51)*

It is the same consistency of patterns of form and process that makes savanna landscapes decomposable into distinct entities and classes of entities that are described in the landscape hierarchy developed in this thesis. By focussing on these consistencies and regularities, describing them in terms of broad-brush conceptual models that are easily adapted to local circumstances, we are able to invoke general principles and broad conceptual models to extrapolate knowledge and experience across time and space. Rather than viewing landscape units as the product of intertwined pathways that are impossible to describe precisely and are rarely exactly reproduced, we can view them as 'causal thickets' (Wimsatt, 1994) that are shaped by the constraints of contextual factors described within a landscape hierarchy, including both vertical, top-down regional attributes and horizontal configuration and connectivities with neighbouring units (Allen & Starr, 1982; Section 2. 2 and Section 3.6).

Furthermore, in Digital Soil Mapping (DSM), techniques have been developed to translate these mental models into rules that can be codified in at least semi-automated digital maps (Burrough, 1989; Bui, 2004). This process of translating expert knowledge and interpretation is invaluable, since it ensures that the assumptions underlying conceptualisations are fully articulated, allowing debate and criticism as well as development and refinement. The possibility of such debate is critical to the development of consensus around conceptualisations that are to be shared by a community: since all conceptualisations are ultimately contestable, it is imperative that each competing conceptualisation (or refinement to conceptualisations that have already been adopted) is supported by narratives demonstrating its credibility and relevance to the purpose(s) in hand (see Cash *et al.*, 2003).

Vegetation, soil and hydrological systems mapping all use classification techniques that involve the identification of representative class samples together with environmental features or gradients that are strongly correlated with that sample to inform spatial extrapolations that

estimate the distribution of each class. These techniques have been particularly well developed in DSM, where techniques of fuzzy classification have been successfully applied to describe the gradual transitions and overlapping classes that often characterise real soil distributions (and real landscapes). In fuzzy classification it is recognised that not all instances of a class are equally good exemplars of the entire class, which has led to the idea of developing *a priori* class prototypes that are used to define classification rules. This is potentially a very powerful way of reconciling the need for generalisation with the desire to retain information about local heterogeneity. These ideas are considered in more detail later in this chapter (Section 8.5.1).

In reviewing existing conceptualisations, it became clear that each approach offered valuable insights and tools that complemented each other and could be woven together to form a truly integrated perspective.

8.3 Foundations for a new conceptualisation

In the conceptualisation developed in this thesis, aquatic and terrestrial perspectives were integrated by simply acknowledging that the spatial distribution of toposequences of associated soils, vegetation and hydrology is structured by the drainage network. A heuristic hierarchy described entities at three levels of organisation: catenal elements, associated with individual hillslopes, catchments, which contain (potentially) hydrologically connected toposequences of catenal elements and physiographic zones, which in turn contain catchments that vary systematically in their morphology and toposequences according to their position in the drainage network. Applying this hierarchy to the classification and mapping of landscape entities at each organisational level involved an interplay between the general abstract concepts of the hierarchy and observations of the attributes and scales associated with repeating patterns that make up the grain of particular landscapes (see Chapters 5-7). Archetypes were used to mediate between general, abstract concept and particular instances, with varying degrees of precision. The conceptual vagueness of archetypes and fuzzy classification methods helped to address the challenges of dealing with the vagueness inherent in geographical concepts and the reality they represent.

In constructing a new conceptualisation, it was important that the various elements should be synthesised in a systematic and transparent manner, carefully articulating the rationale for decisions at each step, identifying uncertainties, strengths and weaknesses along the way. This approach follows the reflective thinking espoused by 'post- reductionist critical complexity' (Preiser & Cilliers, 2010; Preiser, 2012; Audouin *et al.*, 2013). Preiser and Cilliers developed the notion of 'critical complexity' in response to the dilemma posed by the need for reductionist generalisations to describe or analyse complex systems on the one hand, and the impossibility of using traditional reductionist approaches to describe complex systems on the other hand. Post- reductionism offers the possibility of self-reflexive reductionism, using 'reductionist logic that becomes aware of itself'. This is described as a 'shift in attitude', in which limitations, errors and blind spots are acknowledged rather than concealed and which expressly

acknowledges the inclusion of normative values in conceptualisations of complex systems. Audouin *et al.* (2013) even go so far as to claim that:

> *"It (post reductionism) has the potential to disarm the animosities formed by opposing paradigms, for example, reductionism versus holism, without uniting them into a grand unifying truth. The main implication of critical complexity for scientific practice is that it compels the scientist to acknowledge the need for reduction, while making the strategies for such reductionism transparent." (Audouin et al., 2013 p. 2)*

Recognising the need to develop transparent and contestable narratives that can be used to justify the adoption of my conceptualisation, I used a slightly adapted version of Couclelis's meta-ontology of geographic information (Couclelis, 2010) to structure the development of the new conceptualisation, articulating each ontological level of the conceptualisation to demonstrate its completeness and internal coherence (see Section 3.1, Table 8.1).

The transparency of the assumptions underlying the new conceptualisation and its framing within Couclelis's meta-ontology allows the conceptualisation to be both adaptable and rigorous. Adaptability is needed to reconcile tensions created by the need for generalisation and the importance of local differences and by the need to relate general principles to landscapes that are potentially unique. These tensions are reduced through the use of archetypes that can be altered to suit local circumstances. However, this adaptability does not imply that all alterations or refinements are acceptable. On the contrary, each refinement must be presented as a precisiation of a previously agreed archetype. In turn, the narratives supporting the adoption of the archetype in the first place are also systematic and rigorous, since their completeness and coherence can be judged in the light of the meta-ontological framework. The construction and precisiation of archetypes is an ongoing process, during which acknowledged inadequacies and errors can be addressed. In the sections that follow, I address issues raised at each ontological level.

Table 8.1: Ontological levels of the new conceptualisation of savanna landscapes.

Showing sources of uncertainty and ways that complexity, heterogeneity and dynamics are (or could be) addressed at each level.

Ontological level (Based on Couclelis, 2010)	***New conceptualisation***	***Complexity***	***Heterogeneity***	***Dynamics***	***Sources of uncertainty***
Higher levels, generally applicable to all savanna landscapes					
Level 7. **Purpose** (highest level) How the classification is used.	A spatial framework for the description, analysis and mapping of biophysical patterns, providing a framework to facilitate the integrated study and management of savanna systems. Landscapes are conceived in terms of a biophysical template akin to a conceptual mantle draped over the surface of the earth. Situating hillslopes within the context of the drainage network integrates patch, network and gradient perspectives.	Clusters of co-evolved biotic and abiotic attributes are generated and sustained by a tangled web of interactions that resists reductionist descriptions and explanation. Patterns are not self-evident and have indeterminable boundaries. Critical complexity: self-reflection ensures that the conceptualisation is transparent and contestable.	The template varies from place to place. Which local differences are likely to matter for a particular purpose/application?	The template is dynamic, ever-changing and evolving. Can incorporate descriptions of fluxes and connectivities to use the conceptualisation to inform scenario building.	Is the conceptualisation fit for its intended purpose?
Level 6. **Function** Understanding generative processes and other processes where the entity is a driver or control.	Clusters of environmental attributes constrain a wide range of ecological processes. Theory linking patterns to generative and sustaining processes.	Use fuzzy logic based on regularities, approximations and general principles to describe broad patterns resulting from the co-evolution and self-organisation of system components.	Different processes are responsible for the patterns observed in different landscapes and at different scales. Local contingencies and history can shape contemporary processes and future trajectories.	Clusters are constantly changing at many scales. Interactions between system components and the imprint/memory of past events shape the trajectory and evolution of clusters at multiple scales.	Relationships between form and process - equifinality, causal thickets, inherent uncertainty.

Ontological level (Based on Couclelis, 2010)	*New conceptualisation*	*Complexity*	*Heterogeneity*	*Dynamics*	*Sources of uncertainty*
Level 5. **Abstract entities and relationships** Definition of objects and how they are arranged and connected.	Specification of a heuristic, skeletal hierarchy of spatial entities and relationships between them.	Hierarchical constraints limit outcomes of mechanistic interactions in a particular location.	Each entity has a range of natural variability, limited by boundary conditions imposed by its position within the hierarchy.	The configuration and connectivity of entities affects system dynamics. Entities have characteristic hydrological and disturbance regimes and animal/ human influences.	Can the landscape be composed in the way suggested by the hierarchy?
Lower levels, developed for a particular landscape, iterating between ontological levels and between conceptual entities, their representation in imagery, maps, etc. and the landscape itself					
Level 4. **Spatial objects** Defining attributes of an object, supervised allocation of objects into groups.	Archetypes describing objects, object classes and relationships between objects in a particular landscape. The landscape itself is given a voice in the construction of local archetypes, conceptual models and representations/maps.	Entities can be defined by top-down constraints and/or bottom-up aggregates of constituent parts. The configuration and connectivity of constituent parts is important.	Fuzzy classification techniques accommodate fuzzy realities in which gradients and variability are more common than well-bounded, internally homogenous patches. Not all areas are equally well described by the archetypes. Not all instances of a class are equally representative of that class.	Entities have characteristic hydrological and disturbance regimes. Animal and human system components can be introduced.	Vagueness: Contestable conceptual, class and positional boundaries. Degree of similarity / difference needed to specify an object. Selection and combination of defining attributes.

Ontological level (Based on Couclelis, 2010)	***New conceptualisation***	***Complexity***	***Heterogeneity***	***Dynamics***	***Sources of uncertainty***
Level 3. **Similarities** Measureable gradients (fields); Clusters/ groups of measures	Define relevant and measurable candidate variables and explore statistical relationships between them.	Measurable and observable variables are only a subset of all variables in a cluster.	Some variables may be more/less tightly clustered than others. Not all attributes will necessarily align neatly.	Different attributes can be observed and measured at different times.	Measurement errors, required accuracy and precision. Bias introduced by observations framed in terms of archetypes.
Level 2. **Observables** Qualitative assessment	Observe environmental attributes that cluster in ways suggested by the archetype and by the landscape grain.	Fuzzy patterns resulting from self-organisation within open, complex systems.	Different environmental attributes cluster to different degrees in different landscapes.	Regularities in hydrological regimes and frequent disturbances e.g. fire, large herbivores, common human impacts.	Over/ underestimating differences. What information is relevant?
Level 1. **Granules** (lowest level) Discrete granules of time and space	Spatial and temporal scales that reveal patterns suggested by the archetypes and the landscape itself (through topographic grain and the size of patches in repeating landscape patterns).	Granules are fuzzy and heterogenous, even if they are observed as discrete, internally homogenous objects (e.g. pixels, image objects, catchments).	Granules vary in size and in the length of time they persist among different landscapes.	Granules move and change at different rates in different landscapes and at different hierarchical levels.	Are scales of observation suited to purpose and to the landscape being described?

Level 7: Purpose

The purpose of the new conceptualisation was to provide a spatial framework for the description, analysis and mapping of biophysical patterns to inform the integrated study and management of savanna systems in a way that meets challenges posed by landscape complexity, heterogeneity and dynamics.

It is widely recognised that successful collaboration among scientists, managers and policymakers working on the same landscape depends upon their adoption of a shared conceptualisation of that landscape (e.g. Pickett *et al.*, 2007; Stirzaker *et al.*, 2011). To achieve consensus, the conceptualisation must be seen as credible, relevant and legitimate by all end-users (Cash *et al.*, 2003). Although it is unlikely (if not impossible) for a single conceptualisation to meet the needs of all possible users, the conceptualisation developed in this thesis is likely to be useful and relevant to a very wide range of users because:

- Savannas are water-limited systems in which a large number of biotic and abiotic attributes are spatially and temporally clustered (Porporato *et al.*, 2002; Caylor *et al.*, 2005a; Jenerette *et al.*, 2012). So many ecological processes are limited by the availability of water that a large number of processes and attributes are spatially and temporally coupled, resulting in tight clusters of many different system components. These clusters have been recognised and described for decades, notably in Milne's (1935) catena concept, which links soil-vegetation complexes to the drainage characteristics of particular hillslope positions, describing repeating toposequences that recur on all the hillslopes within a particular climatic and geological setting.
- The wide range of ecological processes that are spatially clustered means that the description of these clusters is relevant to a wide range of applications. Even if all the processes geographically contained in each cluster cannot be disentangled, it is reasonable to assume that a patch is associated with a process domain (*sensu* Montgomery, 1999) that is distinct from its neighbours, but similar to other patches that contain similar attributes and occur in similar landscape positions.

The landscape hierarchy presented in this thesis (Section 3.6.2) provides a heuristic structure in which knowledge about the spatial organisation of river systems can be synthesised with knowledge about the spatial arrangement of savanna hillslopes at multiple scales. For example, in developing the *a priori* archetypes for granitic and basalt landscapes (Sections 5.3.1 and 5.4.1), I was able to draw upon a large body of literature that described links between patch character and generative processes from many different perspectives and at many scales (e.g. Milne, 1935; Venter, 1990; Scholes & Walker, 1993; Gillson, 2004; Wu & Archer, 2005; Caylor *et al.*, 2005b; Sankaran *et al.*, 2005; Khomo *et al.*, 2011; Miller *et al.*, 2012; Riddell *et al.*, 2012).

The ability of the conceptualisation to unite terrestrial and aquatic perspectives is particularly important, given the deep divides that exist between these realms in both science and management (Section 1.1) and repeated calls for their integration (Omernik, 2004; Driver *et al.*,

2005). In KNP, for example, separate management plans still exist for aquatic and terrestrial systems, despite calls for their integration since at least 2008 (Freitag-Ronaldson & Venter, 2008). The difficulty of uniting these perspectives stems largely from the way terrestrial ecologists and managers tend to see landscapes in terms of a spatially nested hierarchy of patches, whereas river scientists and managers focus on longitudinal flows through a network. However, these tensions can be reduced by positioning hillslope toposequences within the context of the drainage network (and *vice versa*), adding the perspectives of four-dimensional gradients of a river and networked hydrological connectivity to the idea of a patch mosaic of catenal and channel elements. Thus it is possible to describe both fluxes of energy and materials through the landscape and to describe the resources available within a particular patch. This brings together local perspectives of hillslope and channel toposequences (as described by catenal elements, see Chapter 5) and wider network perspectives (described in terms of catchments and CASSs in different network positions, see Chapter 6). Although the idea of exploring how toposequences change with network position is also not new (Huggett, 1975; Gerrard, 2000; Khomo, 2008; Rogers, K. pers. comm.), to my knowledge, this is the first time that these ideas have been developed systematically and incorporated into a heuristic landscape hierarchy that can be used to inform spatially explicit landscape classifications of savanna landscapes (Chapters 5-7).

The types of uncertainty associated with this level of the meta-ontology centre around the extent to which the conceptualisation is fit for purpose (Table 8.1). Ultimately the question of whether or not the conceptualisation can meet its stated purpose of providing a platform for the integrated study, management and policymaking of savanna systems will be answered by the extent of its uptake. Initial indications are positive, given the enthusiastic reception by the South African Water Research Commission of an initial report (Cullum & Rogers, 2011) and their subsequent funding of a project framed within the conceptualisation presented therein (Riddell *et al.*, 2014). Furthermore, South African National Parks (SANParks) have adopted the conceptualisation to inform the establishment of research 'supersites' in KNP, which will become research hubs, where archetypal patterns and processes will be studied in depth within first to third order catchments in the main physiographic zones of the park (Smit *et al.*, 2013a).

Level 6: Function

The functional level of Couclelis's meta-ontology concerns connections between the ends (the purpose) and the means of achieving those ends. In my conceptualisation the end-purpose of providing a platform for the integrated study and management of savanna systems can only be met if the framework can be used to transfer experience and knowledge between locations (e.g. from study or monitoring sites to locations that are framed as being similar). Such extrapolations need to be based on credible links between observed features and/or attributes and the processes that generate and sustain them, demonstrating that the entities mapped are not merely "boundaries that do not exist around areas that do not matter" (Kimble, 1951). This ontological level is therefore concerned with the reasons why clusters of biophysical attributes are organised in broad patterns that are structured by the drainage network and how these patterns constrain so many ecological processes.

In this thesis I have focussed on the detection and description of ecological patterns, rather than on explaining the processes that generate those patterns. Nevertheless, to build credibility in the potential utility of the conceptualisation, I needed to demonstrate the possibility of developing such explanations, particularly given the inherent uncertainties and consequent unpredictability of complex systems.

If ecological systems are acknowledged to be complex systems in which tangled webs of interactions cannot be easily separated into threads of cause and effect, then how can we link the patterns we see to the processes that generate them? How can we describe these processes in ways that allow the identification of places that are likely to respond to change in similar ways? It is clear that even if detailed process models could be constructed that describe mechanistic interactions between specific objects, they would contain overwhelming detail and contain so many time- and place- specific contingencies that learning would be impossible to transfer elsewhere (e.g. Beven, 1999; Phillips, 2004, 2007). However, Newtonian explanations in terms of mechanistic causes and effects that follow universal laws are not the only forms of scientific explanation. It is becoming increasingly clear that there are many other modes of scientific knowledge and explanation, many of which are associated with particular scale domains (e.g. Funtowicz & Ravetz, 1993; Church, 1996; Cilliers, 2005b). So-called 'Darwinian' explanations (Harte, 2002; Hrachowitz *et al.*, 2013) describe the co-evolution of landscapes in terms of a sequence of events that results from the particular constellation of spatial and historical contingencies encountered in a particular location (Beven, 1999; Phillips, 2007). This type of explanation is more akin to historical narratives (White, 2009), than to scientific explanations. Much has also been written about top-down causation and emergence in complex systems. Top-down causation is ubiquitous in ecological systems because the outcome of lower level interactions is always dependent upon context and high-level boundary conditions (e.g. Wimsatt, 2007; Ellis, 2008; Mitchell, 2009). Goldstein (2011) describes several ways in which complex system can generate new features through emergence, including phase transitions, self-organisation, mathematical emergence (e.g. bifurcations, attractors), computational emergence (e.g. neural nets and cellular automata), social emergence (e.g. internet networks) and biological emergence (e.g. speciation and morphogenesis).

