A Framework for the Classification of Drainage Networks in Savanna Landscapes

Carola Cullum & Kevin Rogers

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COVER PHOTOGRAPH: Vegetation patterns along the N'waswitshaka river,
Shaun Levick April 2009

A FRAMEWORK FOR THE CLASSIFICATION OF DRAINAGE NETWORKS IN SAVANNA LANDSCAPES

EXECUTIVE SUMMARY

The intertwined landscape patterns of water, soil, vegetation and topography are not easy to disentangle, since they occur across many scales and are influenced by the local characteristics of each factor as well as by the climate, geology and relief of the setting in which they occur. However, despite this landscape complexity, in semi-arid environments the distributions of vegetation and soils are often spatially aligned and occur in patterns that are both cause and consequence of topographically controlled water fluxes.

Although the coupling of soils, vegetation, hydrology and topography has long been recognised and forms the basis for the mapping of both soils and ecological regions, there is no standardised approach to such tasks. Indeed, many of these efforts struggle to find appropriate scales and variables to describe landscape patterns and the processes that give rise to them. The framework presented in this report aims to resolve these issues by introducing a hierarchical approach that facilitates the synthesis of knowledge across many disciplines.

The framework is based on an integration of aquatic and terrestrial perspectives, viewing a drainage network as composed of both hillslopes and channels that are intimately connected. Four principles underpin the framework (Figure E1.1). In semi-arid landscapes many geomorphological and ecological processes are tightly coupled to the spatial and temporal distribution of water at various scales. This coupling results in the formation of patches with characteristic water budgets, soils and vegetation. Topography is an important control on the distribution of water and hence on the distribution of landscape patches. Topography is not random, but is highly organised in space, with the hillslopes and channels that makeup a drainage network forming patterns of landscape dissection that vary systematically between different geological and climatic settings.

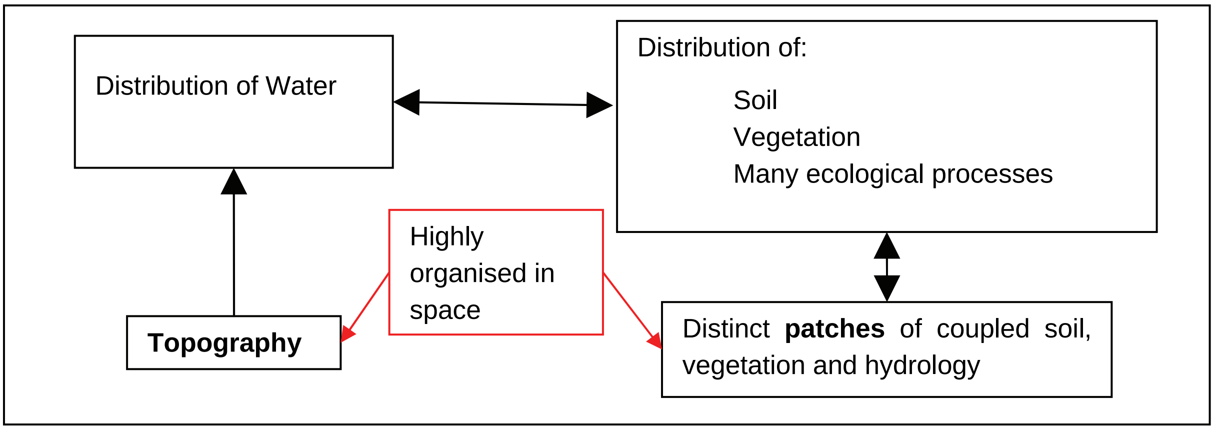

Figure E1.1: Principles on which the framework is based

In semi-arid landscapes, the distribution of soils and vegetation is tightly coupled to water distribution, generating and sustaining a mosaic of distinct landscape patches. Within a particular geoclimatic setting, the distribution of water is largely controlled by the topography that characterises the hillslopes and channels of a drainage network. The slopes and channels of a drainage network are highly organised in space, so topographically controlled landscape patches are also spatially organised.

Based on these principles, we have developed a landscape hierarchy that focuses on spatial and temporal scales relevant to conservation management (10^1-10^3 km^2 and seasons to decades). *Physiographic zones* are with similar geology and patterns of landscape dissection. Each physiographic zone is characterised by *catchments* with hillslope and channel morphology that form repeating patterns throughout the zone. Repeating patterns are also seen in the assemblages of *catenal elements* that occur within catchments. Catenal elements are associated with particular hillslope positions and each has distinct soils, vegetation and water budgets. Both terrestrial landforms, such as crests or toeslopes and fluvial features, such as banks, channels or islands can be described as catenal elements.

We illustrate an approach to landscape classification based on our conceptual framework by delineating physiographic zones within Kruger National Park in terms of catchment morphology and by mapping catenal elements in two contrasting study areas: the N'waswitshaka site covers a fourth order catchment on the southern granites, whilst the Lower Sabie site, situated on the southern basalts, covers most of a third order catchment drained by the Nhlowa river.

These classifications demonstrate how our framework addresses landscape complexity that involves multiple feedbacks within and across scales. Recognising that the processes responsible for generating and sustaining landscape patterns operate at different scales and involve different controls in different contexts, the framework allows for the use of different suites of variables and scales of analysis to describe hierarchical elements in different settings. The choice of scales appropriate to each organisational level is informed by our hierarchy, being largely driven by the intrinsic scales associated with catchment morphology in each physiographic zone.

The classification does not consist merely of statistical constructs, but is purposefully designed within the context of the framework to relate to the processes that generate and sustain the observed patterns. In other words, the classification is based on forms that the framework suggests are reliable indicators of process, such that areas that are grouped into a particular class can be expected to respond in similar ways to a wide range of events, be they natural disturbances, climate change or scientific manipulations. This means that the classification can be used to stratify samples for ecological, hydrological or management experiments or modelling.

Accuracy assessment of the classifications have not been undertaken to establish the degree to which classes have been accurately assigned compared to an expert assessment of reality. Instead, we suggest that the emphasis should be on testing the applicability of the classification scheme itself and its adoption by end users. Ultimately, the validity of our approach can only be demonstrated through its practical application in science and management, proving its usefulness and relevance to various communities of users.

Spatially explicit landscape classification lies at the very heart of both systematic conservation planning and strategic adaptive management. Both activities aim to conserve the heterogeneity of ecological patterns and processes that generate and sustain the compositional, structural and functional dimensions of biodiversity. In order to achieve this objective, spatially explicit landscape classifications are needed that describe ecological patterns and processes at multiple scales. Currently, many different approaches are used to assess spatial biodiversity, reflecting the large variety of ecosystem patterns and processes that can be considered, the multiplicity of datasets available and the fact that the terrestrial, river, estuarine and marine components of biodiversity are assessed separately, by different groups of experts. We suggest that our approach to landscape classification could offer a way of integrating many of these perspectives, at least in water controlled ecosystems such as KNP, where the spatial and temporal distribution of water generates and sustains a multitude of ecological patterns and processes.

The approach to landscape classification developed in this project has great potential application, not only for informing conservation management and planning, but also in providing a framework for organising the repository of knowledge that underpins successful strategic adaptive management. The framework provides a consistent frame of reference for gathering and communicating information on ecological structure, function and dynamics that can be used for scenario building, envisioning the different risks, threats, vulnerabilities and responses of landscapes in different settings and at scales appropriate to the organisational levels of the hierarchy. Furthermore, the holistic standpoint of this classification facilitates the coupling of terrestrial and aquatic systems, offering a framework that can be used and contributed to by scientists and managers from a wide range of perspectives.

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Many of the ideas expressed in this report were refined during the course of two workshops held in Skukuza in April and May 2010. The first workshop was field-based, where a group of academics and SanParks scientists reflected on the applicability of the proposed classification to various landscapes in southern KNP. The second workshop focussed specifically on management applications of the classification and was attended by senior SanParks scientists. Thank you to all those participating: Harry Biggs, Navashni Govender, Rina Grant, Izak Smit and Freek Venter from *SanParks*, Gary Brierley *Auckland University,* Jo Chirima *SAEON*, Shaun Levick *Carnegie Institution for Science,* David Butler *Texas State University,* Pieter le Roux *University of the Free State*, Oliver Chadwick *University of California, Santa Barbara,* Simon Lorentz and Eddie Riddell *University KwaZulu-Natal* and Lesego Khomo *Max-Planck-Institut für Biogeochemie.*

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DATA

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GLOSSARY

Term	Definition	See page
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.	15
Catena	A catena (or toposequence) is a series of soils and associated vegetation linked by their topographic relationship.	11
Catenal elements	Areas that have distinct hydrological regimes which are both cause and consequence of a particular combination of plant cover, soil, slope characteristics (e.g. gradient, curvature and aspect) and slope position.	19
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 (Figure 2.10).	18
Drainage network	A drainage network comprises a network of streams and the hillslopes that they drain.	3
Extent	The total area covered by a map.	32
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.	35
Grain	The smallest spatial unit sampled. In a remotely sensed image, grain is equivalent to the resolution (pixel size).	32
Landscape dissection	The spatial organisation of slopes within a stream network is sometimes referred to as a pattern of 'landscape dissection' or landscape 'texture'.	4
Level of organisation	A vertical level within a hierarchy, associated with a particular spatial and temporal scale domain.	5
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.	35
Membership value	A value that signifies the likelihood of belonging to a certain class.	35
Microfeatures	Local associations between hydrology, soils and vegetation that are found within catenal elements.	19
Minimum Map Unit (MMU)	The smallest area mapped as a discrete unit.	32
Morphology	The shape of the land surface.	2
Morphometrics	Measures of slope and network characteristics	21
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.	41
Patch	Patches are discrete areas, with boundaries that result from discontinuities in environmental conditions.	5

Physiographic zones	Physiographic zones are areas with distinct patterns of geology and landscape dissection.	15
Process domain	A process domain is a patch that is characterised by dominant processes that interact to produce the observed pattern.	5
Prototype	Idealised representations of the central tendency within each class	35
Scale Domain	The range of scales that are characteristic of a hierarchical level and over which patterns of the phenomenon of interest change either very little, or change systematically with changes in scale.	32
Stream order	In the Horton-Strahler method of stream ordering (e.g. Horton, 1945, 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 (Figure 2.7).	16
Super sites	Areas within KNP that are 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.	109
Support	The area over which variables are averaged.	32

ACRONYMS

See page

CAO	Carnegie Airborne Observatory	33
CASS	Contributing Area to Stream Segment	18
DEM	Digital Elevation Model	6
GIS	Geographic Information System	31
HPD	Hierarchical Patch Dynamics	5
KNP	Kruger National Park	8
LiDAR	Light Detection And Ranging	22
MAUP	Modifiable Areal Unit Problem	6
MMU	Minimum Mapping Unit	32
NDVI	Normalized Difference Vegetation Index	41
SAM	Strategic Adaptive Management	107
SRTM	Shuttle Radar Topography Mission	33
TPC	Threshold of Potential Concern	107
TPI	Topographical position index	45

CHAPTER 1 INTRODUCTION

1.1 Project Aims

The overarching aim of this research is to describe patterns of soils, vegetation and hydrology in the savanna landscapes in Kruger National Park (KNP) that are spatially organised at various scales by the configuration of drainage networks.

Specific objectives were to:

- Develop a hierarchical conceptual framework within which the structure, function and dynamics of water-controlled ecosystems can be described, explained and predicted. The framework will include both drainage networks and hillslopes, so that linkages can be described and explored in a holistic manner across the entire landscape.
- Construct a spatially explicit, scaled and hierarchically nested classification of Kruger National Park landscapes, based on the conceptual framework.
- Explore the hydrological, geomorphological and ecological implications of the diversity and spatial arrangement of elements at each scale (representing an organisational level in the hierarchical model).
- Integrate the framework and classification into the Kruger Park management system as a test case for broader application.

1.2 A holistic perspective on landscape structure

The description, explanation and prediction of the intertwined landscape patterns of water, soil, vegetation and topography remain challenges at the frontiers of hydrology, soil science and ecology. These patterns are not easy to disentangle, since they occur across many scales and are influenced by the local characteristics of each factor as well as by the climate, geology and relief of the environment in which they occur (Scull *et al.*, 2003, Ridolfi *et al.*, 2003, Rodriguez-Iturbe, 2000, Grayson and Bloschl, 2000). The characteristics of soil, vegetation and water fluxes are notoriously variable in time and space and are subject to influence by a wide range of other factors such as fire, herbivory and organisms, most of which are also highly variable across small spatial and temporal scales (O'Connell *et al.*, 2000). Many of the interactions are non-linear and often have different outcomes at different times and in different contexts, depending on factors such as antecedent conditions, the sequence of events, the spatial configuration of patches and within-patch heterogeneity. This complexity confounds attempts at deterministic, process-based modelling (Sivakumar, 2008), and has frustrated many scientists attempting to unravel the 'Gordian knot' (Jenny, 1941) of entangled relationships between vegetation, soils and topographically controlled water fluxes.

Despite landscape complexity, in many circumstances the distributions of vegetation and soils are spatially aligned and occur in patterns that are both cause and consequence of topographically controlled water fluxes. The associations between soils, vegetation and hillslope position are exploited by soil mappers, who use terrain and vegetation as indicators of soil patterns (e.g. Moore *et al.*, 1993, Ziadat, 2005, Park *et al.*, 2001), and by hydrological modellers using topography and soils to infer water flows (e.g. Chamran *et al.*, 2002, Guntner *et al.*, 2004, Lin *et al.*, 2006, Park and Van De Giesen, 2004, Beven and Kirkby, 1979). Ecologists and vegetation scientists also recognise the coupling of vegetation, soil, hydrological and topographical patterns in their efforts to map resources available to organisms and to model fluxes of materials such as carbon or nutrients (e.g. Franklin, 1995, Bridge and Johnson, 2000, Florinsky *et al.*, 2002, Porporato *et al.*, 2003). As Mucina and Rutherford comment when introducing their most recent South African vegetation map (2006), the theory and practice of vegetation mapping has moved from a floristic-sociological approach to an approach based on the spatial correlation of a wide range of environmental layers covering climate, soil and topography. Both vegetation and soil maps based largely on topographic analysis have now been produced for most countries and regions of the world, mostly in response to demands for the quantification of agricultural potential and/or for spatial biodiversity assessments used to inform conservation planning.

None of these efforts have so far delivered a conceptual model that can be generally applied across all regions, even at a single scale. This failure to deliver a standard approach is due in part to the nature of surface forms and processes and in part to fragmented approaches arising from the varying paradigms and methods of investigation used in different disciplines.

Reflecting on the complexity of terrain analysis, Pike (2002) adapted physicist Wolfgang Pauli's comment to suggest that "the earth's surface was invented by the devil". Both the variables and parameters that most accurately describe relations between topography and soils or vegetation can vary between geological and climatic settings. Furthermore, local heterogeneity confounds attempts to interpolate results across scales. We propose that these issues often arise from errors and ambiguities due to mismatching scale, pattern and process, and that the framework developed in this project provides a sound basis for describing the landscape patterns produced by the interactions between soil, water and vegetation over a range of spatial and temporal scales. We will suggest not only that landscape patterns are best viewed as a hierarchy, but also explain how the scales associated with each organisational level within the hierarchy vary between physiographic settings.

Disciplinary boundaries have also hampered the development of an integrated conceptual model to inform the description and study of landscape patterns. Many studies designed to describe or predict outcomes of earth-surface processes only incorporate two or three dimensions of the linkages between soil, water, vegetation and relief. Furthermore, the disciplinary fragmentation of landscape perspectives has led to the separation of the study and management of aquatic and terrestrial systems. For example, geographical descriptions of drainage network morphology have generally considered channel and riparian elements and ignored the character of the adjoining slope of the interfluves. Whereas fluvial geomorphologists emphasise the role of the network in determining the character and behaviour of channel and riparian elements, terrestrial geomorphologists focus on hillslope processes that are both cause and consequence of the nature of terrestrial landforms. In soil science, the relationships between terrestrial landforms and soil properties are exploited in predictive soil mapping (see Deng, 2007, McBratney *et al.*, 2003 for reviews). However, these terrestrially-focussed studies do not consider landforms in the context of a stream network in which landscape dissection patterns vary systematically according to network position, such that hillslopes associated with headwater streams have a different character from hillslopes found further downstream. The disciplinary divides within science extend to the application of the science in conservation planning. Systematic conservation planning (Margules and Pressey, 2000) is based on biodiversity assessments in which aquatic and terrestrial components are usually considered separately. Little progress has been made, despite frequent calls for the integration of these components (e.g. in the South African National Spatial Biodiversity Assessment (Driver *et al.*, 2005) and in the Kruger National Park Management Plan (2008). We suggest that this lack of progress is rooted in the challenge of marrying 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.

Despite the challenges of uniting the network and patch perspectives, we consider the integration of riverine and terrestrial perspectives essential to framing system perspectives of landscape patterns and processes. 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 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. 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. 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.

Both in tropical and arid or semi-arid systems, the distinction between riverine and terrestrial systems is often blurred, with little surface differentiation between channelised flow paths and overland or subsurface flow paths. In semi-arid regions it is easy to overlook the important role played by ephemeral streams in shaping landscape patterns of soil and vegetation and subsequent impacts on biodiversity. For example, in our study area, Kruger National Park, aquatic research and management strategy, plans and monitoring have focused on the 600 km of perennial rivers, whilst the 30 000 km of seasonal and ephemeral streams are effectively ignored, falling uncomfortably between the aquatic and terrestrial components of the system (O'Keefe and Rogers, 2003).

A holistic view that unites the slopes and channels of the drainage system provides an important perspective for describing and explaining landscape pattern. The drainage network can be conceived as a four- dimensional 'fluvial hydrosystem' (Petts and Amoros, 1996), in which fluxes of water and sediment produce characteristic physical and biological patterns along the longitudinal course of a river (as described by the River Continuum Concept (Vannote *et al.*, 1980)), laterally along a gradient perpendicular to the channel, vertically both above and below the stream bed and temporally, as seen in successional sequences of the re-establishment of plants and animals following disturbance events such as floods. Although these broad gradients may be frequently interrupted by some aspect of local heterogeneity, the position of a landscape patch within the stream network is usually an important contextual constraint on the character and behaviour of the patch. For example, the topography of a river basin usually varies systematically with network position, such that headwater catchments typically contain shorter steeper slopes than catchments located further downstream (Horton, 1945). This has knock-on effects for water transmission and storage, and hence for the distribution of soils and vegetation. The highly organised spatial arrangement of the hillslopes and channels that form a drainage network thus imposes patterns on soils and vegetation at multiple scales. Since vegetation and soils also influence water distribution, the spatial organisation of the various components of the landscape are best seen as resulting from self-organisation over a long history of co-evolution.

1.3 Integrating terrestrial patches with riverine networks

The key to integrating network and patch perspectives is to stop viewing channels as separate entities from the hillslopes that drain into them. 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)*

When rivers are viewed as 'entire leaves' it becomes easier to place hillslopes in the context of their network position and to see landscape patterns that are associated with network position at different scales. A stream ordering system (e.g. Strahler, 1957, Horton, 1945) provides a convenient way of describing network position, so that patterns 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 (see Figure 2.7 below).

When visualising landscapes in this way the scale issues associated with the detection and description of landscape patterns become easier to grasp. Within a particular physiographic setting, there is usually a limited range of variability in the character of areas draining different order streams, such that catchments associated with first order streams tend to be of a certain size and morphology, those draining into second order streams tend to be a certain (larger) size, with slightly different morphology, etc. These relationships have been recognised for decades and are articulated in Hack’s Law, which relates the area drained to the length of the main stream channel (Hack, 1957) and Horton’s Laws, which relate increasing stream order to the area drained, the length and number of streams and the hillslope gradient (Horton, 1945, Strahler, 1957). The spatial organisation of slopes within a stream network is sometimes referred to as a pattern of 'landscape dissection' or landscape 'texture'.

Whilst stream order is a useful descriptor of network position, it is also extremely scale sensitive, depending on the scale at which streams are mapped: a coarse scale map will ignore small low-order streams and so lower the order assigned to larger streams, whilst a fine scale map will raise the stream order assigned to the same large streams. Furthermore, changing the scale at which stream order is assigned has different effects in different physiographic settings, depending on the way in which streams are initiated. If stream initiation creates a large number of ‘fingertip’ streams, then the order of large streams will be greater than in situations where streams tend to start from a single source, such as a wetland. For this reason, comparisons between the same order streams in different physiographic settings need to be undertaken with caution.

Nevertheless, within a particular physiographic setting, patterns of landscape dissection can be conveniently described in terms of the horizontal and vertical dimensions of the slopes associated with each stream order. Measures of the horizontal dimension (landscape wavelength) include channel spacing and stream density. The vertical dimension (landscape amplitude) can be measured in terms of relief intensity, which is the range of elevation found within catchments of each stream order. However, the optimum scales of observation associated with these measures change between physiographic settings. As stream initiation processes and stream density vary between areas with different geology, climate, soils and vegetation, so do patterns of incision. Whilst some finely dissected areas demand fine scales of analysis, in other areas with low stream density, the large distances between streams demand much larger scales to capture the morphological character of catchment slopes.