Local knowledge, accumulated by farmers, fishermen and birdwatchers (and even by geomorphologists and ecologists!) is often based upon inductions from empirical experience and repeated observations of regularities (Berkes & Berkes, 2009; Wohl, 2013). Because this type of knowledge does not rely upon the simplifications and universal laws upon which deductive explanations depend, it is able to encompass the uncertainties inherent in complex systems and the idiosyncrasies of particular landscapes. A different type of generalisation is used, based on approximate or incomplete information, using rules of thumb and concepts that do not have precise boundaries and which are intricately linked in webs of complex relationships. Humans are expert at this way of thinking and knowing, which in recent decades has been formally described as 'fuzzy logic' (Zadeh, 1965, 1973).

Although this type of reasoning appears at first sight to lack the rigour of conventional scientific argument, this is far from true:

> *"Fuzzy logic is not fuzzy. Basically, fuzzy logic is a precise logic of imprecision and approximate reasoning. More specifically, fuzzy logic may be viewed as an attempt at formalization/mechanization of two remarkable human capabilities. First, the capability to converse, reason and make rational decisions in an environment of imprecision, uncertainty, incompleteness of information, conflicting information, partiality of truth and partiality of possibility – in short, in an environment of imperfect information. And second, the capability to perform a wide variety of physical and mental tasks without any measurements and any computations." (Zadeh, 2008 p. 2751)*

Zadeh neatly separates the concept of precision from that of sound argument, articulating in mathematical form how we communicate and reason in shades of grey rather than in black and white, and how fuzzy linguistic variables that can enclose various degrees of size, value, truth and possibility can describe our inherently fuzzy world far better than the bivalent variables that dominate much of science and mathematics:

> *"Science deals not with reality but with models of reality. More often than not, reality is fuzzy. For this reason, construction of realistic models of reality calls for the use of fuzzy logic rather than bivalent logic." (Zadeh, 2008 p. 2770)*

Given the fuzziness of all ecological systems (a consequence of their complexity), it makes sense to describe and explain these systems using fuzzy logic. Indeed, many people have embraced this way of thinking, such that fuzzy classification is now widely used in both geomorphic mapping and DSM (e.g. Burrough, 1989; Fisher *et al.*, 2004). However, the use of fuzzy logic is less widely acknowledged.

Fuzzy logic uses linguistic variables (e.g. very tall, tall, short) alongside numerical variables, employs fuzzy conditional statements (e.g. If x is very large than y is very small and z is approximately circular) and fuzzy algorithms, such as superimposed constraints or ordered sequences of events (Zadeh, 2008). According to Zadeh (2008), the cornerstones of fuzzy logic are:

- Graduation - everything is allowed to be a matter of degree (or 'fuzzy').
- Granulation - attributes are clumped in termed of their similarity, proximity, functionality, suitability for purpose or in terms of some other criterion.
- Generalised constraint - of possibility, probability or truth.
- Precisiation - a process in which an object becomes progressively more precisely defined, either in terms of meaning or value (in the mathematical, not the normative sense of the word).

This type of reasoning is the same as that used by geomorphologists and soil scientists when 'reading' the landscape, interpreting new landscapes against a backdrop of accumulated experience and knowledge (Fryirs & Brierley, 2012; Brierley *et al.*, 2013; Wohl, 2013). The links made between form and process are not precise or easily described in process models. Instead they are adaptable approximations, capable of incorporating inconsistencies, incomplete information and partial truths. Such framings are just as Zadeh describes fuzzy logic: the

process of adapting a general model to particular circumstances is a process of precisiation, whilst recognising contextual constraints on attributes and processes is a form of articulating generalised constraints.

In my conceptualisation, links between pattern and process are described in terms of mental models, borrowed from soil scientists and geomorphologists, who use fuzzy logic and techniques of precisiation to link form to process and abstract models to particular instances. Both form/process and general/particular are linked via archetypes that describe key system components and the processes and interactions between components that produce the patterns we observe. Not only can features be assessed in terms of their similarity to an archetype (which itself can be specified with more or less precision), but local processes and evolutionary narratives can also be more or less similar to archetypal mental models. Whereas considerable attention has been paid to the use of fuzzy classification to describe the similarity of *features* to archetypes, far less attention has been given to the notion of describing similarity to the archetypal *processes* of landform evolution described in every physical geography textbook. For example, it is likely that the hydrological flows and processes described in the archetypal granitic catena (Section 4.12.3) vary in the different expressions of that archetype found in the N'waswitshaka granite study site: the hydrological regime associated with woody midslopes will differ from that associated with grassy midslopes. It is only by understanding the effect of these variations on an underlying process model that it becomes possible to hypothesise which differences are likely to 'matter'. Once these variations in process are described and understood, local contingencies or differences in initial conditions can be identified that are likely to generate outcomes in response to management or environmental changes (e.g. changes in rainfall, elephant density, fire frequency, etc.) that differ from those resulting from archetypal processes. Thus ecological surprises can be reduced, even if system complexity dictates that they can never be eliminated (Harris & Heathwaite, 2012).

The translation of geomorphological mental models linking form and process into fuzzy logic and detailing the procedures of precisiation used to apply these models to particular landscapes is a task that falls outside the scope of this thesis. For my purposes, it is sufficient to see the possibility of so doing.

In addition to addressing issues of translating imprecise models and reasoning into more formal fuzzy logic, a further challenge lies in the fact that different sets of variables cluster at different scales in different landscapes. A difference that might be considered a subtle nuance in one landscape can become a key difference in another geoclimatic setting or with a different set of dominant disturbances. For example, the changes in gradient that differentiate terrain units in basaltic plains are far smaller than those that characterise different hillslope units in more finely dissected granitic landscapes (see Chapter 5). In addition, clusters are constantly changing at many scales, following a trajectory that is shaped by a myriad of multi-directional interactions at multiple scales. Some form of generalisation is needed to reduce this complexity to make it amenable to science and management. However, this generalisation needs to retain sufficient flexibility to encompass the very heterogeneity it seeks to describe,

but without becoming so flexible that 'anything goes', leading to potential fragmentation of perspectives and a breakdown of the consensus upon which a shared perspective depends.

The flexibility needed to capture local differences is attained by the use of a skeletal hierarchy that defines abstract spatial entities in ways that are grounded in widely accepted theory. The hierarchy can then be populated in different ways for different landscapes, using scales, variables and features that are appropriate to a particular location, as illustrated in Chapters 5-7.

Level 5: Abstract entities and relationships
At this ontological level, spatial entities and the relationships between them are defined. I constructed a three- level hierarchy, drawing heavily on hierarchy theory:

- ***Catenal elements***: Units within individual hillslope toposequences, together with associated river reaches.
- ***Catchments***: Assemblages of these units within a catchment (which may be defined as a CASS or catchment draining streams of different orders).
- ***Physiographic zones***: Different drainage network configurations that contain repeating patterns of similar assemblages of catenal elements and which reflect distinct climatic/geological zones.

The entities described at each hierarchical level are not randomly generated patterns, but are conceived as process domains, in which products of the co-evolution of various attributes and features result from a tangled web of interactions. As in many complex systems, these processes and patterns self-organise to form a somewhat predictable structure that is imposed by contextual constraints on variability (e.g. Rinaldo *et al.*, 1993; Rigon *et al.*, 1994; Levin, 2005) and which is described by horizontal and vertical relationships within the hierarchy (see Section 3.6.2). The dual perspectives of mechanistic interactions at lower levels, constrained to a natural range of variability imposed by higher organisational levels in the hierarchy provide a way of reconciling reductionist and holistic perspectives. Furthermore, conceptualising landscapes in terms of a hierarchy of process domains provides a way of extrapolating these contextual constraints across time and space. This is achieved through the assumption that all elements contained within a certain higher level element and bounded by similar neighbours are constrained in the same way, and are therefore likely to have similar characteristics and behaviour (cf. the dominant process concept in hydrology, e.g. Sivakumar 2004).

Landscape entities are not conceived as static, but as dynamic patches in an ever-changing mosaic. Each entity can not only be characterised in terms of spatial regularities in environmental attributes, but also in terms of temporal regularities in hydrological fluxes, common disturbances (e.g. fire) or the impacts of animals (e.g. the construction of burrows or spawning beds) or humans (e.g. the extraction or damming of water for irrigation).

The concept of a range of variability that is constrained by context (see Section 3.4.1) can be well articulated in fuzzy logic (see discussion of generalised constraints in Zadeh, 2008). Furthermore, fleshing out the skeletal archetypes described in an abstract hierarchy into the

more detailed archetypes that describe a particular landscape is a clear case of precisiation, in which an object becomes successfully more precisely defined, in terms of language and meaning as well as in terms of measurable attributes.

The skeletal, abstract hierarchy is based upon structural features that are present in all savanna landscapes: even the flattest of landscapes that appear to have no toposequences can be characterised in terms of channels and interfluves (see, for example, the classification of the KNP Nhlowa basalts in Section 5.4.6). This has two important and interrelated implications.

Firstly, a hierarchy based on abstracted landscape features does not prescribe set scales and defining attributes for each spatial entity. Instead, it provides a conceptual window through which many different landscapes may be viewed, each at their own scales and with their own attributes. This approach maximises the opportunities for ecological clusters to be detected and mapped in each and every landscape. For example, a range of different vegetation attributes characterise differences between crests and midslopes in the southern granites of KNP (Section 5.2.3). Whilst granitic landscapes near Skukuza are characterised by crests with relatively dense woody cover of taller *Combretum spp.* and midslopes have relatively sparse woody cover, dominated by shorter *Acacia spp.*, the dominant woody species on both crests and midslopes of granitic landscapes near Pretoriuskop is *Terminalia sericea*, which tends to grow more densely on crests than on midslopes, but to a similar height in both hillslope positions (Venter 1990 and personal observations). By contrast, although there was a weak relationship between tree height and hillslope position in the Nhlowa basalt study area, trees are too sparse and the differences too subtle to use any vegetation characteristic as a measurable attribute capable of differentiating between crests and footslopes in this area (Section 5.4.3).

Secondly, the choice of spatial entities into which a particular landscape is decomposed is largely informed by the landscape itself, rather than being totally dependent on subjective judgements. These provides a somewhat neutral basis for landscape classification, moving a long way towards gaining consensus around the otherwise vexed issues of scale and attribute selection. For example, different scales were needed to describe the morphology of terrain units in different hillslope positions in the two study areas: TPI (Topographical Position Index) was calculated over a distance of 850m to describe the long hillslopes of the Nhlowa basalts, whilst 300m sufficed to capture differences across the much shorter hillslopes in the N'waswitshaka area (Section 5.3.4 and Section 5.4.4). Vegetation patterns played different roles in the definition of catenal units in each area. In the N'waswitshaka granites, vegetation differences were key in separating crests from midslopes and in delineating the riparian strip (Section 5.3.6). However, in the Nhlowa basalts, vegetation differences were far less distinct, such that catenal elements were derived mainly in terms of gradual changes in morphology (Section 5.4.6).

Sources of uncertainty associated with this level of the conceptualisation centre around the extent to which savanna landscapes can be decomposed into the units described by the hierarchy (Table 8.1). This question has two sides. On the one hand, it concerns the extent to which landscapes actually are as well- organised as the hierarchy suggests. On the other hand,

it also asks about how well and unambiguously the hierarchy informs the identification and delineation of units at each organisational level. These questions are addressed below (Section 8.4) in my review of the implementation of the conceptualisation to inform classifications of landscapes in KNP.

Levels 1-4: Granules, observables, similarities and simple objects
The lower levels of the Couclelis ontology involve applying the broad conceptual model developed thus far to particular landscapes (Section 3.7 and Table 8.1). In developing, specifying and classifying spatial objects that describe KNP landscapes at the various levels of organisation of the hierarchy described above, I found that an iterative process was needed between top-down and bottom-up conceptualisations and observations. Couclelis proposes that geographic ontologies are developed 'top down', narrowing choices at each level as semantic content is reduced, starting with purpose and finishing with observations of atomistic units that define simple objects (see Table 3.1). Although this approach may describe the construction of ontologies by computer programmers who are responding to a purpose-oriented brief, this prescriptive process forecloses opportunities for the landscape itself to inform cartographical decisions.

Rather than moving steadily down the ontological levels, I found myself repeatedly moving both up *and* down the lower Couclelis levels when applying the conceptualisation to KNP landscapes:

1. Framing descriptions of the spatial entities defined in the hierarchy in terms of *a priori* archetypes (Level 4 'simple objects'), then

2. Qualitatively looking for patterns and regularities in the attributes that characterise these archetypes, using all available imagery at resolutions that provided sufficient detail to see the anticipated patterns (Level 2 'observables' and Level 1 'granules'), then

3. Selecting measurable candidate variables that appeared to be associated with the qualitatively observed patterns (Level 3 'similarities'), then

4. Segmenting the imagery in which patterns were observed into 'image objects' that were relatively homogenous with respect to all these variables (Level 1, 'granules'), then

5. Describing these objects in terms of the candidate variables identified at step 3, and identifying those variables that were both highly correlated and which efficiently described the expression of the archetype found in the particular landscape being described and in the imagery available (Level 3 'similarities'). During this process, the archetype was adapted and refined in the light of the emerging description of observed patterns (Level 3 'similarities' and Level 4 'simple objects').

6. Finally, rules were developed to aggregate and classify image objects into the spatial entities defined by the archetypes (Level 3 'similarities').

At the start of such a procedure, the nature of a spatial entity to be described is specified only by its position in the landscape hierarchy, which guides the initial choice of imagery and the scale at which patterns are expected to be observed. For example, we may only know at this stage that we are looking for a series of catenal elements. However, this description is sufficient to guide observation towards regularities in vegetation patterns that are associated with hillslope positions, occurring in predictable positions within the drainage network. In some circumstances, a body of literature or knowledge exists that describes these patterns in more detail, and maybe even go as far as to hypothesise general principles that are responsible for these patterns (as was the case in my KNP study sites, see Section 4.12.3). All this knowledge, observation and experience is synthesised in the construction of archetypes, which add detail to the landscape hierarchy and customise it for application in a particular location.

The development of these local archetypes is an ongoing process, since knowledge about the archetype can be added at any stage and the archetype is slowly adapted and refined as new knowledge, experience and/or observations are added. This process allows local understandings to be constructed within a general framework, such as the original unpopulated, abstract landscape hierarchy. In this process of precisiation, knowledge that is accumulated around an initially fuzzy archetype becomes more detailed and precise as the archetypes are applied to a particular instance at a particular place and time. This process involves an interplay between top down (theory-based) and bottom -up (empirical, observation based) perspectives in a way similar to that described by Richards and Clifford (2011). The use of adaptable archetypes to guide this process is essential, since the use of standardised archetypes or taxonomies would prohibit this interplay.

An analogous process is used to represent these archetypes in landscape classifications and maps. Repeated iteration between a theoretical, abstract *a priori* archetype and observed patterns of correlated environmental attributes is involved in the construction of the rules that aggregate and classify image objects into the spatial entities depicted on a map (Table 8.2). Again, the adaptability of archetypes in the light of the local heterogeneity of the landscapes studied is an important feature of this approach. The implementation of a standardised and fixed classification would allow no such flexibility, forcing landscapes to fit into predetermined classes, rather than allowing the classification to be largely dictated by characteristics of the landscape itself.

The methods and techniques used in each case are not the only possibilities. For example, had different sets of imagery been available for the two study areas, either showing different attributes (e.g. soil colour or tree species) and/or showing the same scene at different times (e.g. with more/ less surface water, or trees in leaf or bare, etc.), then different variables would have emerged as appropriate to separate the catenal elements and they would have been combined in different ways to produce the maps. However, the underlying assumption of the conceptualisation is that so many attributes are coupled that many different variables can be used to describe the same spatial entity. This flexibility, derived from the spatial persistence of the described entities also allows additional data to be added into the map over time. This allows for ongoing precisiation of archetypes, both in terms of increasing the number of

dimensions in which they are described, and in terms of more precise measurements and parameters that are tailored to a particular landscape.

The sources of uncertainty associated with the lower levels of the conceptualisation centre on the accuracy with which a particular landscape is represented in a map, using the conceptualisation specified by the higher levels. Uncertainties are associated with the variables selected to represent archetypes, the scales at which they are mapped and the precision of the data used. All of these factors are generally considered together in the evaluation of landscape classifications and maps through groundtruthing. A random sample of points is selected and a comparison is made between the true class of each point, as observed in the field, and that assigned in the classification (e.g. Congalton & Green, 2008). However, this type of evaluation is inappropriate for fuzzy classifications where there are degrees of class membership and classes can overlap. In fuzzy classifications, it is recognised that landscapes patches may have affinities to two or more classes, or they may not fit well into any of the defined classes. Fuzzy classifications are therefore better evaluated in terms of a qualitative assessment of user acceptability (Woodcock & Gopal, 2000). It was not feasible to formally undertake such an assessment for this thesis, but a group of experts gathered for a workshop in March 2010 to introduce my conceptualisation and classification agreed that the approach both accurately reflected differences seen in the field and was also likely to prove very useful (see acknowledgements for participant list).

Table 8.2: Moving iteratively between the lower ontological levels.

Procedures adopted when applying the abstract hierarchy to real landscapes at the hierarchical levels of catenal elements, catchments and physiographic zones involved iteration between the four lower levels of the Couclelis meta-ontology (spatial objects, similarities, measurable and observables).

	Catenal Elements	***CASS/ Catchments***	***Physiographic Zones***
1. Defining *a priori* archetypes	Archetypes constructed from literature, field observations and initial impression of available imagery (Section 4.12.3).	Catchment and CASS archetypes are defined in terms of stream order and assemblages of catenal elements described in the literature and observed in the field and in imagery (Section 4.12.3).	*A priori* archetypes of landscape dissection were informed by a cluster analysis of morphological attributes of low-order CASSs (Section 7.2.5).
2. Qualitatively looking for patterns in the attributes that characterise these archetypes	*N'waswitshaka granites:* Changes in relative canopy cover/ vegetation density appear to be associated with hillslope position in the way described by the *a priori* archetype (Section 5.3.6). *Nhlowa basalts:* Vegetation height, rather than cover was most clearly associated with hillslope position. However, apart from tall trees near some of the streams, changes in gradient and vegetation were very gradual and not clearly visible to the naked eye (Section 5.4). Most of the terrain appeared to be occupied by flat crests that contained pans and clusters of vegetation that did not appear to be systematically related to hillslope position or distance from the nearest stream. However, valley bottoms and footslopes were clearly evident, as described by the archetype. However, the densely forested 'valley bottoms' described by Venter (1990) appear to be associated with higher order streams and were not visible in the study area. (Section 5.4.6).	*N'waswitshaka granites:* Many toposequences of catenal elements resemble the *a priori* archetypes (Section 6.3.3). *Nhlowa basalts:* The extensive crests, wide valley bottoms, discontinuous channels and small footslopes described in the priori archetype were observed throughout the study area (Section 6.4.3).	Different stream densities and relief are clearly associated with the different geologies of KNP and with Venter's land systems and land types, but do not correspond exactly. In particular, the hierarchical separation of land systems and land types is not reflected in patterns of landscape dissection. In some cases, different geologies have similar patterns of landscape dissection. Some geologically distinct zones are too small to contain fully developed stream networks that can be used to characterise a physiographic zone. Hence physiographic zones need to be defined in terms of landscape dissection AND geology (Section 7.2.6).

	Catenal Elements	***CASS/ Catchments***	***Physiographic Zones***
3. Selecting measurable 'candidate' variables	*N'waswitshaka granites:* Pan reflectance in SPOT5 imagery was a good proxy for vegetation cover (Figure 5.11), whilst SPOT5 NDVI and NIR clearly separated water and bare patches (Box 5.1). TPI calculated over entire hillslopes (300m), and 'long range' gradient and curvatures measured over 185m revealed morphological differences between the various parts of hillslopes. 'Local' gradients and curvatures distinguished stream banks and locally steep koppies and midslopes (Section 5.3.4). *Nhlowa basalts:* LiDAR imagery was needed to calculate % canopy cover at various maximum heights within a 11m radius of each pixel. Hillslope morphology was seen in TPI with a 850m radius, whilst TPI, gradient and curvatures over 49m distinguish footslopes and detailed channel topography (Sections 5.4.3 and 5.4.4).	Catenal elements formed the basic units of assemblages within catchments and CASSs (Section 6.1).	Landscape dissection was described in terms of the relief, area and gradient of first and second order CASSs (Section 7.2.3).
4. Segmenting imagery into 'image objects'	eCognition (Trimble, 1995) was used to automatically segment imagery into image objects that were relatively homogenous with respect to selected variables. *N'waswitshaka vegetation*: Resolved using multiresolution segmentation of SPOT 5 pan layer (Scale parameter 50, then 30). Morphometric layers were added (4.48m DEM, TPI over 300m, gradient over 15m and 185m, and plan and profile curvatures over 85m) and an even finer scale (parameter 10) used to segment the image objects used to classify terrain units (Sections 5.3.3 and 5.3.4). *Nhlowa vegetation:* SPOT pan, NIR and red layers, canopy height, TPI (851m and 49m), gradient, profile and plan curvatures (49m) all contributed to the segmentation of image objects at a very fine scale (parameter-3) (Sections 5.4.3 and 5.4.4).	Catchments and CASSs were derived from the 90m SRTM data and the stream network depicted on 1:50 000 topographic maps (Section 6.2).	First and second order CASSs were used as the basic unit, effectively inversely weighting variables by drainage area, but allowing the landscape itself to set the resolution used for classification. Since CASSs in different geological settings are of very different sizes, this means that the resolution varied across the landscape (Section 7.2.3).

	Catenal Elements	***CASS/ Catchments***	***Physiographic Zones***
5. Describing these objects in terms of the candidate variables identified at step 3	*N'waswitshaka:* A special procedure was developed to capture relative vegetation cover differences between crests and midslopes (Section 5.3.3, Box 5.1). Terrain units were fuzzily defined in terms of morphological variables that separated hillslopes in a way that reflected vegetation differences (Section 5.3.4, Table 5.2). *Nhlowa*: Canopy height classes were based on visual inspection of relationships with hillslope position (Section 5.4.3, Box 5.2) Terrain units separated hillslopes into the units suggested by the archetypes (Section 5.4.4, Table 5.2). However the transition between crest and footslope was blurred, with no abrupt transitions or visible vegetation associations. An additional midslope class was inserted in a fuzzy classification of terrain units (Section 5.4.5).	Assemblages of catenal elements within catchments and CASSs were described in terms of a) the presence/ absence of catenal elements and b) the proportion of catenal elements that conformed to the *a priori* archetype (Sections 6.3.3 and 6.4.2).	Landscape dissection archetypes were constructed from the characteristics of clusters of relief, area and gradient within first and second order CASSs (Section 7.2.5).
6. Rules to aggregate and classify image objects into spatial entities suggested by the archetypes	*N'waswitshaka*: Vegetation classes and terrain units were intersected to produce catenal elements. A new archetype of 'riparian trees' was developed by merging relatively woody image objects that were located in low-lying parts of the landscape. Unvegetated objects on toeslopes (together with low-lying neighbours) were assumed to be sodic sites. The final image was then smoothed by applying a majority filter over a 25m radius and merging units <1ha (Section 5.3.6). *Nhlowa*: Vegetation differences between terrain units were too subtle and gradual to clearly distinguish between catenal elements. The final classification was therefore based on the terrain units. However, because there was no difference in vegetation classes found on crests and midslopes (Section 5.4.5 and Figure 5.35), these classes were merged. Microfeatures (pans and channels) were removed before the image was smoothed by applying a majority filter over a 25m radius and merging units <1ha (Section 5.4.6, Figure 5.3.6).	Catchments and CASSs were classified in terms of the assemblages of catenal elements they contained (Sections 6.3.2 and 6.4.2). *N'waswitshaka*: Grassy toeslopes and sodic sites were only seen in higher order CASSs (Figure 6.10). First order CASSs were most similar to the archetype, whilst higher order CASSs tend to conform less well (Section 6.3.3). *Nhlowa*: No differences in catenal assemblages were observed between different order CASSs (Section 6.4.3). In neither study area was there any evidence for vegetation patterns associated with different order streams that were superimposed upon each other (Sections 6.3.4 and 6.4.4).	Fuzzy classification of these archetypes was used to generate a geographically coherent map of landscape dissection classes. This map was smoothed by applying a majority filter over a 445m radius and then eliminating zones <1km^2 (Section 7.2.6). Intersecting landscape dissection map with geology yielded 87 potential physiographic zones, many of which occupied very small areas. Classes occupying less than 150km^2 across the whole park were merged with their most similar neighbours, reducing the number of classes to 27 (Section 7.2.6).

Thinking about the ways in which landscape classifications might be evaluated raises concerns related to the flexibility of my approach. Whilst flexibility is needed to accommodate the idiosyncrasies of each landscape encountered, the approach taken for each landscape also needs to be both rigorous and soundly based to win consensus from end users.

Although the approach is highly flexible, it is not the case that 'anything goes'. In the first instance, classification and mapping are constrained by the hierarchy, which demands that catenal elements are related to hillslope position and are situated within catchments and that physiographic zones show distinct patterns of landscape dissection. Secondly, constraints are introduced by the landscape itself. At the level of catenal elements, scales of observation and variables selected are largely determined by the landscape itself, as viewed in available imagery, through the window provided by *a priori* archetypes constructed in accordance with the conceptual hierarchy. Iteration between imagery and the archetypes informs appropriate scales and variables, as described in Table 8.2. Based on the assumption that any spatially correlated morphological or vegetation characteristic can be used to describe catenal elements (Section 5.1), initial qualitative observations of coupled attributes are confirmed by statistical analysis before variables are chosen for the definition of catenal elements and rule sets are constructed (Sections 5.3.5 and 5.4.5).

Both catenal elements and the catchments that form the basic units of analysis for physiographic zones are units whose size and shape are determined more by the nature of the landscape than by subjective judgements on the part of the cartographer. Ultimately, it is the landscape grain, as seen in the typical length of hillslopes that show recurring toposequences of morphology and vegetation, that determines the appropriate scale of observation for catenal elements and the scale at which streams and catchments should be delineated (Sections 5.2 and 8.5.3 below). Thus, although the definition of catenal elements is always open for refinements and improvements, both archetypes and their representation in maps are ultimately judged in terms of how well they describe the actual landscape.

There is more judgement involved in the construction of physiographic zones, in that there are many possible ways of identifying and describing clusters of catchments with similar properties that distinguish between areas with different patterns of landscape dissection. However, this is partly a reflection of the top-down approach to classification that was used in this thesis. If this approach was complemented by a bottom-up method to identify areas with similar assemblages of catenal elements, the results would be more constrained.

My aim in this thesis has been to develop the foundations of a new way of thinking about savanna landscapes, building the scaffolding for much larger project. In this section I have sought to demonstrate that the scaffolding is robust, that the conceptualisation is complete and internally coherent. I now ask whether it works in terms of informing a classification that addresses the challenges posed by system complexity, heterogeneity and dynamics.

8.4 Lessons from the classifications of KNP landscapes

The evaluation of most classifications involves extensive groundtruthing to see whether or not class definitions have been correctly applied. However, the evaluation of my classification of KNP landscapes demands quite different scrutiny, since it is the classification scheme itself that needs assessment, rather than the accuracy of its application. In this section I assess my KNP classifications from two points of view:

- How well did the classification scheme describe the landscape?
  Was the landscape decomposable into the units suggested by the hierarchy? To what extent do landscape patterns actually correspond to the archetypes suggested by the hierarchy?
- How well do the classifications address the challenges posed by system complexity, heterogeneity and dynamics?

8.4.1 How well did the classifications describe the landscape?

This question concerns the extent to which landscapes actually are organised in the way the hierarchy and archetypes suggest. If patterns of savanna vegetation are indeed organised by the drainage network in the ways suggested by the conceptual hierarchy, the following patterns should be evident in KNP:

a) Systematic association of vegetation characteristics with hillslope position (catenal elements)

In the N'waswitshaka granite study area, 80% of the study site was classified into classes that correspond to the archetypes linking vegetation patterns with particular hillslope positions (Section 5.5.1). However, in the Nhlowa basalts, vegetation patterns were much more weakly associated with hillslope positions. Although trees over 0.5m high are more likely to be found on footslopes (42% of sampled points) compared to crests (25%) or valley bottoms (21%) (Figure 5.35), it was not the case that some catenal elements were dominated by trees and others by grass, as in the N'waswitshaka granite study area. Catenal elements were therefore defined solely in terms of morphological characteristics, rather than using a combination of vegetation and morphology.

These results raise issues around the selection of defining variables for catenal elements. Although the conceptualisation suggests that many different attributes are spatially aligned in catenal elements (Section 5.1), not all of these attributes are visible in remotely sensed imagery. Not only are soils and water fluxes expected to differ between catenal elements, but personal observation suggests that very different assemblages of grasses are associated with catenal elements in both study sites. Further fieldwork is needed to establish the suite of characteristics associated with each element and the extent to which these attributes are spatially aligned with each other. Such work is currently being undertaken in connection with the KNP Supersites project (Smit *et al.*, 2013a).

b) Systematically repeating patterns of assemblages of catenal elements within catchments and CASSs

In the N'waswitshaka granite study area, just under half (46%) of CASSs have (mostly) grassy midslopes and woody crests, as suggested by the archetypal toposequence (Table 6.5). Exceptions to the archetype fall into two categories. Firstly, there are many exceptions that are systematically related to landscape organisation. For example, CASSs that occupy low-lying areas between tributary junctions often lack crests (almost) completely, since the upper parts of the hillslope drain into the tributaries (Section 6.3.3). These can be considered as truncated CASSs, in which midslopes, toeslopes and channels are similar to the archetype in both character and behaviour. The current suite of archetypes could be adjusted to accommodate such systematic differences. The second category of exceptions involves CASSs with woody midslopes, grassy crests or bare rock koppies (inselbergs). In these situations, the hydrological fluxes described in the conceptual models associated with the archetypes (Section 4.12.3) are unlikely to hold and completely new archetypes need to be developed.

Whether or not it is worthwhile developing archetypes for small anomalous areas that lie within a larger physiographic zone depends on whether or not such areas warrant separate scientific study or management actions. Whatever that decision may be, it is still important to appreciate the extent to which the archetypes in a particular area actually correspond to the archetypes used to describe and manage them, pinpointing the areas where models and assumptions are less likely to apply.

Landscapes in the Nhlowa basalts consist almost entirely of large crests, which show no systematic pattern of variations in topography or vegetation that relate to hillslope position. However, footslopes and valley bottoms show recurring attributes that characterise the mapped catenal elements and which suggest that the archetype applies consistently throughout the study area (Section 6.4.3).

In neither study area was there any evidence for toposequences associated with high order catchments being superimposed upon the patterns associated with CASSs (Sections 6.3.4 and 6.4.4). This suggests that controls on vegetation (and presumably soil) patterns probably relate to height above the water table rather than elevation. This hypothesis can now be tested in the supersite catchments and also by more precise analysis of changes in vegetation related to height above the nearest stream (as in Baldeck *et al.*, 2014). In turn, these observations and analyses could be used to further refine the archetypes of catenal elements and assemblages of elements, leading to more accurate maps and models of local landscape evolution, thereby improving the foresighting of likely future trajectories under various scenarios (as in Bohn & Kershner, 2002; Gaines *et al.*, 2013, for example),

c) *Systematic variations in the configuration of these toposequences within a stream network (i.e. headwater subcatchments contain different assemblages of catenal elements compared to subcatchments found further downstream).*

In the N'waswitshaka granite study area, higher order CASSs were more likely than low-order CASSs to have larger channels and banks and to contain catenal elements associated with floodplain development (i.e. sodic sites and grassy toeslopes) (Table 6.4). The presence of these elements is likely to alter hydrological fluxes, as anticipated in the *a priori* archetypes for this area (Section 4.12.3).

In the Nhlowa basalts, no difference was seen in the configuration of catenal elements in different network positions, as was suggested by the archetypes (Section 6.4.3 and 4.12.3). This supports the hypotheses that there is little lateral near-surface movement of water (and consequent difference in soil moisture and vegetation) away from the valley bottom and its associated footslope, either across crests or between CASSs.

d) *Different assemblages of catenal elements characterising each physiographic zone.*

The delineated physiographic zones broadly corresponded to the zones previously identified by both Venter (1990) and Gertenbach (1983) as containing distinctive toposequences of vegetation (Section 7.4). This correspondence offers broad-scale validation of the approach and procedures I used to delineate physiographic zones.

Although there was strong evidence of systematically organised, recurring patterns at each hierarchical level that do correspond to the proposed hierarchy and archetypes, I found considerable variation in the extent to which the conceptualisation accurately described the whole landscape. Although some scope for improving the archetypes has been identified, this variation largely reflects diversity in the landscapes studied. For example, catenal elements in the Nhlowa basalt study area are far more homogenous than those in the N'waswitshaka granite study area and correspond more closely to their archetypes (Section 5.5.1).

Detailed mapping of individual toposequences of catenal elements opens the possibility of identifying specific areas where the archetypes apply well and areas where the archetype applies poorly or not at all. In the past, it has generally been assumed that classifications apply equally well across an entire landscape, so that soil landscape or catenal models can be used with impunity to describe processes across large areas. Understanding where these models do not apply is as important for many applications as understanding where they do apply. For example, sample, monitoring or reference sites need to be selected that are as representative as possible of the class archetype. Similarly, the spatial extrapolation and modelling of observations, knowledge and experience from these sites needs to take account of within-class similarities and differences to the archetype. These similarities and differences are likely to reduce ecological surprises, by pinpointing locations where extrapolations and models are more or less likely to apply. Surprises could be further reduced by identifying those differences that are most likely to influence a particular process of interest. However, this step relies on the availability of detailed understanding of the processes involved, together with the effects of changes in drivers, controls and contextual constraints.