Thus both the assignment of stream order and the optimum scales for describing patterns of incision vary between physiographic settings. The use of a hierarchical framework helps to resolve this issue, since each pattern of landscape dissection can be analysed separately within the context of its own physiographic zone. Such an approach helps to avoid mismatches of scale, pattern and process and to address the landscape complexity that arises from multiple feedbacks within and across scales.

1.4 A hierarchical basis for our framework

The framework is developed within the paradigm of 'hierarchical patch dynamics' (HPD). Linking ideas from hierarchy theory and complex systems theory, Wu and Loucks (1995) suggested that the temporal and spatial heterogeneity of ecosystems can 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 (Figure 1.1). Patches are discrete areas, with boundaries that result from discontinuities in environmental conditions that are large enough to be perceived by an organism of interest or to influence an ecological process of interest (Wiens, 1976). Each patch can be considered as a 'process domain', characterised by dominant processes that interact to produce the observed pattern. If the nature and rate of the dominant process(es) is(are) similar across the whole patch, then the patch will appear homogenous. Where fractal patterns are seen across several scales, this suggests that the same processes dominate across these scales, indicating the limits at which cross-scale extrapolations are valid (Wiens *et al.*, 1995).

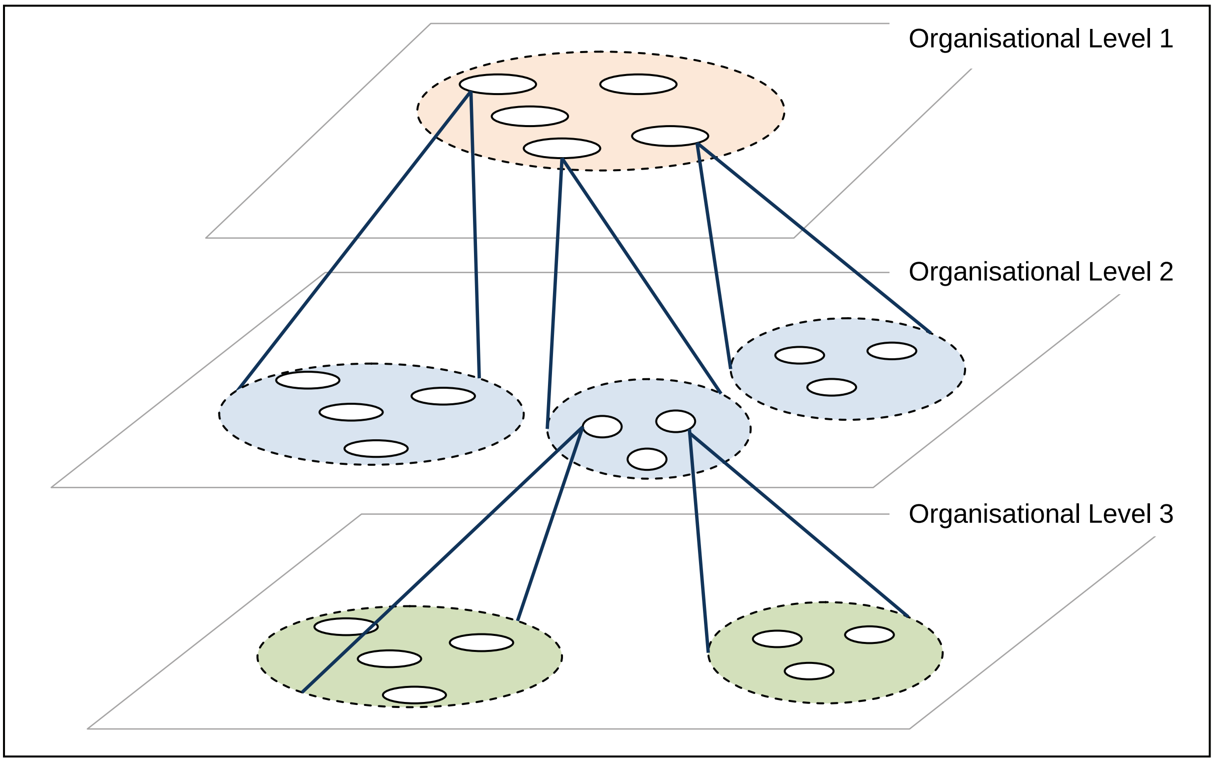


Figure 1.1: Conceptual diagram of a nested hierarchy.

At each organisational level, landscape patches are seen as system components, and are characterised by pattern and processes that are more different between than within patches.

According to HPD and hierarchy theory, each hierarchical level of organisation within a given system is associated within a characteristic spatial and temporal scale domain, determined by the rates of the processes that produce the observed patterns. Higher levels are characterised by patterns evident at coarse spatial and temporal scales, produced by processes that operate at relatively slow rates. Faster processes characterise lower levels of organisation and are responsible for the patterns observed at finer scales (Turner *et al.*, 2001).

The focus for this project is on change within the annual and decadal timeframes relevant to conservation management, rather than on system evolution over far longer periods. Although we assume that patch boundaries are static, we recognise that the character and behaviour of some landscape elements may change within management timeframes as a result of herbivory, disturbances such as fire or flood and/or human intervention. The vast majority of these changes operate within boundary conditions imposed by the hierarchical spatial context that limit the range within which form and process can vary. Occasionally a response may completely alter the state of a patch, sometimes irreversibly (Scheffer *et al.*, 2001) . When such a ‘catastrophic state shift’ occurs, boundary conditions may be altered, both for contained elements and possibly for higher level elements as well. This framework is not intended to cover such eventualities, addressing only the variability in form that is associated with common events. We hope that subsequent projects will build on our research, describing and understanding the boundary conditions that limit the range of variability in form for classes of elements located in different spatial contexts.

The definition of patches and the scale at which they are best observed is entirely dependent on the perspective and purpose of the observer. Although patches are viewed as internally homogeneous at the focal scale of a study, at smaller scales patches are usually highly variable and may have component parts and at larger scales, the heterogeneity observed in a patch mosaic may no longer be visible (Wiens, 1989, Wu and David, 2002). This observation is related to the first component of the the Modifiable Areal Unit Problem (MAUP) (Openshaw and Taylor, 1979, 1981), which describes changes in the perception of spatial entities that result from changes in grain, which in our case is equivalent to pixel size.

The second component of the MAUP, which has received far less attention in the ecological literature (Jelinksi and Wu, 1996), considers changes in the perception of objects resulting from different ways of aggregating the basic units. For example, the shape and size of a moving window used to calculate gradient and other measures of topographical variation has profound effects on the delineation and characterisation of hillslope elements such as crests and valley bottoms (e.g. Figure 4.11 below).

One solution to the MAUP is to identify meaningful spatial entities or objects that have an intrinsic scale (Fotheringham, 1989). For example, if the focus is on individual trees, then a suitable grain size, minimum mapping unit (MMU) and extent can be determined based on the dimensions of the trees and the required boundary precision. In this study, we address the MAUP by focussing on catchments, which are both ecologically meaningful spatial entities and have an intrinsic scale. Catchments are natural units, with both channels and watersheds acting as boundaries for many fluxes of materials and energy. Although catchments can be delineated in many ways and mapped at different scales (see chapters 3 and 5), within each of these perspectives, catchments are distinct entities with boundaries that can be determined from a Digital Elevation Model (DEM). In our landscape hierarchy, physiographic zones are characterised by patterns of landscape dissection that are analysed in terms of the morphology of the catchments they contain. At a lower level of organisation, catchments contain assemblages of catenal elements, patches with distinct associations between soil, vegetation and hydrology that are arranged down catchment slopes in a sequence that is characteristic of a certain network position within a particular physiographic zone (see chapter 2).

1.5 Ecological landscape classification

Dividing the landscape into spatial units that are internally relatively similar in terms of both biotic and abiotic features falls within a long tradition of ecological land classification. Such classifications have been developed in most countries, in order to pragmatically apply ecological science to support decisions related to land use planning and policy and are usually based on similar principles to those described above. In working towards delineating ecological regions in North America, a group of American, Canadian and Mexican scientists neatly summarised the key points in mapping ecological regions (Commission for Environmental Cooperation, 1997 p.6):

- "Ecological land classification incorporates all major components of ecosystems: air, water, land, and biota, including humans.
- It is holistic; 'the whole is greater than the sum of its parts'.

- The number and relative importance of factors helpful in delineating ecological units varies from one area to another, regardless of the level of generalization.
- It is based on a hierarchy with ecosystems nested within ecosystems.
- It involves integration of knowledge and is not simply an overlay process.
- It recognizes that ecosystems are interactive and that characteristics of one ecosystem blend with those of another.
- It recognizes that map lines generally depict the location of zones of transition."

The task of ecological land mapping is grounded in a view of the universe that treats land units holistically as complex webs of components and linkages, as opposed to treating individual components separately. A holistic, systems-based approach to ecology stresses that a component of the system can only be fully understood in relation to the whole. For example, organisms can only be fully understood in relation to their environment, with which they co-evolve. Complexity science develops these ideas further, noting that since the behaviour of a system component cannot be entirely predicted from the character and behaviour of its constituent elements, system behaviour cannot be perfectly predicted, no matter how many data sets are available. Holism stands in opposition to scientific reductionalism, which holds that the behaviour of any part of a system can be fully understood, modelled and predicted from a comprehensive understanding of its constituent elements.

The emphasis on a holistic description and study of ecosystems finds widespread practical application in conservation planning, and informs conservation management policies that aim to conserve the processes and connectivities that sustain healthy ecosystems rather than focussing on the individual species or system components that the system supports.

However, the central concept of ecosystems as spatial entities with discernable boundaries is questioned by others, who demonstrate not only that the central notion of discrete ecosystems is highly ambiguous, but also that such entities do not exist other than as mental constructs in the mind of observers (Fitzsimmons, 1996, Jax, 2006, Pickett *et al.*, 2005, Pickett and Cadenasso, 2002, O'Neill, 2001).

Accepting the ambiguity and subjectivity inherent in the definition and delineation of ecological land units does not necessarily imply that such units cannot be characterised, mapped or studied, nor does it imply that land management based on such units is misguided. Instead, we are challenged to devise new ways of studying and managing ecological systems, dealing with complexity, uncertainty and fuzzy boundaries. We believe that our approach, grounded on catchments as meaningful, unambiguous spatial entities, offers a way forward that is useful to environmental managers and scientists alike.

1.6 Evaluation of the proposed framework

Our conceptual framework aims to provide a perspective within which the structure, function and dynamics of water-controlled ecosystems can be described, explained and predicted, helping managers and scientists avoid the errors and ambiguities that arise when scale, pattern and process are mismatched. The framework is not a theory, but rather a contribution to an emerging holistic paradigm (sensu Kuhn, 1962) of natural systems, a 'portrait' of the world that contains theories, models, concepts, knowledge, assumptions and values that can help scientists and conservation managers frame research problems and solutions that can deal with the complexity of natural systems.

A paradigm cannot be formally evaluated, since no independent standards exist. Instead, paradigms succeed or fail according to the extent to which they are adopted by a community of people. In order to gain acceptance, a paradigm, or part of a paradigm, such as our conceptual framework, must be both credible and useful (see e.g. Cash *et al.*, 2003).

In order for our framework to be *credible*, it needs to be founded on convincing arguments with no internal contradictions and to be consistent with empirical observations and the previous experience of potential users.

In order for the framework to be *useful*, not only does it need to be relevant and fit for purpose, but it also needs to be easily communicated and not overly complex, yet contain sufficient detail to meet users needs. It should also be cost effective to apply, using highly automated routines, without being entirely dependent on expensive data sets or imagery, extensive surveys or expert knowledge.

We have validated our framework against these criteria by using the framework to inform a spatially explicit classification of ecological units in Kruger National Park (KNP). This classification demonstrates that the framework is consistent with empirical observations and is therefore credible. It should be noted that consistency does not imply a perfect fit, since the complexity of natural systems defies even the most detailed description, and can only be captured in the most simple form in a series of maps. Furthermore, there is no widely accepted way of assessing the accuracy of maps of ecological units, particularly those using fuzzy classifications.

We also suggest ways in which the framework can be used to link the patterns described in the classification with likely causal processes (see chapter 7). The classification does not consist merely of statistical constructs, but is purposefully designed within the context of the framework to relate to the processes that generate and sustain the observed patterns. In other words, the classification is based on process, rather than form, such that areas that are grouped into a particular class can be expected to respond in similar ways to a wide range of events, be they natural disturbances, climate change or scientific manipulations. This means that the classification can be used to stratify samples for ecological, hydrological or management experiments or modelling. As McMahon *et al.* explain:

> *"A theory-based understanding of a region's identity is a necessary condition not only for developing and testing hypotheses about the regional framework, but also for understanding the capabilities and limits of a framework for management and planning purposes." (McMahon et al., 2004 p. S122)*

This project represents only the initial stage of a large undertaking. Much work remains to be done as the framework is used, refined and expanded to include new knowledge and methodologies. As more is learnt about the relationships between pattern and process at different scales in different contexts, so the framework and the classifications derived from it will be developed together in an iterative, adaptive, transdisciplinary process.

1.7 Report outline

The first part of this report presents the framework we propose for the study and management of water-controlled ecosystems. In chapter 2 we review the theoretical basis for the framework and its underlying assumptions and present the landscape hierarchy that is used to decompose landscapes and riverscapes into discrete components. In chapter 3 we explain the methods used to develop a classification of landscape units in KNP that is based on the framework. Chapters 4-6 illustrate the application of the framework to landscape classifications at three hierarchical levels of organisation: physiographic zones, catchments and catenal elements. In chapter 7 we review the classifications that have been produced in southern KNP, relating the observed patterns to likely causal processes and drawing out some of the hydrological, geomorphological and ecological implications of the diversity and spatial arrangement of elements at each level of organisation. In conclusion, chapter 8 examines some potential applications of the framework in conservation planning, management and science.

CHAPTER 2 A CONCEPTUAL FRAMEWORK FOR THE STUDY AND MANAGEMENT OF WATER-CONTROLLED ECOSYSTEMS

2.1 Introduction

In this chapter we review the principles upon which our framework is based, and from which a hierarchy of landscape units is derived. In subsequent chapters we demonstrate how this hierarchy can be used to derive robust landscape classifications that have multiple potential applications in conservation management and science.

2.2 Principles

The framework is built on four key principles:

1) In water-controlled ecosystems, such as the savannas of KNP, many geomorphological and ecological processes are tightly coupled to the spatial and temporal distribution of water at various scales.

Since water is a limiting factor for a wide range of biogeochemical processes, including photosynthesis, seed germination, nutrient mineralization, soil weathering and the microbial breakdown of organic matter, a lack of water places severe constraints on ecosystem composition, structure and dynamics. In areas with little rainfall, the effects of water availability are so profound and wide-ranging that arid and semi-arid systems may be called ‘water-controlled ecosystems’ (Rodríguez-Iturbe and Porporato, 2004).

In semi-arid savannas, such as those found in KNP, water availability is a major control both on the range of plant species that can survive in a particular location and on plant productivity (e.g. Sankaran *et al.*, 2005, Scholes and Walker, 1993, Gessler *et al.*, 2000). In turn, the distribution of animals is influenced by the quantity and quality of forage available. The frequency and intensity of fires is largely controlled by the quantity and wetness of plant fuel. The nature and extent of vegetative cover also impacts the development of soils and the likelihood of erosion (Jenny, 1941, O'Connell *et al.*, 2000, Caylor *et al.*, 2006) (Figure 2.1).

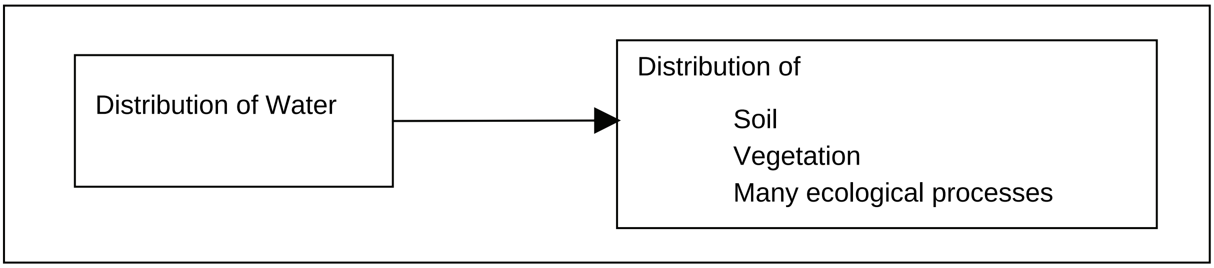


Figure 2.1: In semi arid systems, the distribution of soils, vegetation and many ecological processes is tightly coupled to the spatial and temporal distribution of water at many scales

2) Tight coupling of geomorphological, hydrological and ecological processes generates and sustains distinct landscape patches that are characterised by strong soil-vegetation associations. Each patch in the mosaic can be characterised by a hydrological regime that is both cause and consequence of the types of soils and vegetation found in the unit.

Since so many ecological and geomorphological processes are water-limited, they can only occur at places and times when sufficient water is available and often occur to a degree that is also dependent upon water availability. The amount of water at a particular place and time is determined not only by rainfall, but also by the partitioning of precipitation into water that is either *lost* through evapotranspiration, is *stored* locally or *moves* to an adjacent downslope area. The partitioning of water inputs depends on a multitude of interacting factors, including the amount of radiation, the type of precipitation (e.g. short intensive thunderstorms, extended periods of drizzle, etc.), the extent of vegetative cover, the infiltration and transmissive qualities of the soil and bedrock, the current water-holding capacity of the soil, aquifers and surface pools and the hillslope or channel gradient, which determines the amount of potential energy available to move water downhill. In short, hydrological partitioning is determined by *climate* (amount and intensity of rainfall and radiation), *lithology* (including both soil and substrate), *vegetation* and *topography*. Topography includes hillslope gradient (affecting the ability of water to drain away), aspect (affecting radiation and hence evaporation), curvature (affecting the rate of flow and flow path direction) and slope position (whether or not the area is in a position to deliver or receive water from adjacent areas).

However, climate, lithology, vegetation and topography are not independent factors. 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 and Shugart, 1993). Lithology, vegetation and climate interact to produce weathering and erosion regimes that are largely responsible for topography (e.g. Bull and Kirkby, 2002, Howard, 1967).

Within a given geological and climatic setting, the way rainfall and other water inputs are partitioned within a particular patch is both a consequence of and a control on the combination of soil and vegetation. Thus, in situations where water limits the processes controlling soil production and plant distribution, patches with relatively similar hydrological regimes and water budgets also contain relatively similar soils and vegetation (Figure 2.2).

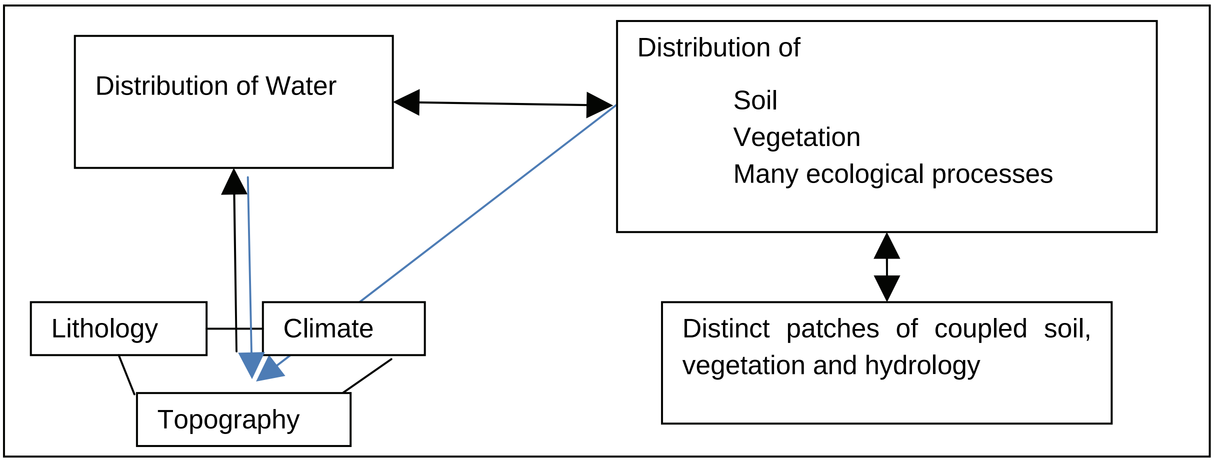


Figure 2.2: Tight coupling of soil and vegetation to the distribution of water generates and sustains distinct landscape patches Each patch has a combination of soil, vegetation and a hydrological regime that is different from its neighbours.

The distribution of water is controlled by interactions between climate, lithology and topography. The distribution of water, soils and vegetation also feed back to influence climate, lithology and topography at various spatial and temporal scales.

3) In a particular geo-climatic setting, topography is an important control on the redistribution of water across and through the landscape. At a hillslope scale, downslope landscape units may gain water at the expense of upslope units, which tends to result in repeated sequences of soil and vegetation units on similar slopes in a given geological and climate setting.

Topography is major control on the distribution of water within catchments, determining the direction of flow paths and the potential energy available for the gravity-induced movement of water and particles (Horton, 1945, Leopold *et al.*, 1964, Beven and Kirkby, 1979). This control is particularly evident at scales associated with individual hillslopes (Figure 2.3).