System complexity, heterogeneity and dynamics all militate against the acquisition and extrapolation of such detailed reductionist explanations. How then can the demand for maps that facilitate spatially explicit extrapolations be reconciled with the challenges raised by these issues?

8.4.2 How well do the conceptualisation and derived classifications meet the challenges of system complexity, heterogeneity and dynamics?

Complexity

The complexity 'turn' (Urry, 2005) seriously challenges classical landscape conceptualisations and approaches to classification that are framed by reductionist perspectives (Sections 1.1 and 8.1). However, the adoption of constructivist or relativist approaches lead to fragmented views of landscapes that both deny the reality of clustered attributes and processes and fail to provide the integrated perspectives demanded by ecological scientists, managers and policymakers (see Chapter 2). In this thesis I have sought to gather together strategies and tools that can be used to reduce the tensions between the needs to:

- Generalise and simplify to share knowledge and extrapolate findings in time and space and
- Recognise the impossibility of disentangling 'causal thickets' (Wimsatt, 1994) and the potential importance of local contingencies.

This tension has been described not as a 'problem to be solved', but as a 'condition to be lived with' (Preiser, 2012). This position derives from an appreciation of the need to conceptualise and model complex systems alongside recognition of the impossibility of describing or modelling a complex system in its entirety:

> *".. because complex systems are open systems, we need to understand the system's complete environment before we can understand the system, and, of course, the environment is complex in itself. There is no human way of doing this. The knowledge we have of complex systems is based on the models we make of these systems, but in order to function as models – and not merely as a repetition of the system – they have to reduce the complexity of the system. This means that some aspects of the system are always left out of consideration. The problem is compounded by the fact that that which is left out, interacts with the rest of the system in a non-linear way and we can therefore not predict what the effects of our reduction of the complexity will be, especially not as the system and its environment develops and transforms in time." (Cilliers, 2005a p. 258)*

The reduction of complexity entails choices:

> *"We cannot have complete knowledge of complex systems; we can only have knowledge in terms of a certain framework. There is no stepping outside of complexity (we are finite beings), thus there is no framework for frameworks. We choose our frameworks. This choice need not be arbitrary in any way, but it does mean that the status of the framework (and the framework itself) will have to be continually revised. Our knowledge of complex systems is always provisional. We*

have to be modest about the claims we make about such knowledge." (Cilliers, 2005a pp. 258–9)

In other words, neither my conceptualisation, nor any other, can claim to be the only possible perspective that provides an integrated view of landscapes. At best, the narratives that support the conceptualisation can only claim that it offers a useful heuristic device, a starting point for discussion and collaboration.

Reductionism is also implicit in the hierarchical framing and in the singular emphasis on biophysical archetypes that are central to my conceptualisation. Both heuristics entail the simplification and approximation of real world situations in exchange for the ability to compare and group landscapes to share knowledge and experience among different locations. However, both heuristics create perspectives that enable us to reach outside a wholly reductionist paradigm. By invoking a hierarchy, we are able to understand and explain phenomena both in terms of low-level mechanistic processes and in terms of higher-level and neighbourhood contextual constraints (Allen & Starr, 1982). By invoking archetypes, we are able to move away from bivalent concepts and relationships into a world of fuzzy logic, in which everything is graded and both objects and processes can be described and explained in a more or less precise manner, as circumstances require (Zadeh, 2008). Both of these perspectives offer new ways of thinking about cause and effect that are more helpful than classical reductionist approaches when dealing with complex systems (Wimsatt, 1994; Mitchell, 2009).

The conceptualisation is not only reductionist by virtue of its incompleteness and its use of simple conceptual models, it is also reductionist in terms of its atomism. Physiographic zones are constructed from catchments and catchments contain assemblages of catenal elements: units at upper levels of the hierarchy can be decomposed into lower level units. In each case, much of the character and behaviour of landscape units can be inferred from the character and behaviour of its constituent units. For example, many character traits and behaviours of a physiographic zone consisting of assemblages of catchments similar to those found in the Nhlowa basalt study site can be inferred from studies in Nhlowa. However, other emergent properties are less easily inferred: for example, a vast area of Nhlowa -like catchments could well develop its own microclimate, or attract large herds of herbivores, or the extensive flat lands could provide good sites for building roads or cities Furthermore, the variability within the physiographic zone cannot be inferred from the study of one example: subtle ways in which catchments within the zone differ to the archetype may have profound implications for the character and behaviour of the entire zone. Thus, while the atomistic view allows valuable insights and extrapolations, it only reveals part of the picture.

The atomist perspective proposed in this thesis also differs from classical atomism in that the lowest levels of the hierarchy do not consist of indivisible units with self-evident and incontestable boundaries. Catenal elements are formed by aggregating artificial image objects that have been created by segmenting multiple GIS data layers into relatively internally homogeneous virtual objects. Although the choice of the layers to be used and the scale at which they are overlaid and aggregated are informed by observations and analyses of local landscape characteristics that are framed by an *a priori* archetype, many decisions remain the

responsibility of the cartographer. The boundaries of these virtual basic objects' are highly contestable, they can potentially be defined at many scales and may or may not form clusters that are useful ways of partitioning landscapes. Although it might be argued that the hierarchy could be extended down to atomic and sub-atomic particles, the nature of the intervening units is not self-evident: should they consist of soil pedons with associated vegetation and hydrology, or trees with associated soils and water budgets? Should we consider individual leaves, water packets and/or soil particles? How is the integrated nature of the hierarchy to be preserved at small scales? I would suggest that such discussions are not relevant to the purposes of this hierarchy, which does not seek to describe and explain the entire world, but only to provide a heuristic framework for the integrated description of biophysical patterns at the 1-100km^2 and decadal scales that are most relevant to land managers and policymakers (see Section 3.4.1).

Although it is acknowledged that the conceptualisation itself and classifications derived from it are contestable, I have aimed to allow the landscape itself to have a loud 'voice' in the narratives that justify their adoption. For example, at each hierarchical level, the atomistic base units that are aggregated to form higher level units are derived largely from the landscape itself, rather than being imposed by an external framing. At the level of the virtual image objects that are aggregated to form catenal elements, the choice of data layers and scales of observation are guided by observations and analyses of the landscape, seeking to reflect associations between vegetation and topography that recur throughout a physiographic zone and which are described in an *a priori* archetype (see, for example, Section 5.3.2). The scale at which streams, catchments and CASSs are mapped also depends on the perception of these repeating toposequences (see Section 6.3.2). In turn, the resolution used to calculate patterns of landscape dissection depends on the size of these CASSs (see Section 7.7.2). The size and shape of each of these units is irregular, being dictated largely by the characteristics of the landscape rather than by cartographer choices. The implications of this diversity, both in terms of ecosystem function and management and in terms of describing and mapping local heterogeneity are discussed below (Section 8.5.3).

Given that I cannot claim that my conceptualisation is the only valid way of looking at savanna landscapes and that it contains many reductionist elements, how can I assess whether or not the conceptualisation is capable of rising to the challenges posed by the complexity of natural systems? Ultimately, such assessment is the responsibility of end-users; I can only expose the foundations and assumptions in ways that allow debate and refinement, in the spirit of post-reductionist critical complexity (Cilliers & Preisler, 2010; Section 8.3). Such a conceptualisation is a perpetual work in progress: the scaffolding of the landscape hierarchy merely offers a starting point, upon which archetypes can be built and developed, moving in an adaptive and iterative manner between theory and practice, and between generalisations and local observations.

Heterogeneity

The interplay between theoretical framings and local observation that lies at the heart of the precisiation of archetypes is one of the ways local heterogeneity is built into the conceptualisation. At the heart of the conceptualisation the landscape hierarchy is just an

abstract skeleton. Implementation requires observation of a particular landscape to delineate the stream network and to recognise repeating assemblages of catenal elements. The intertwined drivers, controls and responses of hydrological regimes differ between landscapes, so that different archetypes are needed to describe the character and behaviour of each landscape. This means that each landscape demands different combinations of variables and scales of observation to describe and map catenal elements, as seen in the different approaches to mapping catenal elements in the basalt and granite study areas (Chapter 5).

In the same way that soil forming factors are described by Jenny (1941) in very general terms, so the landscape forming factors of hydrology (water budget), vegetation, soil and morphology can also be described in very general terms. Indeed, accounts of the general principles of interaction between these factors form the basis of textbooks in all the earth sciences, including physical geography, soil science, hydrology and ecology. However, as in soil science, the precise nature and relative importance of each of these factors varies between locations and is also heavily influenced by historical legacies and human modifications. This means that it is not possible to devise a single set of classes, or indeed a single set of variables and scales that usefully partition landscapes at anything but the coarsest scales. Broad differences in elevation, rainfall and temperature serve well to differentiate between biotic communities at global or continental scales, such that broad agreement can be reached on maps of the world's biomes (e.g. Holdridge, 1967; Whittaker, 1967; Olson *et al.*, 2012). However, at finer scales, local heterogeneity militates against the use of standardised sets of variables. Very different sets of variables are often needed to describe and map landscape units in different settings, even though they may all relate to the core landscape forming factors. For example, whereas canopy height was a useful indicator of catenal elements in the Nhlowa basalts, canopy cover was more useful in N'waswitshaka granite study area (Chapter 5). Even if the same variables are used, the same extent of variability in one factor can have very different effects in different locations. For example, different class intervals are needed to describe the subtle differences in gradient that characterise different catenal elements in flat plains, compared to the much wider intervals that separate catenal elements in mountainous environments. Even within the two study areas in KNP (which are only about 40km apart), differences of 10^{-1} degrees in gradient were used to distinguish terrain units in the Nhlowa basalts, whilst in the N'waswitshaka granite study area, differences in the characteristic gradients of various catenal elements were measured in whole degrees. Other reasons why different variables may be needed to characterise catenal elements in different settings include the effects of fire regimes, the distribution of large herbivores and land use or management practices, all of which can 'disturb' landscape patterns, so that they no longer relate to hillslope position. For example, in The Nhlowa basalt study site, the distribution of tree clusters on crests appears to be more closely related to fire history than to topographical position (Section 5.4.3).

Local heterogeneity is not only manifest in the factors that separate classes, but also in differences within classes. In most approaches to classification, each class is conceived as internally homogeneous, with average values often assumed to apply evenly over the whole class. Discounting local differences in this way can be very misleading, since apparently small local differences can have large impacts on outcomes, causing ecological surprises (Phillips,

2004; Harris & Heathwaite, 2012). In this thesis, I have sought ways of generalising and classifying that retain information about within-class heterogeneity, including:

- Retaining lower-level elements in the description of higher level landscape units: higher-level units are described in terms of *assemblages of lower-level units*, rather than in terms of averaged variables.
- Using fuzzy classification and other methods for assessing the varying degrees of similarity between class members and the class archetype.

The use of assemblages of lower-level units rather than averages to describe the characteristics of large-scale landscape units

The description of catchment properties in terms of overall averages can be very misleading, since the diversity of catenal elements and the spatial and temporal connections between them can easily be overlooked. In reality, this local heterogeneity is often very important, resulting in outcomes that are quite different to those suggested by an overall catchment average.

Characterising larger land units in terms of recurring archetypal assemblages of lower-level units neatly allows coarse-scale generalisations whilst retaining information about local heterogeneity. Important characteristics that occur only in a small part of each catchment or physiographic zone can be associated with particular catenal elements that are present in contained assemblages, rather than being lost in average values that assume internal homogeneity within catchments.

For example, granitic catchments in KNP are often described as having infertile soils and poor forage compared to the basalts (Scholes, 1990; Venter *et al.*, 2003). Nevertheless, these areas are able to support large numbers of herbivores due to hotspots such as sodic sites and grazing lawns that offer highly nutritious grasses (Grant & Scholes, 2006). Since many of these hotspots are relatively small and are therefore only seen at very fine scales, they are not generally mapped over large areas. This means that there is little appreciation of the overall area of these hotspots and their contribution to the grazing requirements of herbivore populations, l*et al*one opportunities to devise management plans that specifically focus on these critical areas.

There are many other situations in which mapping fine-scale ecological patterns is critical to management, including the identification of habitats that support rare species and the distribution of refugia for species that are threatened by climate change (e.g. Hilderbrand *et al.*, 2005). Similarly, the identification of areas at risk of erosion from intense flooding is also likely to be very useful for management, particularly in water-limited systems, where the overall mean rate of weathering and erosion are very slow, but there are large pulses of activity when water does become available. In these periods processes operate extremely rapidly and intensely (e.g. Noy-Meir, 1973; Jenerette *et al.*, 2012) and are often very localised. For example, local events such as bank collapse or gully erosion occur infrequently, but can occur suddenly as a geomorphic threshold is crossed after a large, intense rainfall event.

The distribution of resources and vulnerability to many disturbances are closely associated with the character, configuration and connectivity of catenal elements. Understanding the distribution of these elements within catchments of a particular physiographic zone therefore sheds light on the likely distribution of these small areas of interest, even if fine-resolution data are not available to map each individually. Furthermore, management efforts can be directed towards management of complete catchment assemblages within each physiographic zone, without the need to micro-manage at unreasonably small scales.

Not only does the characterisation of catchments in terms of assemblages of catenal elements allow recognition of the presence of small elements in coarsely scaled units, it also provides a way of scaling up from the characteristics of individual catchments to wider areas. For example, whereas it may not be feasible to model hydrological flows between individually mapped catenal units, it may be easier to construct whole-catchment values based on archetypal catenal assemblages and then extrapolate these values across the entire area in which such archetypes are found. Such an approach is beginning to be adopted as part of the initiative to improve predictions of hydrological flows in ungauged basins (Hrachowitz *et al.*, 2013) and also underpins the recent adoption of research supersites in KNP (Smit *et al.*, 2013a).

This approach is commonly used in soil mapping and early landscape classifications, where large areas are described in terms of the toposequences typically found within them (e.g. Venter's classifications of KNP (1990) and MacVicar's (1974) delineation of South African land types). However, the drawback with these approaches has been that they are essentially qualitative, with no attempts to map individual toposequences or to assess the degree to which the idealised toposequences are actually present within each area designated as a specific land system or type. The increasing availability of fine-scaled imagery has begun to make such detailed mapping possible, as demonstrated in this thesis. However, a large amount of work remains to be done to map all catenal elements in this way, even if imagery is available.

Assessing the varying degrees of similarity between class members and the class archetype
Within a crisp classification all the image objects that make up a patch are assigned the same value, hiding any within-patch variation. However, within fuzzy classifications objects retain their membership values for each and every class, even though each image object may be assigned to the class for which it has the highest membership value. Thus information that describes local differences within and between patches is not only retained, but can also be quantified and mapped, using measures such as the highest class membership value and classification stability (Benz *et al.*, 2004).

The 'highest class membership value' indicates the confidence with which classes have been assigned. 'Classification stability' is the difference between the highest membership value (which indicates the class to which the object would normally be assigned) and the next highest membership value (which indicates the next most appropriate class to which the object could be assigned). A high 'classification stability' value indicates that the classification is unambiguous, with clear separation between the classes, whilst low values suggest a somewhat arbitrary assignment of objects to each class. In theory, both these measures can be used to quantify and map the degree of heterogeneity within and between classes, to identify

transition zones and to help refine the definition of archetypes so that they capture local heterogeneity in ways that are most useful to the purpose in hand.

However, I found that applying these measures is not straightforward, since both measures are highly sensitive to the classification rules used. For example, in the N'waswitshaka granite study area, both crests and midslopes have high mean 'highest membership values', suggesting that they both are almost identical to their archetypes (Table 8.3). However, both classes also have low 'classification stability', suggesting that many objects would qualify almost equally as well for both classes. However, as seen in the area shown in Figure 8.1, crests are relatively well defined, with an abrupt transition in membership values (Figure 8.1 c), whilst midslopes are much fuzzier with a wider variety of membership values (Figure 8.1 d). It is clear that it is the wide range of membership values for midslopes that contributes to the low classification stability of both crests and midslopes.

Using the same measures to shed light on boundary characteristics would also be misleading in this case, since the evidence is conflicting. Whilst 'classification stability' and the mean 'highest class membership values' for midslopes (Figure 8.1 b and d) suggest a gradual transition between crests and midslopes, the mean 'highest membership value' for crests suggests an abrupt transition. In fact, the transitions in this area are generally very abrupt (Figure 8.1 e).

This example illustrates an important lesson in the degree to which classification rules (see Table 5.2) play a key role in determining the measures of 'highest membership class' and 'classification stability' relative to the characteristics of the landscape itself. Although the use of archetypes and fuzzy classification techniques also neatly sidesteps the need to specify the determination of precise boundaries and thresholds by focussing attention on the definition of the central tendencies of each class, boundaries still need to be parameterised. For example, the maximum and minimum 'acceptable' values for a class need to be set, together with the shape and steepness of the membership function curve that described the transition between 'acceptable' and 'less acceptable' values. The way these membership curves are constructed has profound influence on the distribution of class membership values, such that had other rules been used to define the terrain units, it is possible that the distribution of classification stability and class memberships would be quite different.

Since fuzzy logic and classification is now widely applied in many fields, new methods of identifying class archetypes and quantifying similarity to these archetypes are slowly emerging (e.g. Frey & Dueck, 2007), so hopefully new techniques for defining class archetypes and evaluating similarity to these archetypes will soon be developed.

Table 8.3: Mean highest membership class and classification stability for crests and midslopes in the N'waswitshaka granite study area.

	Mean 'Highest membership class' *1= identical to archetype*	***Mean 'Classification stability'***	
Class	*0 = totally dissimilar*	*1=crisp, 0 = ambiguous*	***n=***
Crest	0.979	0.259	13 580
Midslope	0.903	0.258	19 427

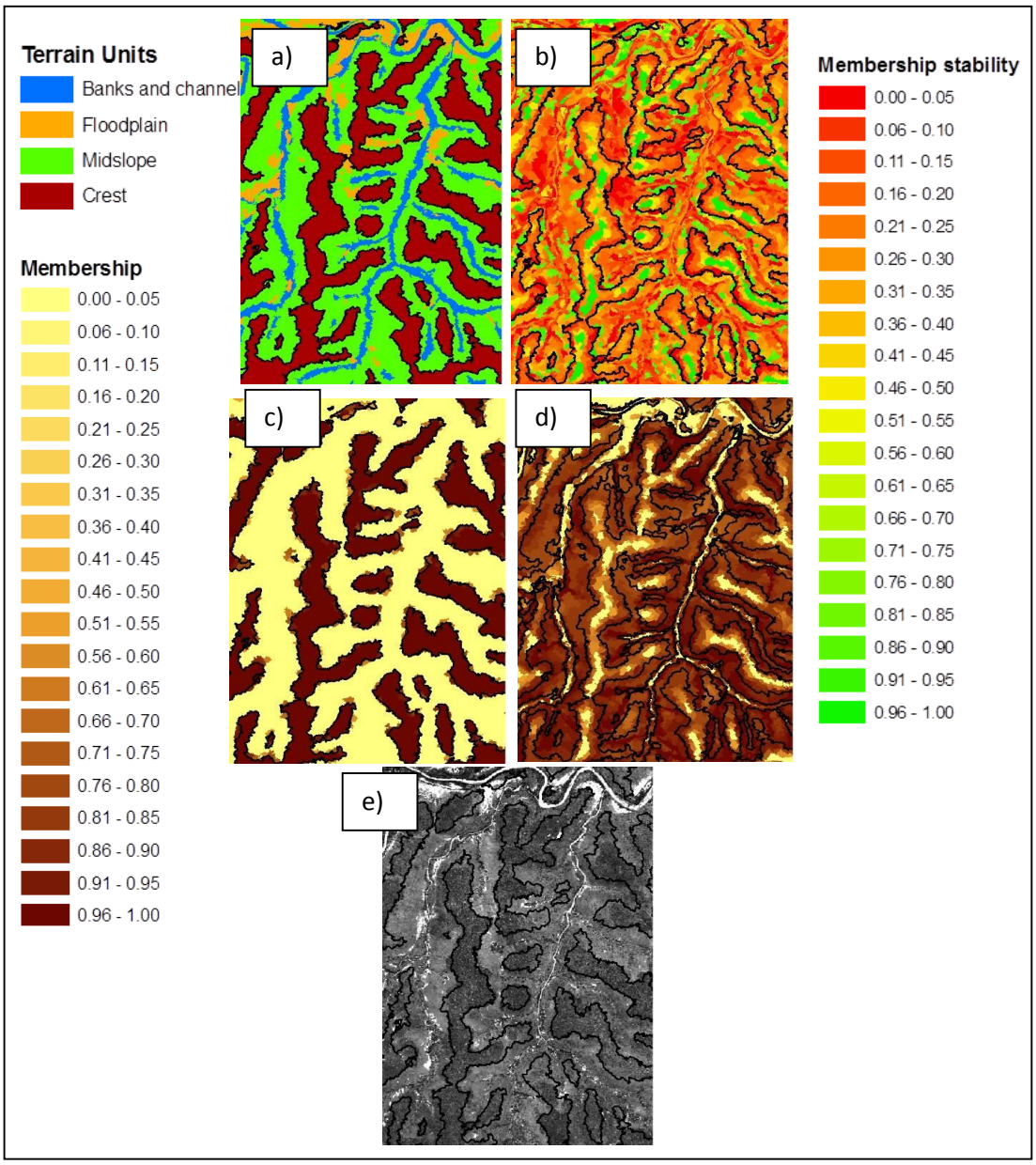


Figure 8.1: Terrain Units in the N'waswitshaka granite study area.

a) Final classification of terrain units. b) Classification stability (1.00 /green = crisp, 0.00/red = ambiguous). c) Membership values for 'crest' (1.00/brown = identical to archetype, 0.00/yellow = totally dissimilar to archetype. Crests are outlined in black in a, b, c and e. d) Membership values for 'midslope'. Midslopes are outlined in black. e) SPOT5 pan image (March 2006).

Assessing the similarity between archetypal catenal assemblages and those found in reality is even more challenging, since there are no established ways of quantitatively describing recurring landscape patterns (MacMillan & Shary, 2009). I experimented with virtual transects, but rejected their use as being too sensitive to the positioning of the transect. For example, transects placed perpendicular to the centre of the stream in a CASS often failed to detect crest elements located at higher elevations in first-order CASSs. Instead, I assessed the similarity of catenal toposequences to archetypal assemblages in the N'waswitshaka granite study area in terms of the occurrence of both woody crests and grassy midslopes, as described by the

archetype. The proportions of the crest and midslope areas of each CASS classified as 'woody' or grassy' respectively were calculated. The smaller of these two proportions was then used as a membership value for the class 'both woody crests and grassy midslopes' (Section 6.7). This procedure identified those areas where either the crests or the midslopes were not as predicted by the archetype (Figure 6.14).

Assessing the similarity between archetypal and actual processes is likely to be more challenging again. Although the similarity between outcomes can be readily assessed by comparing results predicted from a model of the archetype with those observed in reality, field observations of outcomes are often difficult and expensive to observe. For example, many local measurements are needed to parameterise hydrological models and it is not feasible to instrument all CASSs to determine which are most similar to the archetype. Even if similarities and differences in hydrological outcomes were measured, pinpointing the differences in processes that are responsible for these differences would be nigh impossible.

However, once some appreciation is gained of the variability of catenal elements and assemblages in a particular region, it is possible to assemble evidence of the factors that are associated with these differences. In the N'waswitshaka granite study area, for example, it would be possible to interrogate a database of environmental attributes to identify the particular attributes of the CASSs that differ most from the archetypes. These findings could then be used in conjunction with the archetypal conceptual model of hydrological fluxes to hypothesise the effect that these variations would have on hydrological outcomes, or to establish whether or not these variations are likely to impact other processes of interest. Detailed data about individual attributes associated with overall differences and similarity to archetypes will also lead to refinements of the archetypes themselves, the variables used to delineate them in maps and the conceptual models describing formative processes. As more data are gathered, opportunities for subdividing classes increase at all hierarchical levels, so that descriptions and understandings become more and more tailored to particular circumstances. How much detail (precisiation) is needed will depend on the purposes for which the classification is used.

Dynamics

Although the conceptualisation allows for the description of connectivity and flows between landscape units, this was not fully implemented within this thesis. Whilst the archetypes developed for catenal assemblages in various order catchments in the two study areas contained descriptions of hypothesised hydrological flows between the elements, these flows were not tested or measured. However, hydrological instrumentation has now been installed in a follow-on project in two KNP supersites: on the southern basalts in Nhlowa and in the Stevenson-Hamilton catchments, which have a similar climate and geology to the N'waswitshaka granites (Smit *et al.*, 2013a). Early results suggest flows that are in broad agreement with those hypothesised in the *a priori* archetypal models (Riddell *et al.*, 2014).

Many other landscape dynamics have been studied in KNP, notably the 50 year record of the combined effects of herbivory and fire on vegetation in the experimental burn plots (Biggs *et al.*, 2003) and long term tracking of the effects of herbivore exclosure on vegetation

communities (O'Keefe & Alard, 2002; Asner *et al.*, 2009). However, relatively few studies have examined integrated responses of vegetation, soils and water to fire and herbivory in different hillslope positions (Lorentz *et al.,* 2013 is a notable exception). It is anticipated that the establishment of the supersites will offer many more opportunities for similarly integrated projects.

The long-term monitoring of hydrology and vegetation in the supersites will also provide valuable data on the temporal range of variability around the archetypes for these sites, increasing our understanding of contemporary dynamics and improving our ability to foresight future trajectories.

8.5 Emerging themes

8.5.1 Fuzzy reasoning: The value of vagueness

Although savanna landscapes are highly organised in space, they are not precisely organised. Given the amount of local variation, both scientific understanding and management actions will never apply precisely to any given area. Instead, we need to learn to live with approximations and to become more relaxed with vagueness. Reflecting on 15 years of experience implementing adaptive management in KNP, Biggs and Roux concluded that the institutional culture of SANParks had learned to be more 'relaxed with complex issues' and that 'muddling through' had become 'more acceptable, even desirable' in the face of scepticism about the possibility of 'perfect' management control' (Biggs & Roux, 2013 p. 2). In the same way, learning to reason and do science with fuzzy logic involves being relaxed with imprecision, adopting a new mindset that is comfortable with approximation and accepts that there may be multiple, overlapping and sometimes conflicting answers to the same question (Biggs *et al.*, 2009).

Furthermore, accepting that there can be no definitive conceptualisations of ecological processes that are characterised by complex interactions and local contingencies means that even useful hypotheses are likely to be falsified in some circumstances. Replacing a reductionist approach to science with an approach that can address complexity and heterogeneity entails accepting that multiple conceptualisations and explanations of the same feature or event are possible. Indeed, conceptualisations can only be justified using narratives to demonstrate their utility and relevance to a particular purpose, rather than being assessed solely in terms of their correspondence to reality.

However, the possibility of multiple conceptualisations of the same reality opens the door to a myriad of views, each offering partial, fragmented perspectives that focus on different attributes at different scales. This fragmentation seriously hinders communication and collaboration between scientists, managers and planners, since the sharing of knowledge and experience depends upon shared vocabulary, concepts and frameworks that structure cognition and perception (e.g. Pickett *et al.*, 2007; Stirzaker *et al.*, 2011).

In this thesis, I have developed a conceptualisation of savanna landscapes that is rooted in fuzzy logic. The framework is adaptable, rather than prescriptive, allowing for different levels of approximation as one moves from the general schematic hierarchy to descriptions and understandings that relate to specific locations.

Fuzzy logic

Fuzzy logic has developed enormously over the last five decades as Zadeh's original paper on fuzzy sets (1965) has spawned a whole new branch of mathematics and soft computing. Fuzzy mathematics, modeling languages and computational methods are tolerant of sub-optimality and vagueness, aiming to deliver quick, simple and sufficiently good solutions (Hajek, 2010) with applications in fields as diverse as artificial intelligence, linguistics, pattern recognition and engineering (Nguyen & Walker, 2005; Singh *et al.*, 2013) as well as digital soil mapping (Section 2.6). Fuzzy logic mimics human perception and cognition, dealing with concepts, data and lines of reasoning that are uncertain, imprecise, vague, partially true, or without sharp boundaries (Zadeh, 2008).

Fuzzy logic gives us the tools we need to describe and analyse subjectively defined geographic regions such as landscape units, which are not only imprecisely organised in reality, but are also subject to being viewed in multiple ways and from multiple perspectives that are inherently partial, imprecise and often conflicting. Without such tools, descriptions and analyses fall prey either to spurious certainty and precision that inhibits the transfer of knowledge (both between people and across space /time) (Biggs *et al.*, 2009) or to accusations of obscure or tacit subjectivity that do not easily permit criticism or iterative development. It is no longer necessary to justify descriptions of landscape patterns and processes as self-evident. Instead, the logic of fuzzy classifications and fuzzy descriptions of processes can be formally stated for all to debate, refine and develop over time. The use of such an approach to landscape classification and analysis therefore offers a path between the precise, but fragmented perspectives of American landscape ecologists (Section 2.3.2) and the holistic, but obscure and incontestable perspectives of the European school (Section 2.3.4).

The cornerstones of fuzzy logic

Zadeh (2008) describes fuzzy logic as having four cornerstones: graduation, granulation, precisiation and generalised restraint. Each of these cornerstones is present in the conceptualisation presented in this thesis.

Graduation means that everything described in terms of fuzzy logic is allowed to be graduated and expressed as a matter of degree rather than being forced into bivalent categories, as is the case with classical logic. Not only can class membership be graded (as in fuzzy classification) but truth, causality, dependence, similarity, possibility and probability can be all described in terms of degrees.

A simple example of graduation is the use of fuzzy logic in fuzzy classification, where class membership is graded, rather than a bivalent yes/no (Section 3.54). The possibility of graded class membership was what first drew Burrough (1989) to use fuzzy classification techniques to map the gradual changes in soils. The ability of fuzzy classifications to deal with gradual

changes in environmental attributes was particularly important for the classification of crest and footslope catenal elements in the Nhlowa basalts. Changes in both gradient and vegetation cover were very gradual, so it was not clear where, or if, a boundary might be drawn. Overlapping, fuzzy classes were defined for terrain units, including crest, footslope and an intervening midslope area (Table 5.2). These classes were based on a fuzzy combination of TPI (Topographical Position Index) measured over the whole hillslope (a measure of hillslope position) and 'long range' gradient (a measure of steepness at the hillslope scale). The use of fuzzy classification avoided the need to set arbitrary boundaries, allowing the classes to be defined in a way that corresponded to semantic definitions of crest as "high on the hillslope and relatively flat", footslope as "low on the hillslope and relatively steep" and midslope as "somewhere in between". Statistical analysis then showed that trees and shrubs over 0.5m high were more likely to be found on footslopes (Figure 5.33). Crest and midslope areas were therefore merged in the final delineation of catenal elements.

The ability to map objects as fields is a way of straddling the patch and gradient perspectives on landscapes, revealing within-patch heterogeneity as well as allowing patch boundaries to be explored. For example, mapping classification stability and class membership values in the Nhlowa basalts reveals the spatial extent of potential overlap between the classes, identifying areas where transitions are comparatively abrupt and other areas where transitions are more gradual (Figures 8.2 and 8.3). Mapping boundaries in this way is likely to reveal information relevant to inter-patch connectivity. Abrupt boundaries are more likely to be associated with rapid rates of change across short distances for many attributes and processes, whilst gradual transitions are likely to be associated with more gradual rates of change and possibly looser spatial coupling between environmental attributes. Although the impact of these differences on the permeability of the boundary will clearly differ according to the variables being mapped and the fluxes considered, mapping transitions in terms of class stability and membership values may reveal some useful insights and hypotheses. However, the effect of the rule sets chosen to define landscape units should be carefully considered, as evidenced by the example shown above in Figure 8.1.

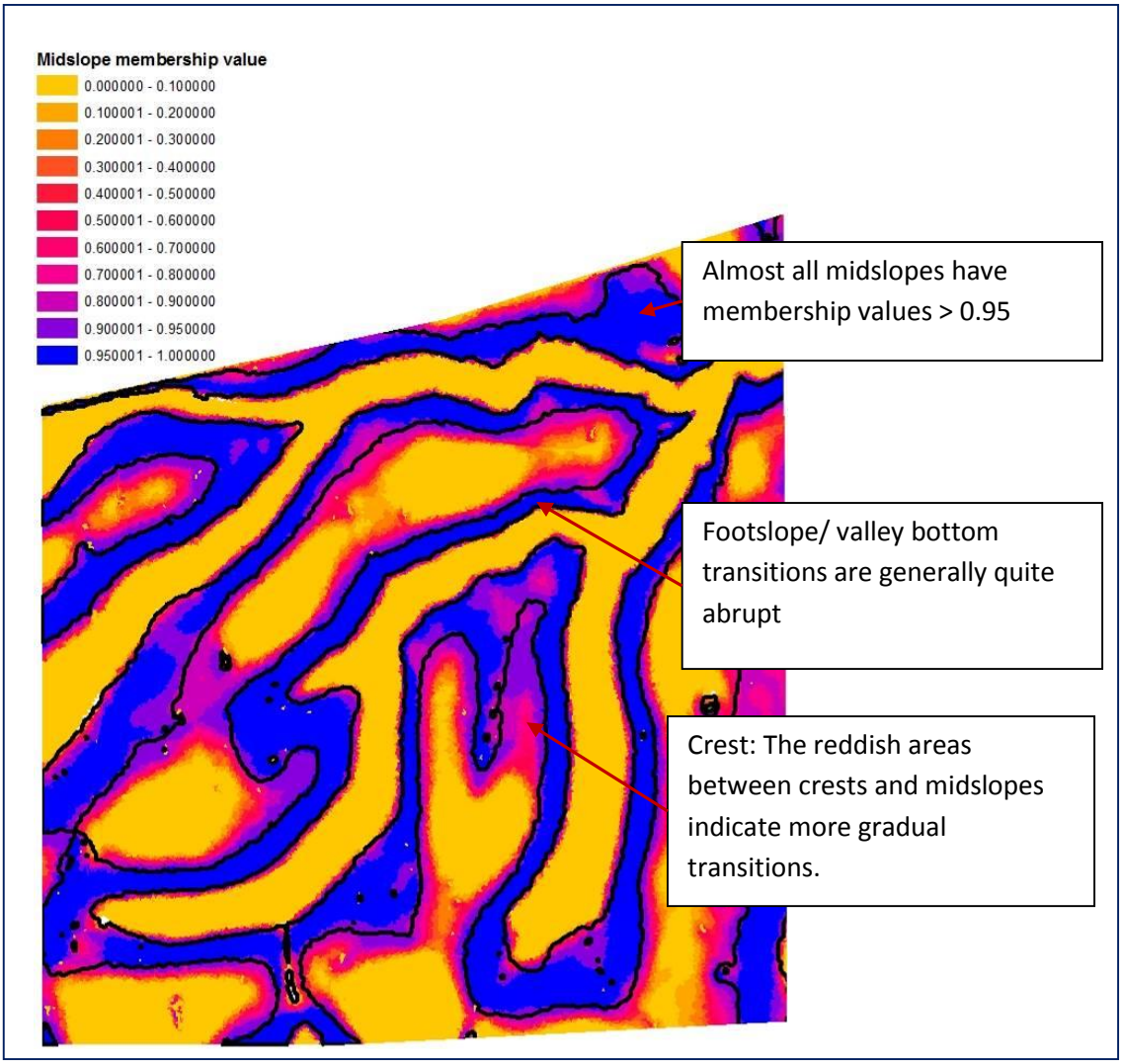


Figure 8.2: Membership values for midslopes in the Nhlowa basalts.