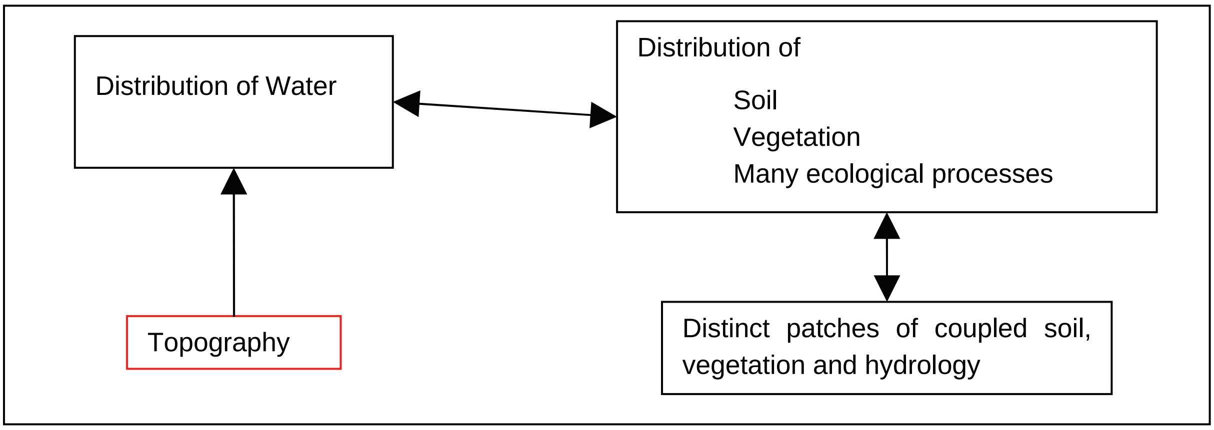


Figure 2.3: In a particular geo-climatic setting, topography is an important control on the redistribution of water across and through the landscape

Milne (1935) coined the term 'catena' to describe a series of soils linked by their topographic relationship. The catenal concept was further developed by Conacher and Dalrymple (1977) who suggested that the soils in a catenal series are formed through the different surface processes associated with particular hillslope forms. Their 'nine-unit model' identified nine such hillslope forms, each characterised by a dominant contemporary hydro-pedologic process regime responsible for characteristic soil and landform attributes (Figure 2.4). It is recognised that not all units are necessarily present on every slope and that the same units can be repeated down or across a slope. Differences between the process regimes associated with each unit are relative and context-dependent, such that there is no standard definition for units across all landscapes.

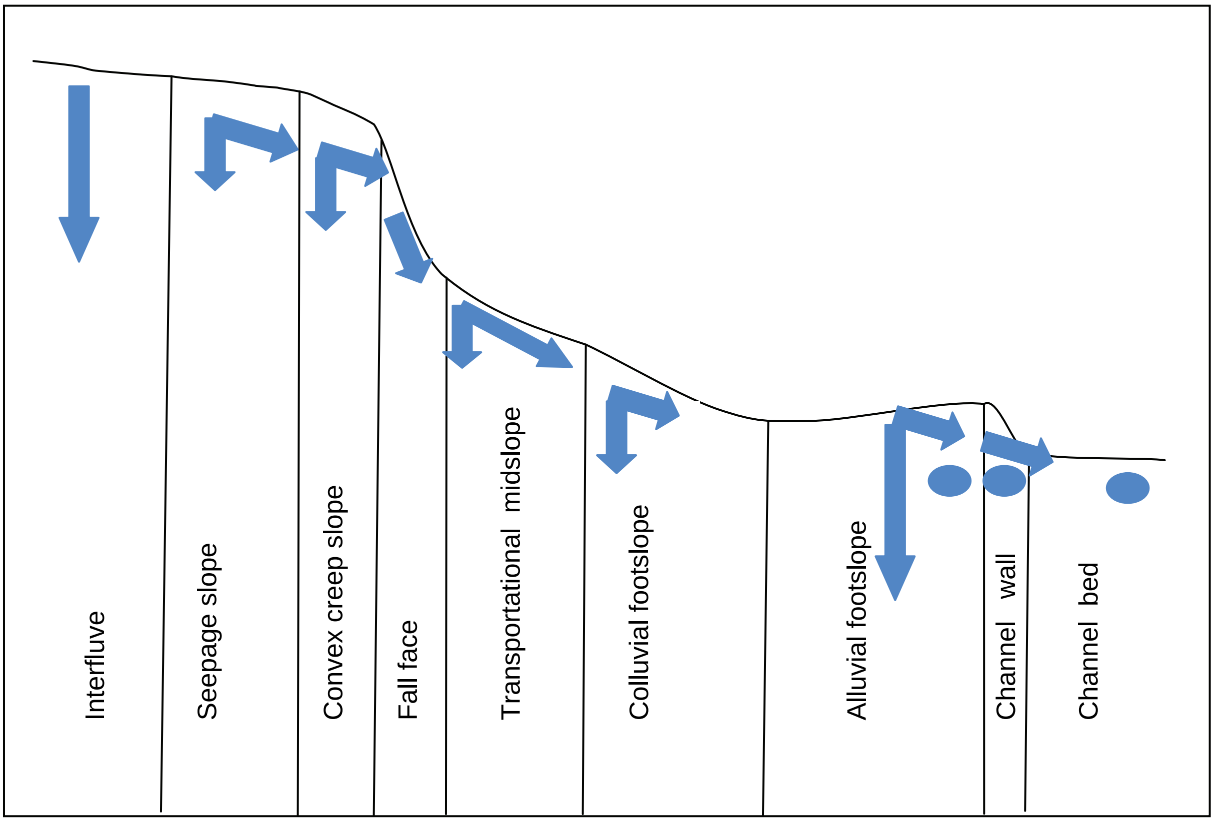


Figure 2.4: The 9-Unit Slope Model (after Conacher and Dalrymple, 1977)

The 9 slope units are not necessarily present on all slopes. Each unit is characterised by a distinct hydrological regime, with associated soil and vegetation. Blue arrows show the predominant directions of water movement in each unit. Oval circles represent flow along a stream (i.e. perpendicular to the surface of this paper)

Slope form and position have been shown to be closely associated with soil patterns in many different settings. For example, the crests of granite slopes in southern KNP often consist of well drained crests, with leached sandy soil that supports *Combretum spp*., whilst accumulation zones in the valley bottoms have nutrient rich, clayey soils that are dominated by *Acacia spp*. (Venter, 1990).

Links between slope topography and soil types have been used by soil mappers for decades in the field surveys, in photo interpretation and, more recently, in digital predictive soil mapping (see reviews by McBratney *et al.*, 2003, Deng, 2007).

The catenal and the nine unit models only considered hillslopes in two dimensions, as a downslope transect perpendicular to a channel, assuming straight overland and through-slope flow lines (Thwaites, 2006) and characteristics of the channel were ignored. Lateral boundaries to each landscape unit were also not defined. By contrast, sequences of elements that form a catchment mosaic are here treated as three-dimensional and fluvial elements are included.

4) Hillslopes and channels are highly organised within a drainage network, forming patterns of landscape dissection that vary systematically between different geological and climatic settings.

A drainage network includes not only the stream channels, but also the interfluvial hillslopes. Together, hillslopes and channels form a pattern of landscape dissection that is shaped by the flow of water and are highly organised in space (Figure 2.5).

The tendency to minimize total energy dissipation produces fractal patterns in drainage networks, with scale-invariant relationships between many topographical and network attributes (Rodriguez-Iturbe and Rinaldo, 1997). Geological and climate settings constrain these scale-invariant patterns of channels and slopes. It has long been recognised that particular drainage patterns (e.g. dendritic, rectangular, etc.) are associated with various substrates (e.g. Howard, 1967). It has also been suggested that the scaling exponents of Hack's and Horton's Laws are related to basin shape, stream density and channel sinuosity, functions associated with particular geologies and landscape histories (Rodriguez-Iturbe and Rinaldo, 1997, Rinaldo *et al.*, 1998).

Different patterns of landscape dissection are associated with different climate and geological histories, since variation in effective precipitation (rainfall less evapotranspiration), substrate permeability and relief lead to differences in the nature and degree of bedrock weathering and erosion. For example, impermeable substrates tend to generate more runoff than more permeable substrates. Increased runoff leads to a more dissected landscape, with higher drainage density and steeper, shorter slopes. Permeable substrates tend to favour vertical infiltration over surface runoff, generating a lower density drainage network with longer, shallower slopes.

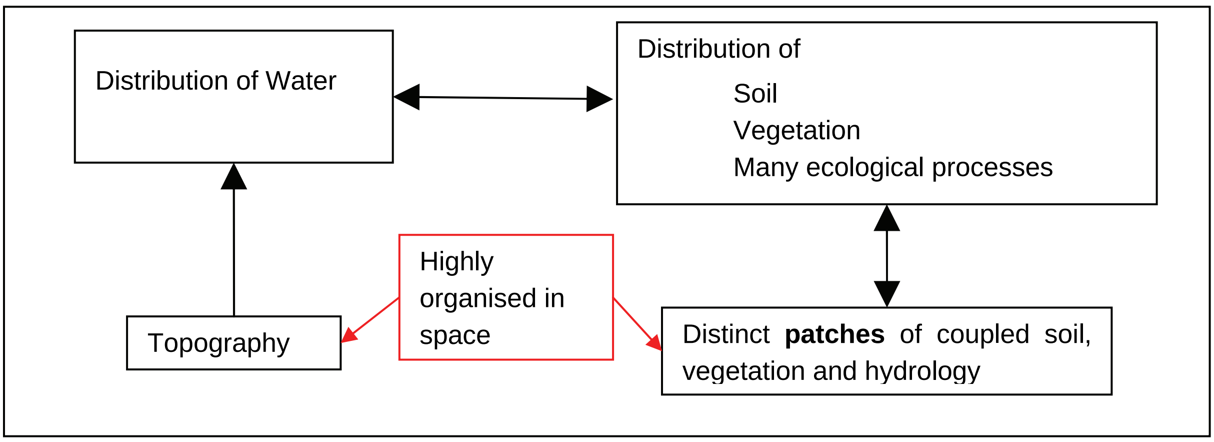


Figure 2.5: The topography of a drainage network is highly organised in space, which also organises patches of coupled soil, vegetation and hydrology

The gravity-induced movement of water, particles and solutes down and through hillslopes and channels not only shapes the landscape, but also is a major factor in the formation of soils and the distribution of vegetation. In turn, vegetation and soils feed back to influence fluxes of water and solutes. Thus biological patterns are linked to the morphological patterns and so vary systematically within a drainage network, forming a biophysical template upon which ecological processes are played out. These biophysical patterns are recognised in the River Continuum Concept (Vannote *et al.*, 1980), but are not only present in the longitudinal dimension along the course of a river. Patterns in all four dimensions of a river system (longitudinal, lateral, vertical and temporal) are described by Petts and Amoros (1996) in their concept of a 'fluvial hydrosystem', in which the spatial arrangement of both physical and biological elements is largely determined by fluxes of water that transport sediment, nutrients and organic material. Functional and genetic links between adjoining elements allow cascading interactions and the transfer of matter and energy between landscape elements. These interactions and transfers result in clinal patterns that can be conceptualised as continua in all four dimensions. Although Petts and Amoros focus on stream channels in describing their hydrosystem, given the intimate relationship between fluvial channels and the hillslopes that drain into them, the concept can be extended to include the entire landscape.