Black outlines show the boundaries of midslopes, which are the areas where the midslope membership value is higher than those for all other classes.

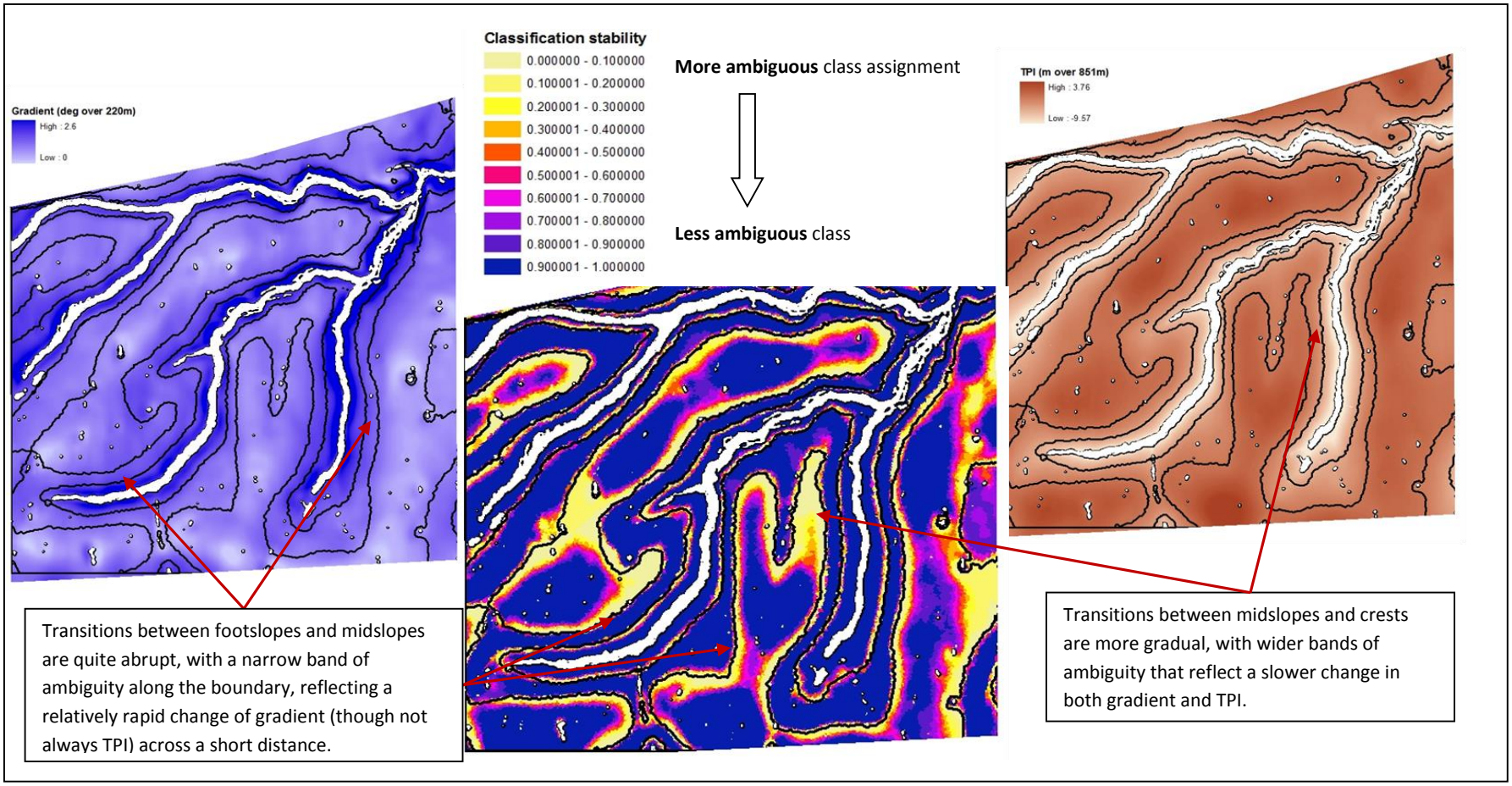


Figure 8.3: Information about transitions between crests, midslopes and footslopes in the Nhlowa basalts that is encoded in fuzzy membership values.

Black outlines show the boundaries of terrain units, classified according to the highest class membership values. Classification stability is the difference between the two highest membership values. Yellow and pink 'bands of uncertainty' show areas of ambiguity in class assignment. White areas are valley bottoms, pans and channels, which are excluded from this analysis.

Granulation is the second of Zadeh's cornerstones of fuzzy logic. He defines a granule as 'a clump of attribute-values drawn together by indistinguishability, similarity, proximity or functionality' (Zadeh, 1996 p. 2754). Granulation is conceived by Zadeh as a form of information compression, in which a fuzzily defined range of values is reduced to a single granule. Unlike Couclelis's 'granules' (see section 3.3), Zadeh's 'granules' are not confined to scales associated with atomistic units of space and time, but can be described at any scale. For example, 'linguistic' variables (Zadeh, 1996) are a common type of granule used in fuzzy logic. Unlike numerical (continuous) variables, linguistic variables are qualitative and imprecise, yet they can contain granules that are ordered and which can describe relative positions and be used in fuzzy reasoning. For example, the linguistic variable 'gradient' can contain overlapping granules of 'flat, 'gentle' and 'steep', each of which can be graduated, as in 'very flat' or 'extremely steep'. Such variables can be combined in fuzzy reasoning (Zadeh 2008). For example, 'If a hillslope is very steep and has very concave profile curvature, then it is likely to generate runoff and water may collect at the bottom of the hillslope', a proposition that may be more or less true, depending on vegetation, climate, geology and other contexts.

Like Rosch's cognitive categories (Rosch, 1973, 1975; Section 3.8.3), Zadeh's linguistic variables represent classes with graded membership and imprecise and overlapping membership criteria. However, whilst Rosch describes cognitive categories in terms of similarity to a prototype, Zadeh describes linguistic variables in terms of 'granules' that are bounded by constraints. The conceptualisation presented in this thesis echoes both theories. On the one hand, archetypes are equivalent to the 'exemplars' or 'prototypes' described by Rosch (1973, 1975) as epitomising the central tendency of a class, whilst on the other hand, membership of the class epitomised by an archetype is bounded by constraints imposed by its context, as described by its position in the landscape hierarchy (Section 3.6.2). Whereas granules are qualitative variables that are defined by fuzzy membership functions, archetypes are real or idealised entities that are used as class exemplars. Thus a single archetype is just one of the possibilities that falls within the range of a granule or a combination of granules.

Precisiation is "an operation which transforms an object, p, into an object, p*, which in some specified sense is defined more precisely than p" (Zadeh, 1996 p. 2754). The object of precisiation can be a numerical value or a semantic meaning, in either a human or a machine language.

Precisiation involves movement from the general to the particular, be that from:

- General theory to particular instances of that theory
- Schematic descriptions that apply to all savanna landscapes to detailed descriptions of a particular location, or from
- Broad regional descriptions of physiographic zones to finer-scaled descriptions of catenal elements at a lower hierarchical level.

Movements from the general to the particular always carry a heavy cost. Data are expanded (entailing increased collection and storage costs) and conceptualisation and models become

both more complicated and less transferable to other locations. Conversely, the reverse process of 'imprecisiation' allows summaries, comparisons and extrapolations across space and time.

This thesis is largely concerned with the need to reconcile the demand for generalised landscape descriptions and maps that allow comparisons and extrapolations whilst addressing concerns that local heterogeneity potentially affects landscape responses to many types of change. Such a reconciliation is effected by the use of archetypes to mediate the processes of precisiation and imprecisiation, facilitating interplay between the general and particular in many ways. For example, the approach to mapping landscape units developed in this thesis involves several stages of precisiation, all using archetypes as the vehicle to carry information from one level of precisiation to the next (see chapter 5-7):

- The schematic landscape hierarchy is populated with *a priori* archetypes appropriate to the particular landscape being mapped.
- The central tendencies of these *a priori* archetypes are then encoded into fuzzy rule sets, with parameters appropriate to the location being mapped.
- Both archetypes and rule sets may be further precisiated following detailed observations, analyses and/or the acquisition of new data. This may involve splitting or clumping archetypes and derived classes.
- Conceptual process models underlying the archetype may also be precisiated in the development of understandings that relate to a specific location.

Imprecisiation is involved in the very notion of an archetype, which serves as a simplified representation of many class members. By generalising these members in terms of their similarity to an archetype, it becomes possible to compare groups of instances and to extrapolate knowledge and experience across the whole class. However, by separating the archetype from the aggregate of class members, it becomes possible to both generalise and to retain information about heterogeneity in terms of differences between each class member and the class archetype.

Other examples of imprecisiation include the generalising and smoothing of maps and the distillation of findings from one location to serve as the initial archetypes for a new location (e.g. if mapping another location within the same physiographic zones as the study sites).

The last of Zadeh's cornerstones of fuzzy logic is the concept of *generalized constraints* that bound granules. These constraints can be hard or elastic and can take many forms, relating to truth, possibility, probability, group membership or 'usuality' (Zadeh 2008). In the conceptualisation developed within this thesis, archetypes are constrained by their position in the landscape hierarchy. Vertical constraints associated with the climate and geology of a physiographic zone limits the range of variability of archetypal catchments or catenal elements found within that zone. Horizontal constraints derive from the position of a landscape unit within a patch mosaic and the nature of boundaries and connectivities with neighbouring units. The range of variability associated with landscape archetypes not only includes local differences

in environmental attributes (such as geology, vegetation, etc.) and associated generative processes, but also includes temporal variability associated with changing water inputs, seasons and disturbances such as fire or flood over decadal time scales (Sections 3.4.1 and 3.8.6).

The second emerging theme that runs through this thesis is that of a conceptualisation that gains legitimacy amongst end-users by being informed by the landscape itself, rather than being based solely on subjective decisions of the map producer.

8.6 Archetypes integrate different types of knowledge and gain legitimacy from the landscape itself

8.6.1 Archetypes offer a platform for the integration of different types of knowledge and mediation between science and action

Archetypes offer an approach to describing and understanding landscapes that makes explicit the assumptions that frame ecological mapping, scientific enquiry and management decisions. Since these assumptions are explicit, they can be debated, modified, taught and shared. Thus, once archetypes of landscape structure and function are accepted by users and stakeholders, they provide a platform to organise and integrate knowledge, facilitating the ongoing production of shared, local, transdisciplinary knowledge and experience (*sensu* Lave, 2009, Parker *et al.*, 2012).

Uniting observations and theory, archetypes can not only inform the production of ecological maps, but can also frame both scientific enquiry and management decisions. If the same partitioning of land is accepted as relevant to a wide range of disciplines, as well as managers and planners, then it becomes much easier to share knowledge and develop holistic understandings of particular landscapes as different facets of the same archetype can be explored and developed. Furthermore, adaptive management (learning by doing) (Holling, 1978; Walters & Holling, 1990; Lee, 1999; Biggs & Rogers, 2003) is helped by the adoption of a spatial framework shared between scientists and managers, facilitating the flow of data, experience and knowledge in both directions.

8.6.2 Building local understanding

As more instances are observed, more areas are mapped and more hypotheses are tested, so the archetypes and their conceptual models are refined and developed to accommodate local differences. If these differences are thought either to affect the hypothesised processes described in the conceptual model or occupy an area of land larger than the minimum mapping unit appropriate to the purpose at hand, then new archetypes, conceptual models and map classes can be developed. Throughout this process, theory, observation and action are linked by their relationship to a shared archetype. In this way, integrated perspectives can be constructed that are grounded in local, spatially explicit observation and experience.

As archetypes are refined and developed, local knowledge is built that can inform management and policy decisions far more reliably than can universal models and classifications. The open nature of fuzzy classifications and the iterative development of archetypes facilitate mediation

between the general and the particular, and the local and the regional, to continually refine and improve place-based understandings that can inform both adaptive learning and management. This local knowledge not only allows for improved selection of reference or sample sites, providing information about the relative representativeness of proposed sites, but also indicates where spatial extrapolations are more or less likely to apply and where surprises are to be expected. For example, during the classification of catenal elements in the N'waswitshaka granite study site, it became evident that a new archetype was needed to describe 'koppies', since these rocky outcrops were highly unlikely to behave in the same way as wooded crests with sandy soils (Section 5.3.4).

8.6.3 Conceptualisations that are informed by landscapes themselves

My conceptualisation of savanna landscapes can potentially gain much of its legitimacy among end users from the way it is constructed using the actual attributes and scales that characterise the landscapes being described or mapped, rather than using prescribed units that are supposedly universally applicable or by relying entirely on subjective judgements made by the cartographer. By allowing landscapes to 'speak for themselves', not only are classifications able to represent individual landscapes more accurately, but they also gain legitimacy among end users who can easily recognise and agree on prominent patches as units of analysis and management.

Landscapes 'find a voice' in my approach to the conceptualisation and mapping of savanna landscapes in the process of precisiation: firstly in specifying *a priori* archetypes to populate the schematic hierarchy, secondly in choosing scales, variables and rule sets for classification and mapping and thirdly in the ongoing, iterative process of building local archetypes that link observed attributes to generative processes.

Finding the scales and variables that most appropriately define units for a particular landscape is not only essential for classification and mapping, but it also reveals important information about the landscape itself. On the one hand, the variables implicated in landscape patterns are strong indicators of formative processes, whilst on the other hand, the scales used to define landscape units indicate landscape 'grain'. Landscape grain describes the size of the clusters of attributes that form landscape units, and the scale domains that characterise each level of the landscape hierarchy in a particular location. Whilst relationships between environmental attributes and formative processes are the subject of vast literatures and entire disciplines, comparatively little has been written about the implications of differences in landscape grain, a situation which I attempt to redress below.

8.6.4 Landscape grain

In the most general sense, I use the term landscape 'grain' to describe the patch size typical of a patch mosaic. Each patch is considered analogous to a pixel or cell in a gridded image, such that landscape grain is analogous to the resolution of that image.

The concept of landscape grain can be applied at all levels of organisation within the landscape hierarchy. At each level, landscape grain is measured in terms of units at the next lowest level

in the hierarchy. For example, at catchment level, grain is measured in term of the typical size of catenal elements (or different categories of catenal element), whilst at the level of physiographic zones, landscape grain is measured in terms of the typical size of catchments or CASSs. In each case, landscape grain is equivalent to the scale domain characteristic of a particular organisational level of the landscape hierarchy. Clearly, the various grains found at different organisational levels within the same landscape are related: catenal elements contained within relatively small CASSs will also be smaller than their counterparts in larger CASSs.

Landscape grain within physiographic zones can also be considered in terms of the morphological character of high order catchments. The horizontal spacing of major ridges and valleys has been called 'topographic grain' (Wood & Snell, 1960; Pike, 1988; Pike *et al.*, 1989). Topographic grain is closely related to stream density and the degree of landscape dissection, both of which co-vary with geology and climate to form a topographic signature that characterises a physiographic zone (Pike, 1988; Partridge *et al.*, 2010).

In most landscape and river hierarchies that have been developed, scale domains are presented that are claimed to be typically associated with each organisational level (Rosgen, 1994; Bastian & Steinhart, 2002; Brierley & Fryirs, 2005). Whilst these claims may be useful ways of communicating the way the author sees their hierarchy, they are potentially misleading in at least two ways. Firstly, many of the self-organising patterns described in these hierarchies are often fractal, such that each level of organisation can be seen at different scales within the same landscape (e.g. Rodriguez-Iturbe & Rinaldo, 1997). For example, geomorphic units, stream reaches, segments and process zones can be distinguished both at the small scales associated with a stream running across a beach, at medium scales within the headwaters of a low-relief catchment, or at large scales within the entire catchment of a large river in the flat landscapes of KNP.