However, climatic and geological boundaries frequently cut across drainage basins, imposing different patterns of landscape dissection on top of the broad-scale patterns associated with network position. Thus, many river systems appear to break all the 'rules' of idealised 'fluvial hydrosystems', confounding attempts to predict the spatial organisation of different elements. Geomorphological landforms and biological assemblages not only often fail to conform to the sequences predicted by the idealised theories, but transitions are often abrupt, rather than exhibiting the gradual changes suggested by the notion of a continuum (Townsend, 1989, Montgomery, 1999, Poole, 2002). We will suggest that such transitions are often associated with transitions between the physiographic zones that form higher level elements of the landscape hierarchy and that viewing the landscape from a hierarchical perspective provides a framework within which many of the discrepancies observed between real and idealised systems can be resolved.

2.3 A hierarchy of landscape units

A fundamental concept in our framework is that soils, vegetation and topography co-evolve, creating distinct patterns in the landscape. However, the perception of pattern depends entirely on the scale of observation (Levin, 1992). A hierarchical perspective can be used to guide this choice of scale, structuring our viewpoint so that we can discern and consequently map discrete landscape entities.

A hierarchical perspective of the landscape involves viewing patches of land as components of a system that is structured both

- *vertically*, where the components are separated into different levels of organisation, each of which has a characteristic scale and
- *horizontally*, where differences between components are greater than differences within components (Allen and Starr, 1982) (Figure 1.1).

The landscape hierarchy has five organisational levels:

- Biomes
- Physiographic zones
- Catchments – which may be defined in relation to different order streams, forming nested sub-levels (see below)
- Catenal elements
- Microfeatures

Biomes

Biomes are the highest level at which biotic and abiotic associations can be identified and mapped, characterised by the emergent properties of species assemblages and broad scale environmental factors such as climate and fire regime (see Rutherford and Westfall, 1986 for full discussion on issues regarding the definition of biomes, also, Bond, 2005). KNP lies within the savanna biome of South Africa (Mucina and Rutherford, 2006).

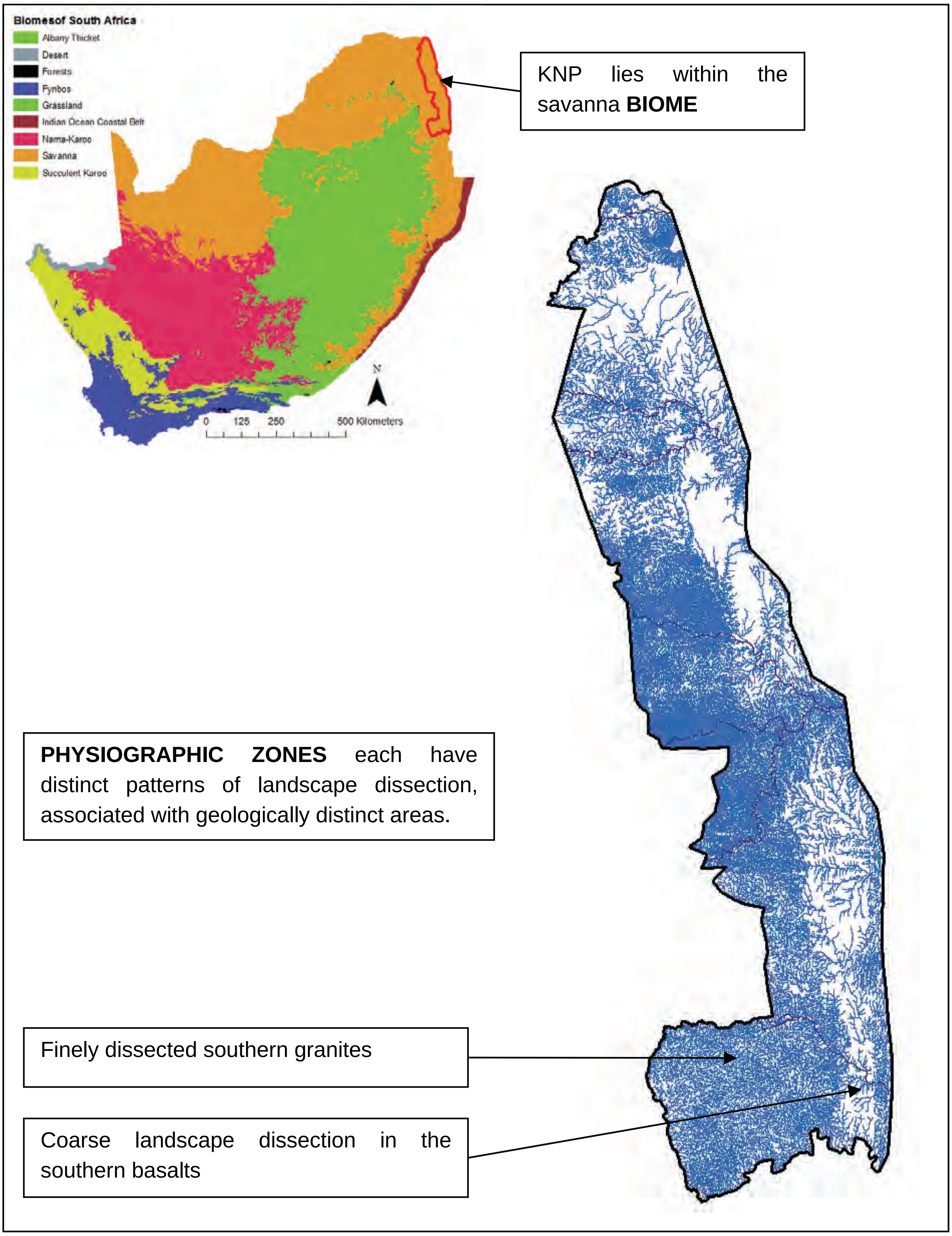


Figure 2.6: Biomes of South Africa ((Mucina and Rutherford, 2006) and stream density, illustrating different physiographic zones in KNP

Physiographic zones

Physiographic zones are areas with distinct patterns of geology and landscape dissection, which is defined in terms of catchment, hillslope and stream network morphology. Patterns of landscape dissection show spatial grouping as they result from landscape evolution shaped by similar processes of erosion under the same climatic and geological history. Patterns associated with network position are repeated within areas of similar landscape dissection, such that headwater streams and slopes are similar throughout the region, as are the streams and slopes found at various downstream positions.

Catchments

Catchments are areas that drain into a particular stream or stream segment. Catchments are natural units, in which both channels and watersheds act as boundaries for many fluxes of materials and energy. Catchment morphology is also a major control on the direction and speed of water movements within and through a catchment.

In theory, catchments can be defined in an infinite number of ways, as they can be areas that drain to any 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. We define catchments as areas that drain the whole of a stream of a particular stream order, using the Horton-Strahler method of stream ordering (Horton, 1945, 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 (Figure 2.7).

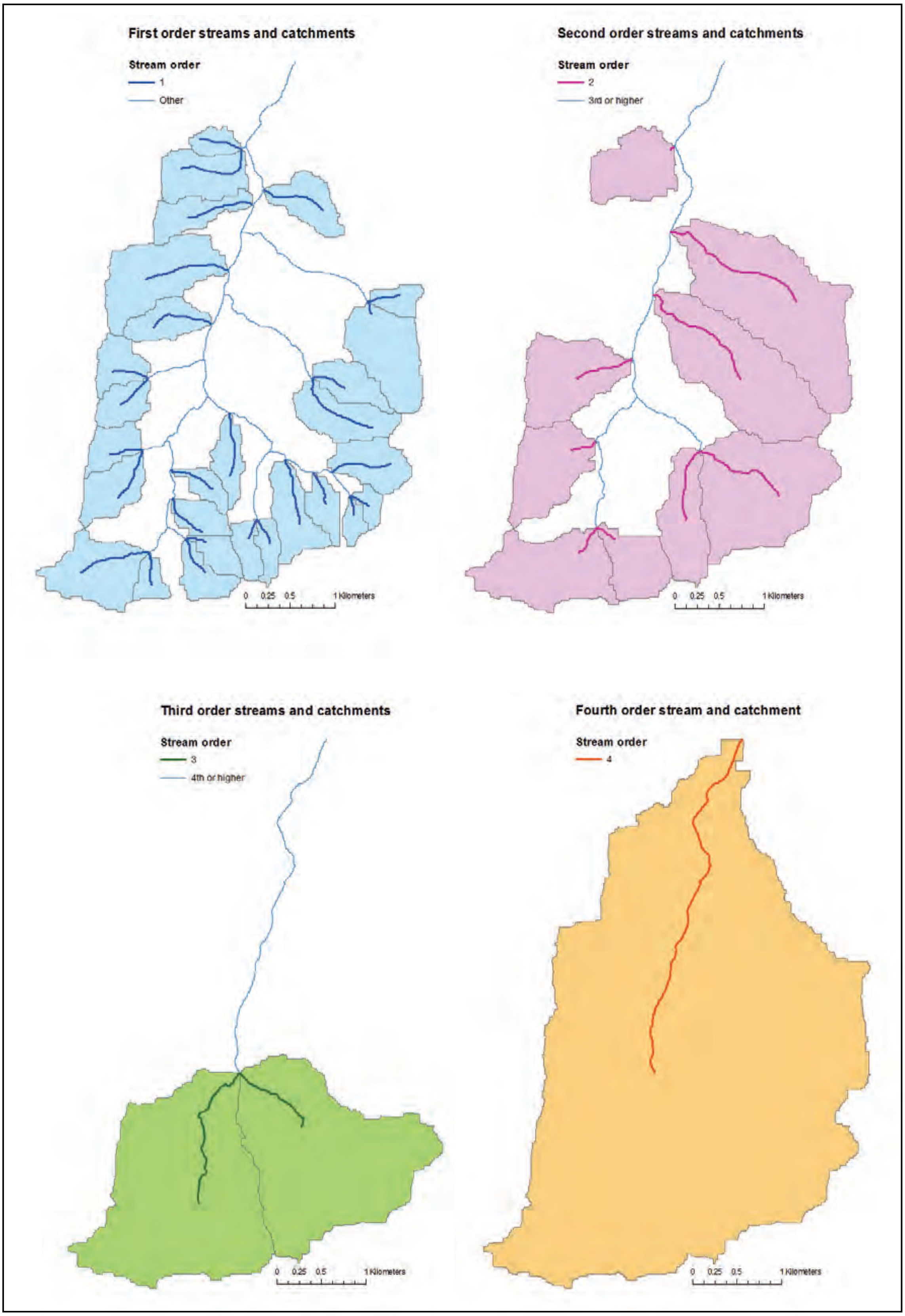


Figure 2.7: Catchments of different stream orders

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.

It is possible that different landscape patterns are associated with each stream order. For example, there may be a vegetation/soil gradient associated with a large fourth order catchment, upon which patterns associated with first and second order catchments are superimposed (Figure 2.8). In such circumstances, the catchment level of organisation may be further decomposed into various sub-levels, each associated with a particular stream order.

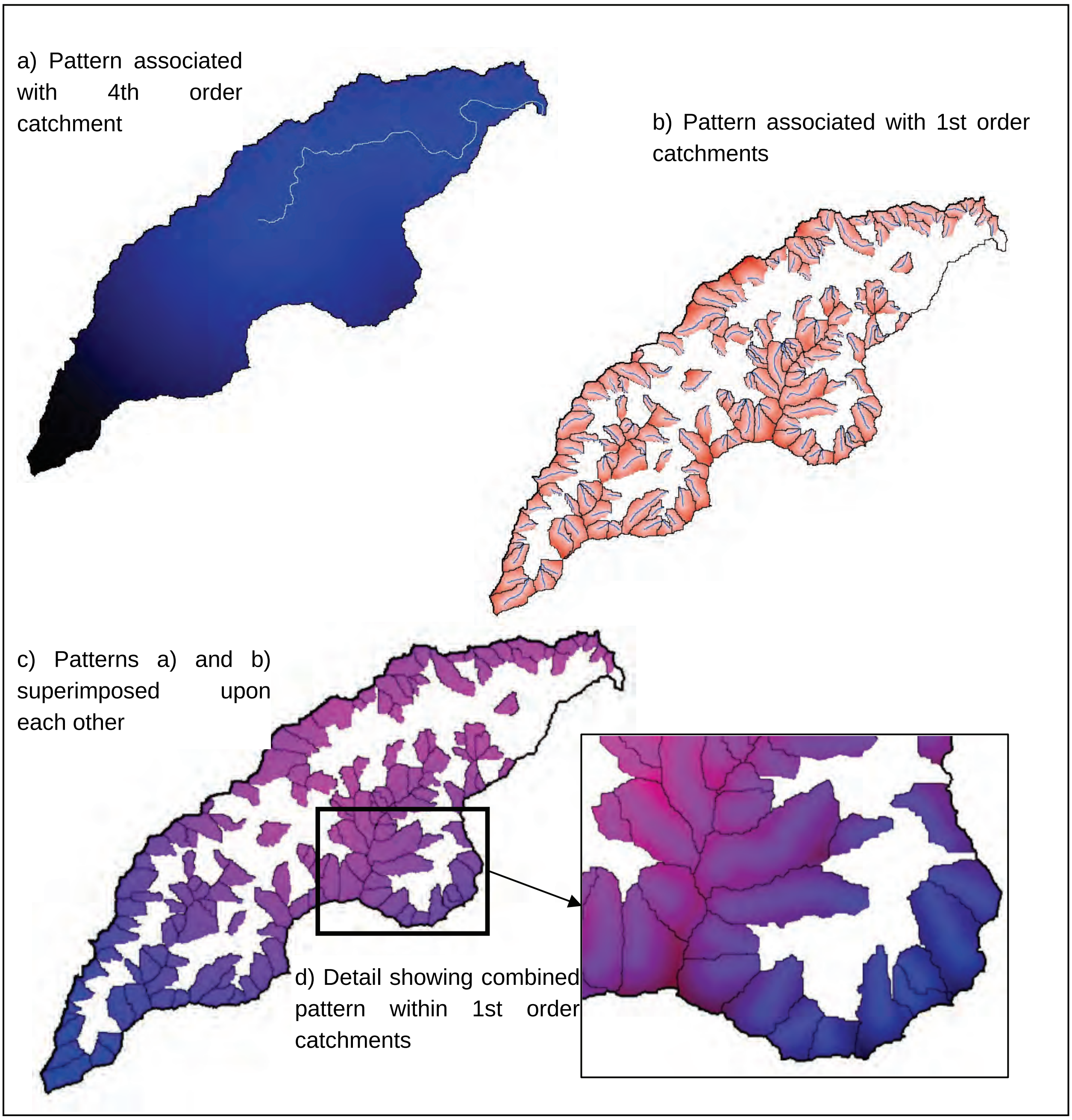


Figure 2.8: Different patterns of soil and vegetation may be associated with different stream orders

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.

Catchments defined in terms of the area draining to an nth order stream do not cover the entire landscape, since 'interior' ('adjoint') catchments lie between each basin (Figure 2.9). In order to analyse the whole landscape in terms of areas draining to a stream of a particular order, we use CASSs (Contributing Areas to Stream Segments). 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 (Figure 2.9). Large areas of the landscape are excluded when catchments of any particular order are considered, whereas partitioning into CASSs achieves coverage of the entire landscape (Figure 2.10).

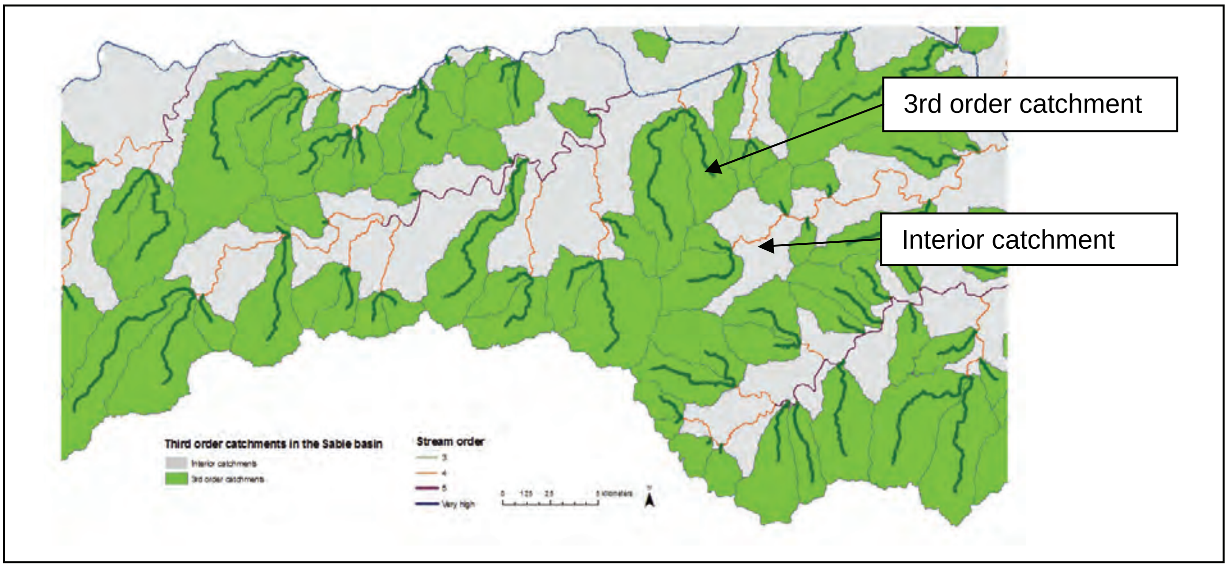


Figure 2.9: Third order catchments in the Sabie basin

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

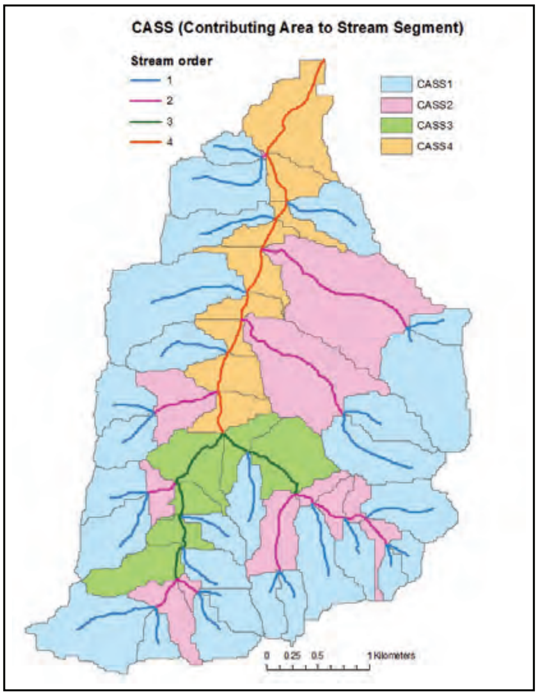


Figure 2.10: CASSs of different stream orders

Contributing areas are numbered according to the order of the stream segment they drain into.

Catenal elements

Catenal elements are areas that have distinct hydrological regimes which are both cause and consequence of a particular combination of plant cover, soil, slope characteristics (e.g. gradient, curvature and aspect) and slope position (Figure 2.11). Distinct assemblages of catenal elements are usually associated with different network positions within each physiographic zone, forming a repeating pattern characteristic of that zone.

Catenal elements reflect the soil/vegetation associations described in the catenal and 9-unit models (see p10 above). Catenal elements are three-dimensional entities that are found over the entire landscape, including channel and riparian zones as well as hillslopes.

In theory, catenal elements may be delineated using slope positions calculated in relation to catchments of any steam order. We start by defining hillslope positions (e.g. crests, valley bottoms, etc.) in relation to CASSs, since these units offer complete coverage of the landscape at the finest scale at which the drainage network is mapped. We then explore whether or not other sets of catenal elements need to be defined in relation to large order catchments by determining whether or not there are superimposed vegetation patterns associated with 2nd and higher order streams.

Microfeatures

Microfeatures are local associations between hydrology, soils and vegetation that result in features such as pans, termite mounds or gravel bars (Figure 2.11).