Secondly, even if the scale of observation is agreed, the scales associated with each organisational level vary widely between physiographic zones. For example, stream reaches in the lower Amazon are likely to be several orders of magnitude larger than reaches of small streams in finely dissected landscapes.

The widely varying topographic grain between different physiographic zones has important implications for the way we perceive, represent, study and manage these areas. Our natural tendency is to view all zones at the same scale, usually dictated by the scale(s) at which data happens to be available. However, landscapes dictate their own optimum scales for observation, study and management. In a granitic landscape (e.g. N'waswitshaka), catenal elements are much smaller than those found in the basaltic landscape of Nhlowa. Viewing the two landscapes at the same scale is therefore likely to lead to the identification of features and patterns that are not functionally or structurally equivalent. For example, walking across the large open crests of the Nhlowa basalts, one might be tempted to consider scattered clumps of shrubs or trees as patches that are equivalent to similarly sized midslope patches in the N'waswitshaka granites. Since the Nhlowa tree clusters follow no detectable systematic pattern, one might then falsely conclude that Nhlowa basalt landscapes lack the drainage

network-based organisation seen in the N'waswitshaka granites. However, once both landscapes are viewed at scales commensurate with that embodied in the drainage network, the systematic patterns become clear.

Implications of varying landscape grain for the construction of ecological maps

The wide differences in landscape grain between different physiographic zones have substantial implications for the construction of ecological maps, since the optimum scales of observation for the same level of the landscape hierarchy differs between landscapes. The use of different window sizes (or wavelet transformations) to derive multiscale terrain attributes is a tactic that has been employed by numerous researchers (e.g. Gallant & Dowling, 2003; Fisher *et al.*, 2004; Schmidt & Hewitt, 2004). However, this approach assumes that the same window size(s) capture similar features in all landscapes. This is patently untrue, since first order streams in a landscape with a coarse grain (low stream density and large CASSs) may well be similarly spaced to third or fourth order valleys in finely dissected landscapes.

In my study, where streams and catchments in KNP were delineated at a scale of 1:50 000, the sizes of stream reaches, segments and CASSs vary significantly between physiographic zones. Differences in the optimum scale for observing landscapes are particularly evident in the distances over which gradients, curvatures and elevation indices are measured to distinguish different terrain units that form part of a hillslope toposequence. For example, while TPI measured over 300m served to distinguish between crests, midslopes and valley bottoms in the N'waswitshaka granites, TPI measured over 850m was needed to separate terrain units in the Nhlowa basalts (Sections 5.3.4 and 5.4.4). If the same kernel had been used in both areas, the results would have failed to capture the relevant differences in one or other of the landscapes (Figure 8.4).

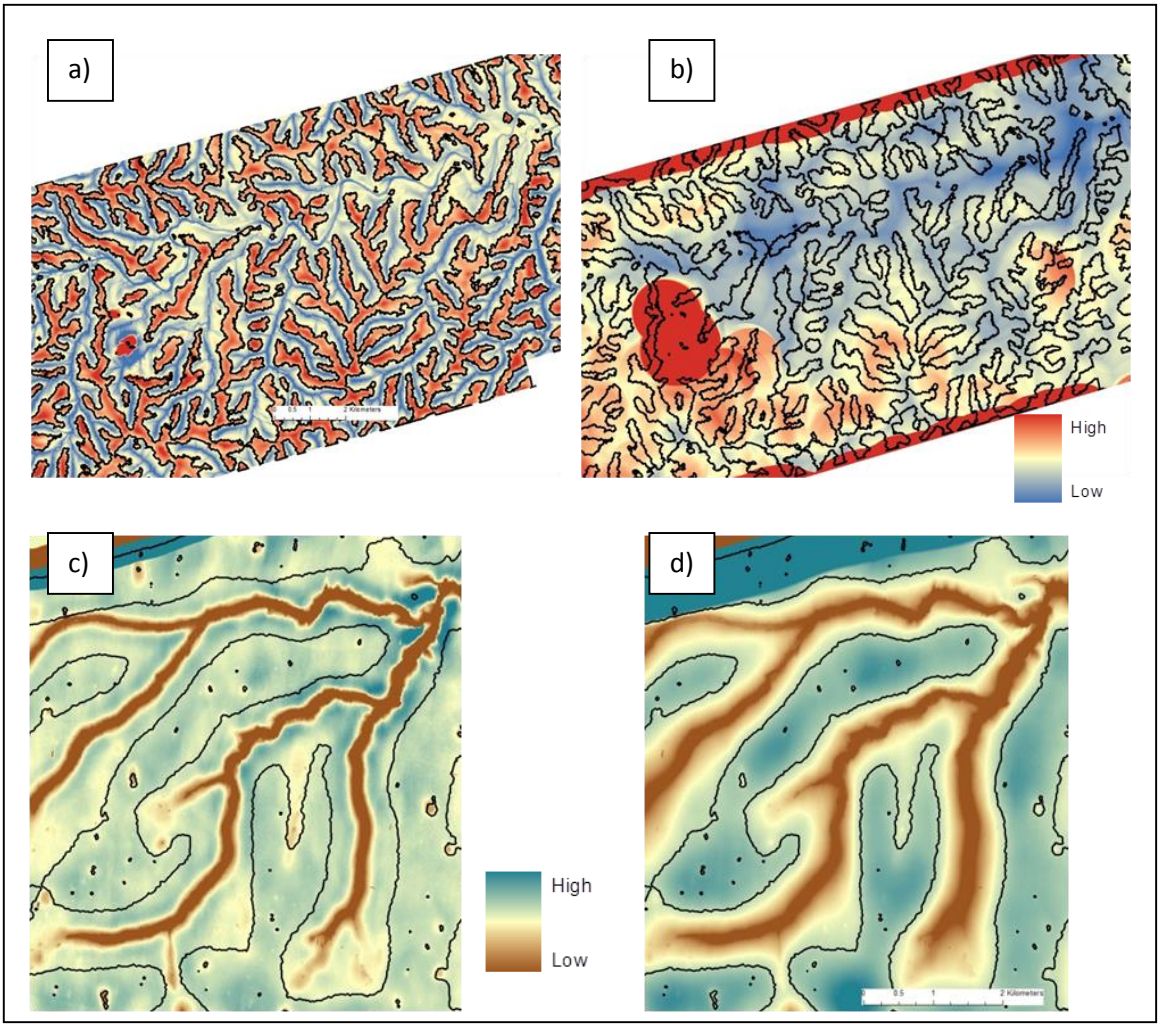
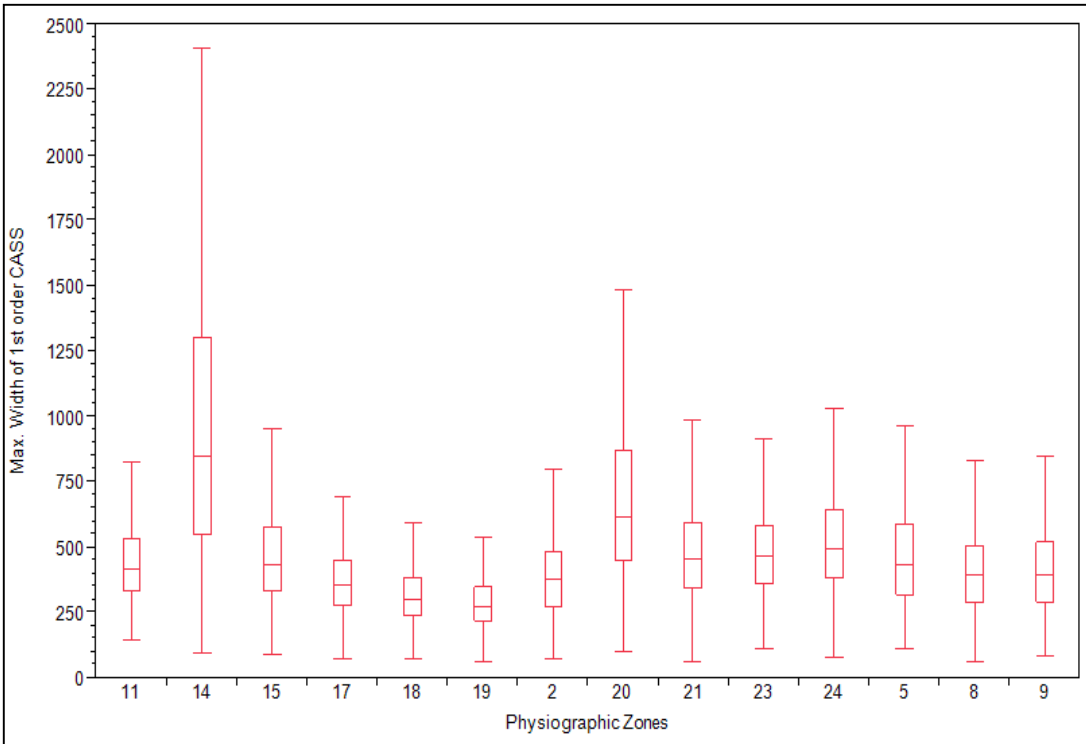


Figure 8.4: TPI needs to be measured over different distances in order to separate terrain units in the two study areas with very difference topographic grain.

TPI in N'waswitshaka granite study area measured over a) 300m and b) 850m. TPI in Nhlowa basalt study area measured over c) 300m and d) 850m.
Boundaries of delineated crest terrain units are shown in black in all scenes. Whereas TPI over 300m is closely associated with hillslopes and valleys related to 1: 50 000 streams in N'waswitshaka, TPI over 850m in this area merely picks out highly elevated points such as the koppies. Conversely, TPI over 850m is associated with the 1:50 000 streams in the Nhlowa study site, whilst the 300m TPI focuses on elevation distances to depressed pans.

The mean maximum width of first order catchments varies significantly between physiographic zones in KNP (Figure 8.5). Since the maximum width of a CASS indicates hillslope length, this variation shows the range of scales that are appropriate to mapping catenal elements in KNP. For example, in physiographic zone 14 (which accounts for most of the basalts in KNP), the mean width of 1st order CASSs is 1017m, suggesting that gradient, curvature or TPI that are intended to capture differences over entire hillslopes should be measured over distances of about 1017/2=508.5m. By contrast, first order CASSs in zone 19 (granites bordering the Olifants River near Tsheri) are generally about 290m wide, suggesting that gradients, etc. would need to be measured over about 145m to capture hillslope differences in morphology.



Physio-graphic zones	Mean Width 1st order CASS (m)														N=
14	1017	A													740
20	694		B												331
5	532			C	D										209
24	518			C											1068
21	487				D	E									1606
23	486				D	E									2447
15	470					E	F								639
11	441						F	G							537
9	426							G	H						794
8	419							G	H						1313
2	396								H	I					707
17	369									I					1790
18	318											J			4627
19	290													K	2012

Levels not connected by same letter are significantly different
(Tukey Kramer, α=0.05)

Figure 8.5: Maximum width of first order CASSs in each physiographic zone.

CASS widths (which indicate hillslope length) differ significantly between physiographic zones. Box plots show plot the median value (line in centre of box), the interquartile values (edges of box) and the limits within which 90% of the values lie (whiskers). Each circle represents a single physiographic zone and the size of the circle indicates the variance of CASS widths within the physiographic zone. The distance between the circles shows the degree of difference between the means for each physiographic zone. Analysis based on 18 820 1st order CASSs lying completely within physiographic zones that each occupy at least 1% of the total area of KNP.

Implications of varying landscape grain for ecological processes

The fact that landscape grain varies between landscapes has several noteworthy implications for ecological processes:

- Finely dissected landscapes contain a larger number of smaller, more fragmented patches than do coarsely-grained landscapes. Finely dissected landscapes are therefore more heterogeneous per unit area than are coarsely dissected landscapes. This diversity results from smaller catenal elements, each of which offers distinct resources for flora and fauna and is generated and sustained by a different suite of biophysical processes. Spatial heterogeneity in environmental attributes is one if the key determinants of species richness (e.g. Sarr *et al.*, 2005).
- Fine-grained landscapes contain longer lengths of riparian strips per unit area than do coarse-grained landscapes, each of which potentially buffers the spread of nutrients and pollutants through the landscape (Osborne & Kovacic, 1993), as well as adding to local heterogeneity (e.g. Naiman *et al.*, 1993).
- Fine-grained landscapes contain more tributaries, and hence more diversity stemming from the variety of hydraulic and substrate conditions (Benda *et al.*, 2004).
- Riverine areas also act as corridors for the dispersion of many species (e.g. Reiners & Driese, 2004), so that fine-grained landscapes may facilitate biotic dispersal, with both undesirable effects such as the spread of invasive organisms and desirable outcomes such as providing refugia during migrations of species threatened by climate-change in their present habitats (e.g. Heller & Zavaleta, 2009).
- The spread of fire, disease and floods may also be limited by the increased density of natural barriers to each type of phenomenon, so that coarse-grained landscapes are more susceptible to intense and widespread disturbances (e.g. Smit *et al.*, 2013b).
- The larger patch sizes found in coarse-grained landscapes may impose limits associated with increased distances between patches offering different resources for the same animal (e.g. food, water, shade, concealment, etc.).
- Many geomorphological processes are affected by valley width. In more confined valleys (and hence in finer-grained landscapes) less space is available to store water and sediment than in the wide, unconfined valleys that are more likely to be found in coarse-grained landscapes. Valley confinement thus inhibits the development of floodplains, wide streams and lakes (e.g. Bellmore & Baxter, 2014). Furthermore, narrow valleys are more susceptible to the accumulation of sediment and debris that can form barriers, damming hydrological flows (Fryirs *et al.*, 2007).
- The same processes are likely to operate at different scales in landscapes with different grains. This includes physical processes such as erosion and deposition, biological processes such as dispersion and predation and biophysical processes such as desertification.

In many cases, the size of the area or distance over which a hydrological and geomorphological process operates affects the outcome of that process. For example, run-off travels a shorter distance and therefore tends to reach a channel more quickly in areas with higher stream density than in areas with low stream density, such that areas with relatively high stream density tend to have flashier hydrographs and higher mean annual discharge (Carlston, 1963). Stream power in channels and erosion rates and sediment yield on hillslopes are affected by

discharge area and hillslope length. The longer hillslope lengths found in coarse-grained landscapes therefore contribute to potentially higher flow acceleration and hence higher capacity to transport materials across and through the landscape (Wischmeier & Murphy, 1978).

However, the potential energy available for fluxes of water and consequent transport of materials also depends on relief and gradient, as well as the infiltration capacity of soils and vegetation cover. Thus, less water may flow over and through coarse grained landscapes with long slopes in very flat areas with easily infiltrated soils and dense grasses than through fine-grained landscapes with shorter hillslopes but with steeper gradients and less permeable soils or bare rock. In the Nhlowa basalts, for example, water fluxes are generally limited to vertical infiltration, with little lateral water movement and consequently little opportunity for materials to be transported across the landscape. Furthermore, transmission and ET losses reduce the amount of water travelling downslope, particularly in arid and semi-arid climates. In these circumstances, the concentration time needed to develop continuous runoff may also exceed the duration of rainfall events (Yair & Raz-Yassif, 2004). Furthermore, in fine grained landscapes, a greater proportion of the surface area is exposed, so that more sediment is available to be transported as and when water flows through the channels. Thus it is likely to be the case that the short hillslopes associated with fine grained landscapes in semi-arid regions have higher capacity to transport materials than do long slopes in flat areas.

Implications of varying landscape grain for environmental science and management
Aside from differences in character and behaviour, the different scales at which structural-functional patterns are systematically repeated in differently grained landscapes has important implications for the way we understand and manage these landscapes.

Even though two landscapes may contain the same amount of biophysical diversity over the same area, a larger window size is needed to capture the complete range of that diversity in a more coarsely-grained landscape compared to a more finely-grained landscape (Figure 8.6). This means that measurements of biodiversity taken in the same sized site in the two landscapes will tend to underestimate the diversity in the coarse-grained site. The most efficient way of capturing, measuring and monitoring diversity is to have different sized windows in the two sites.

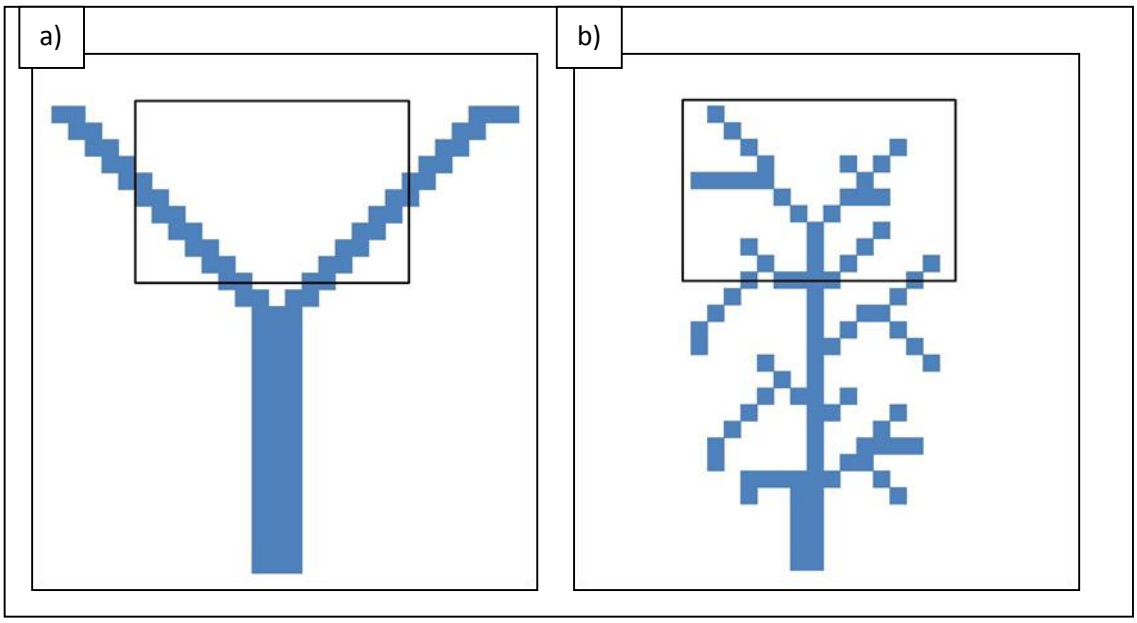


Figure 8.6: Two contrasting landscapes with different grains.

The area occupied by blue 'river' cells is the same in both the coarse-grained (a) and the fine-grained (b) landscapes. However, the coarse-grained landscape appears to be relatively homogenous compared to the fine scaled landscape. Different minimum window sizes are also needed to capture the diversity present in each landscape. For example, whilst the small window shown above captures the range of diversity associated with 1st 2nd and 3rd order CASSs in the fine-grained landscape, the same sized window only captures diversity associated with 1st order CASSs in the coarse-grained landscape.

Not only does landscape grain have implications both for the way we study, measure and manage biodiversity but it also affects the ways in which we compare landscapes more generally. Comparing features or processes occurring in the two windows in Figure 8.6 could potentially be very misleading, since for many processes, one window would capture multiple examples of entire cycles of spatial variation, the other window would only capture part of the cycle, which is likely to contain only one part of the process or feature of interest.

These potential scale mismatches have implications for the design of sample and reference sites. In general, it is well understood that if features and processes are to be compared across several locations, sites in each location need to be stratified to ensure that they are situated in comparable contexts. For example, to compare vegetation communities in different landscapes, it is important to compare floodplains with floodplains and crests with crests and so on, or else run the risk of topographical effects outweighing the differences the study or monitoring is trying to capture. However, it is sometimes less well understood that to compare features and processes between different systems, the same entities need to be compared in each system. For example, in comparing hillslope hydrology, entire catchments need to be studied or monitored. Furthermore, it is important to compare similar order catchments in each setting, which often necessitates very different sampling scales in each location (as for the selection of KNP supersites (Smit *et al.*, 2013a).

It is often the case that certain parts of a landscape provide resources critical to the survival of many species and are also particularly sensitive to change. For example, sodic sites on the

floodplains of rivers in the granitic areas of KNP provide highly nutritious grasses favoured by herbivores, but are also vulnerable to erosion due to the fragility of the crust (A horizon) protecting easily eroded deflocculated clays below (B horizon) (Venter, 1990). The size of these sites varies enormously, not only between rivers of different orders, but also between same-order rivers in the relatively coarsely grained granites in northern KNP and the very finely dissected granites near Tsheri. This means that these sites demand study and management at quite different scales.

The consequences of studying or managing at the wrong scale for the setting are at least twofold. On the one hand, systematic relationships may be overlooked if the system is viewed at an inappropriate scale. In the same way that blind people exploring different parts of an elephant fail to grasp the concept of the whole animal, so viewing a landscape system at too small a scale can obscure patterns of self-organisation that are critical to understanding the drivers and controls on system behaviour. On the other hand, inappropriate comparisons may be made, leading to misleading conceptualisations of underlying processes and ultimately to inappropriate management strategies.

8.7 Limitations of the conceptualisation presented in this thesis

Any conceptualisation or model of landscapes necessarily includes numerous assumptions and generalisations that often do not hold in real landscapes. This does not mean that general principles and conceptual models are not useful. Such principles and models serve as a starting point for the construction of local understanding, providing a basis for the assessment of when and where local differences may alter the basic model. However, in some circumstances, local differences demand that new conceptual models and archetypes are developed. This situation occurs when the underlying assumptions of the model are violated or the partial view of the world encapsulated in the model does not include the dominant processes that are responsible for generating and sustaining observed patterns.

The fundamental assumption of the conceptualisation developed in this thesis is that savanna landscapes are organised by the structure of the drainage system, since the spatial availability of water is linked to gravity-induced fluxes of water across and through hillslopes and channels. This assumption also requires that the assumptions of the soil-landscape model are met: hydrological and soil-forming processes are governed mostly by surface relief, subsurface controls result in the same patterns as surface controls, and the patterns and processes controlling water budgets, vegetation and soils are tightly coupled (Section 1.6.2).

The identification of catenal elements also requires that:

- Repeating patterns of vegetation and/or morphology are associated with hillslope positions.
- Hillslope units exist as reasonably discrete entities that are identifiable at a characteristic scale in terms of relatively homogeneous patches of vegetation and/or morphology that differ from neighbouring patches.

- There are many places in which these assumptions do not hold. For example, the presence of connections between the surface and groundwater that lie outside the predictable structure of the drainage network (e.g. springs) would disrupt the hydrological, soil and vegetation patterns upon which my conceptualisation depends. Even in areas where the model is generally applicable, there are many reasons why it will not apply in certain locations or at certain times. For example, the presence of boulders or burrows will divert flow paths and create macropores that can both accelerate flow and reduce flow by when pathways are blocked by air bubbles (Baird, 2004).
- However, although local spatial heterogeneity might sometimes undermine the general principles described in the model, the conceptualisation is designed to give a broad picture that is tolerant of local differences and aberrations. The bigger question is to appreciate the extent to which the conceptualisation is generic: can it be applied in all savannas? Or, indeed, in all landscapes?

In semi-arid climates, where water availability is limited, coupling between biophysical attributes is likely to be tighter than in other climates where water is plentiful and other factors also limit the distribution of plants, animals and soils (Porporato *et al.*, 2002). Although I applied the complete conceptualisation in only two study sites, I believe it would have worked just as well elsewhere in KNP, since recurring toposequences have been described in all parts of the park (Venter 1990). Given that these recurring patterns are the product of co-adaptation of topography, vegetation and soils to a particular set of climatic and geological circumstances, I am confident that the conceptualisation is likely to apply well to all savannas. However, it may need to be adapted for it to apply well in other contexts. Although water availability is an important driver and control of ecological systems in all landscapes, many other topographically influenced factors may also play important roles in systems that are not as limited by water availability as are semi-arid savannas. For example, in the sub-tropical kauri forests of New Zealand, where soils and vegetation communities are strongly influenced by the presence of kauri trees, the spatial distribution of kauri patches has been linked to exposed ridges that are subject to the windfalls needed for the establishment of kauri (Ogden & Stewart, 1995). In mountainous areas, vegetation and soils are limited by climate attributes associated with altitude. It is therefore highly likely that the distribution of vegetation and soil patches in both kauri forests and mountainous areas can be explained and predicted using a conceptualisation based on the structure of the morphology associated with river networks, in a way similar to that used in this study. Although in both these cases water is not the single main factor controlling landscape organisation in all parts of the landscape, the other dominant factors are also topographically related and will thus generate patterns that can be described in terms of toposequences associated with the hillslopes of different stream orders. Thus the general approach is likely to be generally applicable.

At present, the conceptualisation focuses on a biophysical template, with little consideration given to humans (or animals) as system components, drivers and controls. This focus was adopted partly to facilitate the adoption of the soil-landscape model (Section 2. 6), partly

because vegetation and topography are more readily visible in remotely sensed imagery and partly to avoid the complications associated with moving organisms that interact with the biophysical template in many different ways in different locations and times. However, I acknowledge that ecological systems are better described as 'socio-ecological' systems, given that human impacts are pervasive and our actions have modified 'natural' systems, often to the extent that humans are now the dominant system drivers and controllers in the 'Anthropocene' (Crutzen & Stoermer, 2000; Folke *et al.*, 2005). Although the environmental impacts of both humans and animals often follow patterns related to topography (e.g. large settlements on flatter flood or coastal plains near rivers, agriculture on midslopes and forests on higher slopes), these associations are likely to be weaker than those generated by the smaller-scale interactions between plants, water and soils. Thus the conceptualisation will apply less well to urban areas and modifications will be required to account for the impacts of forestry, fishing or dammed rivers.

8.8 Future directions

The conceptualisation developed in this thesis is considered to represent a scaffolded framework for a host of future applications. For example, a series of classifications based on different images could be used to detect temporal changes related processes such as bush encroachment (e.g. Wiegand *et al.*, 2005) or desertification (e.g. Reynolds *et al.*, 2007) or spatial changes resulting from different management strategies in similar landscapes (e.g. Kotschy, 2013). The dynamic dimensions of inter-patch flows and connectivity could be developed and linked to conceptual models that describe dominant processes and then used to foresight likely future trajectories under various scenarios. Emerging techniques for geographic visualisation offer exciting possibilities for the representation of historical data and future possible scenarios (e.g. Dodge *et al.* 2011; Mitasova *et al.* 2012).

The next stage of this research will be to apply the conceptualisation in different locations to see the extent to which it is able to gain acceptance amongst a wide spectrum of users to provide a platform to integrate scientific research, management actions and strategic land use planning. Although this process has already started with the establishment of KNP supersites, it remains to be seen how widespread the adoption of the framework will be in other savanna parks and whether it is able to serve the needs of those working outside conservation areas (e.g. in catchment management agencies, private reserves or regional planning). Future possibilities also include trialling the application of the approach in landscapes other than savannas.

There are multiple potential applications for landscape classifications based on the conceptualisation developed in this thesis. The classifications can inform biodiversity assessments and inventories in many ways. For example, the diversity of different classes can be described at each organisational level of the hierarchy, within-class variability can be assessed or the classification can be used to stratify species based assessments of biodiversity.

The conceptualisation and derived maps can also be used to situate sample, reference and motoring sites within the context of the range of variability of the class they represent, recognising that some sites are more representative of the class than others. Whereas in conventional sample designs it is commonly assumed that several randomly selected sites will capture any within-class variation, the use of archetypes allows the purposive selection of sites that represent distinct variations from the archetype, where local differences are likely to 'matter' to the processes of interest. The landscape hierarchy provides a rationale for both horizontal (same scale) and vertical (multi-scale) stratifications for both sampling and modelling, facilitating spatial extrapolation and scaling up and down.

The systematic observation, analysis and mapping of landscape patterns at fine resolution, but over large extents, provides new insights into geomorphic and ecological processes, generating hypotheses for future testing. In turn, these insights can feed back to refine and develop the conceptual models incorporated in the archetypes. These refined archetypes can then inform a new generation of mapping in an iterative cycle that moves between theory and observation. One such insight that emerges from the mapping of catenal elements in this thesis is that controls on vegetation (and presumably soil) patterns are very local and are closely related to elevation above the nearest stream, particularly in the N'waswitshaka granites. This suggests that in the N'waswitshaka study area, the distribution of tree species, and of trees in relation to grasses, is likely to be related to height above the water table and the frequency and extent of soil saturation and throughflow between catenal elements. Such an interpretation is consistent with the conceptualisation of savannas as water-limited systems in which there is a response to every additional drop of water and in which rainfall (and consequent soil saturation and channelized flows) is both infrequent and very spatially and temporally variable. This hypothesis can now be tested in the supersite catchments where extensive hydrological instrumentation has been installed. It can also be tested by more precise analysis of changes in vegetation related to height above the nearest stream. In turn, these observations can be used to refine the archetypes of catenal elements and assemblages of these elements and used to inform more accurate maps and models of landscape evolution or likely future trajectories under various scenarios.

However, although the theory of archetypes holds much promise for the description and mapping of ecological phenomena, more work is needed to develop a toolbox of techniques for its application. Although the intention was originally to use fuzzy techniques throughout the classification of KNP landscapes, this was not always possible. For example, it proved impossible (at least using widely available software or routines) to fuzzily map the relative differences in vegetation that helped to differentiate between crests and midslopes in the N'waswitshaka granite study area (Section 5.3.3). Similarly, I could not develop a way of fuzzily classifying assemblages of catenal elements in terms of their similarity to archetypal toposequences (see Section 6.3.2). I also had to resort to conventional cluster techniques to inform the development of archetypes for physiographic zones before I could apply fuzzy techniques to their classification (see Section 7.2.4).

New techniques are also required to better describe, analyse and represent:

- Repeating patterns of catenal elements, recognising that each repeated unit has multiple parts, not all of which are always present
- Similarities to and differences from archetypes
- Fuzzy boundaries and transition zones
- Inter-patch connectivities and networks, together with temporal changes in these connectivities.

I hope that by situating landscape classification and the development and mapping of archetypes within the ambit of fuzzy logic, new possibilities arise for the transfer of learning and techniques from the vast and rapidly increasing body of mathematical and computational theory and tools for fuzzy modelling and pattern recognition.

Ultimately, I hope that this conceptualisation can provide a shared framework for interdisciplinary approaches, uniting terrestrial and aquatic perspectives on landscapes in a shared understanding of the importance of hydrological connectivity between landscape units at various scales. Such an approach opens the way towards using the same ecoregions for strategic conservation planning in both the aquatic and terrestrial realms. It also opens the way to structuring a repository for knowledge in a consistent manner, so that data, observations, analyses and archetypes can easily be accessed and shared. This structure can also serve as an excellent starting point for participatory mapping, allowing many layers of meaning to be associated with each archetypal landscape unit.

Even if the conceptualisation is not universally embraced, I hope that understanding the need to justify the adoption of conceptual frameworks by making definitions, assumptions and processes transparent and contestable will provide a way of negotiating the politics of landscape classification (Tadaki *et al.*, 2014) and working towards uniting disciplinary and agency perspectives.

8.9 Closing comments

Reaching the end of my long journey, I realise that this thesis has come full circle, ending up with new ways of legitimising very old ideas. Throughout history humans have recognised landscape patterns formed by spatially co-varying environmental attributes such as climate, soil, biota and topography and have exploited them for multiple purposes, including hunting, settlement and agriculture. Although much attention was given to these patterns by 19th century naturalists and biogeographers (e.g. Lyell 1797 –1875, Wallace 1823 – 1913, Darwin 1809–1882, Von Humboldt, 1769–1859), such patterns are now rarely studied in an integrated fashion. Instead, most conceptualisations of ecological patterns and processes are developed with a single disciplinary perspective and focus on a single system component. Given the interconnections between the various components of ecological systems, it is hardly surprising that this fragmentation has generated repeated calls for integration both from those seeking to manage natural resources and those studying interrelated system components (e.g. Driver *et al.*, 2005; Zhou & Seethal, 2011). Furthermore, emerging technologies such as GIS, LiDAR and satellite imagery have given us new tools with which to detect patterns in environmental

attributes at fine resolution over large extents, generating new understandings of earth surface processes (Roering *et al.*, 1999; Tarolli, 2013, 2014), stimulating links between geomorphology, soil, hydrology and vegetation patterns (Levick *et al.*, 2010 p. e.g. ; Carbonneau *et al.*, 2012; Baldeck *et al.*, 2014) and giving new impetus to place-based research and management (e.g. Billick & Price, 2011).

To meet these challenges we need to develop conceptual models that can offer integrated perspectives that are not discipline-bound and tools that can deal with the vagueness and approximation needed to accommodate the 'naughtiness' of the real world (Kennedy, 1979). It is also becoming increasingly clear that standardised toolsets and classifications are not universally applicable (e.g. Lave, 2009; Harris & Heathwaite, 2012). Instead, each new location demands an interplay between general principles and local contingencies (Phillips, 2004). Classification schemes need to be open-ended and adaptable so that they can be tailored to suit local circumstances and to accommodate new data and knowledge (Brierley *et al.*, 2013).

However, given that we can never conceive of complex systems in their entirety, it is not possible to construct truly holistic perspectives on natural systems: some reduction, simplification and generalisation is necessary (Cilliers, 2005b). Moreover, without such reduction, systems are potentially unique and cannot be compared, so that it is impossible to transfer knowledge and experience between locations. In conventional approaches to landscape classification, these simplifications are often tacit and are almost always biased towards a single system component that is the object of interest for a particular discipline or environmental management agency. Given the increasing recognition that the conceptualisations of landscapes that frame our view of the world are contestable and that there is no *a priori* way of choosing between competing perspectives (Allen, 2001; Tadaki *et al.*, 2014), narratives are needed to justify and legitimise the conceptualisations that underpin landscape classifications.

In this thesis I have developed narratives to support the adoption of new way of conceptualising savanna landscapes that are designed to meet the demands of scientists, managers and planners for integrated, holistic perspectives, serving as a platform to bring together expertise across the terrestrial and aquatic realms. In many ways this task has been one of re-legitimising 19th century holistic perspectives that have been seriously challenged by relativist philosophies of science and recognition of the complexity of ecological systems and the importance of local heterogeneity. However, I have merged these old ideas with new tools and techniques, ranging from LiDAR imagery to fuzzy logic... it seems as though the journey has taken me 'back to the future'!

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