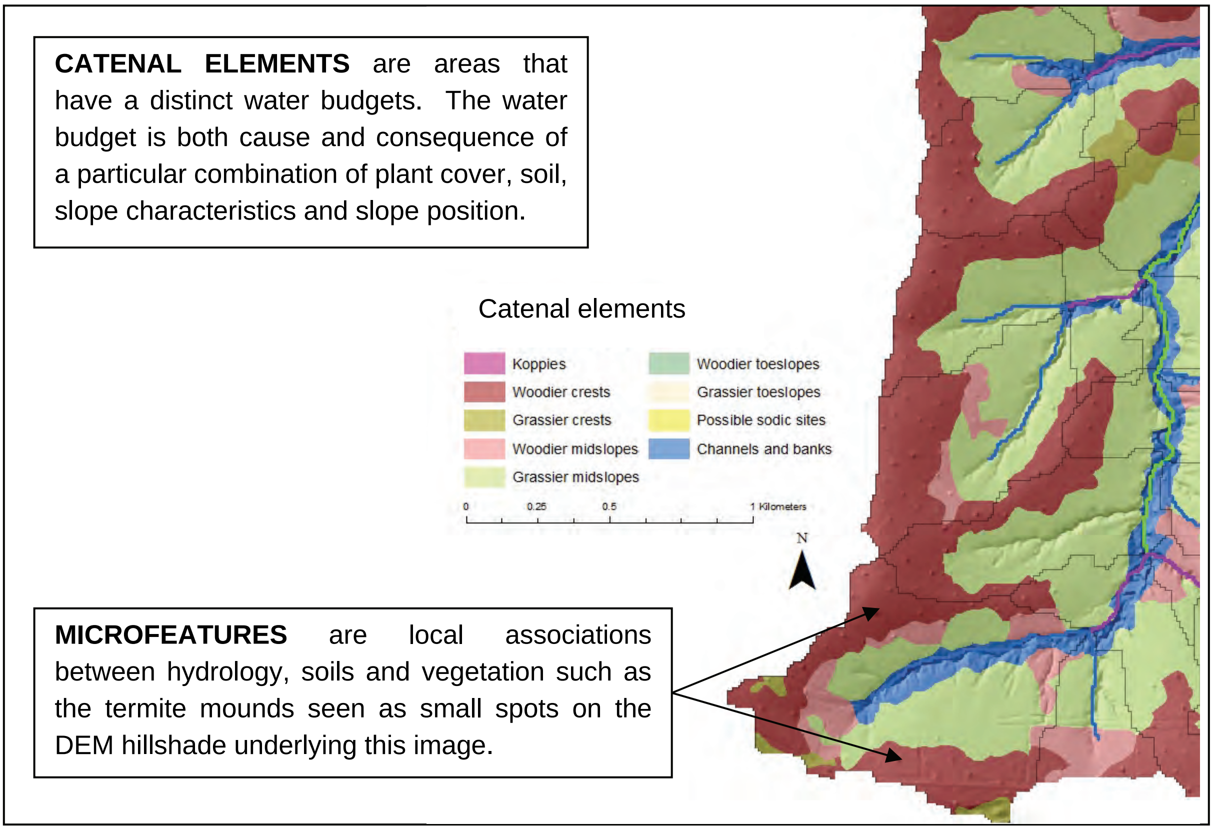


Figure 2.11: Catenal elements and microfeatures

2.4 Hierarchical constraints

Components at each level of the hierarchy impose contextual constraints on interactions between soil, water, vegetation, organisms and disturbances such as fire or flood. These constraints limit the range of variability that can be found in other landscape units, providing boundary conditions to form an environment niche or envelope. The constraints operate both vertically and horizontally in the hierarchy. From a vertical perspective, higher level elements impose constraints on lower-level components that can be conceptualised as environmental filters (Poff, 1997). For example, the landscape dissection patterns that characterise a particular physiographic zone constrain the character and behaviour of catchments in different network positions. In turn, the nature of the slopes in a catchment constrains the composition and arrangement of contained catenal elements.

Neighbourhood relations can also constrain landscape units in the horizontal dimension of the hierarchy. This is what landscape ecologists call the effect of pattern on process (e.g. Turner *et al.*, 2001), citing examples that demonstrate how patch shape and size, as well as the nature of neighbouring patches and the nature of boundaries can affect patch character and behaviour (e.g. Turner *et al.*, 2001). For example, both the character of an upslope catenal element and the nature of its downslope boundary determine the amount of water that can be transferred to a downslope neighbour, limiting the range of soils and vegetation that can be found within the downslope catenal element.

2.5 How our landscape hierarchy differs from others

Our landscape hierarchy is similar to those suggested by several very different groups of scientists. MacMillan (2004) can be taken to represent the group whose work stems from the analysis of DEMs (Digital Elevation Models) to detect geomorphological landforms, using methods which often involve the drainage network as a means of separating landforms into distinct entities, for example separating crests and valley bottoms at a hillslope scale or recognising patterns in ridge-valley spacing at a regional scale. Much of this work stems from the early DEM-based hierarchical landform classifications of Dikau (1989). Zonneveld (1989) is an example of the European school of landscape ecologists, who adopt a holistic approach to landscape classification that is firmly rooted in hierarchy theory. Hierarchical classifications are also widely used by river scientists, who, on the whole, agree that river systems can be viewed at scales that range from morphological units such as pools or bars, through reaches that contain assemblages of these units to the organisational levels that broadly correspond to the physiographic zones identified by those with a more terrestrial focus (e.g. Brierley and Fryirs, 2005, Kleynhans *et al.*, 2005).

Venter's classification of KNP land types (1990) stems from a conservation management perspective married to an appreciation of the strong associations between lithology, vegetation and morphology in KNP. Although Venter nests 'land types' within 'land systems', this is presented as a classification subdivision and not as levels in a process-based hierarchy.

However, unlike most of the above hierarchies, we include an organisational level of catchments, emphasising the role of the drainage network in landscape organisation. In our hierarchy, catchments not only provide a way of anchoring observational scales for each level of organisation, but also provide a means of marrying the network perspective associated with streams to the areal perspective associated with terrestrial landscape patches.

It is interesting to note that although many of the more 'terrestrial' landscape hierarchies use channels and divides of drainage networks in landscape characterisation at several scales, they do not include fine-scale channel characteristics (such as channel morphology or bed type) either as diagnostic criteria for landscape classes or as indicators of the nature of the water and sediment fluxes that often control the distribution of soils and vegetation. Conversely, although river scientists acknowledge the strong influence of catchment soils and vegetation on stream characteristics, attention is not given to the downslope arrangement of soil and vegetation units which largely controls fluxes of water and sediment into the drainage network. This paradox is a fascinating example of how the disciplinary divides work to the detriment of all and which we strive to overcome in this study.

The inclusion of a catchment level in the hierarchy enables us to characterise the composition and structure of assemblages of catenal elements within a specific area, facilitating the description of repeating patterns that characterise physiographic zones. These repeating patterns have been observed and described by many people, being mentioned in almost all literature on ecological land classification. However, we have not found reference to any method of formally delineating or analysing these patterns and the extent to which they are repeated. Although measures of landscape texture (e.g. valley-ridge spacing and relief intensity) encode signals of the morphology of these repeating patterns, and are therefore widely used to delineate physiographic zone (e.g. MacMillan and Shary, 2009, Iwahashi and Pike, 2007, Dobos *et al.*, 2005), these morphometrics represent very generalised measures that can smooth out valuable local detail .

The catchment level of organisation also allows us to capture variation associated with the structure of a drainage network, a perspective that is otherwise easy to overlook and which strongly influences landscape organisation.

2.6 Assumptions and limitations

The framework is 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 some circumstances where the framework is less useful or even inappropriate, including 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) will change the relationships between soils, vegetation, topography and hydrology on which the framework depends.

The framework is designed for use in semi-arid, water-limited systems, where there is strong coupling between water distribution, soils and vegetation. In very arid systems, where water travels infrequently through the landscape, drainage networks may not be highly structured and surface topography may not be a major influence on the distribution of vegetation and soils. On the other hand, in humid environments there may be such wide water availability that few ecological processes are water limited and factors other than topography influence spatial patterns of soil and vegetation.

CHAPTER 3 APPROACH TO THE CLASSIFICATION OF KNP LANDSCAPES

3.1 Introduction

In order to demonstrate the credibility and utility of our framework, we illustrate how the framework can be used to develop landscape classifications in KNP. We focus on the three organisational levels in the landscape hierarchy with most relevance for conservation management and planning. The whole park has been classified in terms of physiographic units and catchments. However, classification of catenal elements is currently only possible for those areas for which LiDAR data exist, so our approach to the classification of catenal elements is illustrated on two sites in southern KNP (See Chapter 4 below).

After introducing the study area, we briefly review existing landscape classifications of KNP, showing how our approach develops and improves upon them. Our approach to the identification, mapping and classification of landscape elements is then described. We discuss the choice of mapping scales, the variables used and how they are combined to detect patches, the derivation of classes and ways of evaluating the results. Following chapters apply this approach to classifications of catenal elements, catchments and physiographic zones. Methodological details relevant only to a particular hierarchical level or to a particular case study are presented in these chapters: here we focus on the broad approach.

3.2 Study area

The Kruger National Park is situated on the Lowveld of South Africa, which is bounded to the west by the Great Escarpment and slopes gently to the east, where the Lebombo Mountains form a barrier between the Lowveld and the extensive coastal plains of Mozambique (Figure 3.1). KNP lies within the savanna biome of South Africa (Mucina and Rutherford, 2006), which is characterised by a discontinuous tree canopy and a herbaceous layer dominated by C4 grasses (Venter *et al.*, 2003).

3.2.1. Why KNP has been chosen as a study site

Kruger National Park has been selected as a study site since it is:

- A semi-arid system, in which water is the limiting factor for many biotic and geomorphic processes. This results in tight spatial coupling of hydrological, geomorphic and biotic processes, which generates and sustains a mosaic of patches with relatively homogenous combinations of soil and vegetation that is visible in remotely sensed imagery.
- A stable landscape, undisturbed by quaternary tectonic activity and with little climate change in thousands, if not millions of years. The broad climate pattern of hot, wet summers and mild, dry winters is likely to have existed in KNP for millions of years, whilst temperature and rainfall have varied little over at least the last 3000 years (Tyson and Partridge 2000, cited in Venter et al,. 2003). This climatic and tectonic stability 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 process can be inferred from form.
- A diverse landscape, with variations in both geology and rainfall that provide a range of physiographic zones in which to explore variations in the composition and structure of catenal elements.
- A conservation area, with relatively little recent human impact compared to other areas, and hence relatively little disturbance of natural processes and vegetation.

- A comparatively well-studied area, with opportunities to share findings and use data and evidence collected in the course of other projects.

3.2.2. Geology and drainage patterns

Following the breakup of Gondwana, the escarpment gradually retreated westwards as rivers cut back into the scarp, eroding the Lowveld plains and exposing the underlying Karoo sediments. Subsequent uplifts and crustal deformation, together with sea level changes triggered a number of different periods of plantation. About 20mya a series of volcanic events created the Lebombos. At this time, the rivers were predominantly flowing west to east, from the Escarpment to the Mozambican delta. In order to maintain their course, these rivers cut gorges though the new mountains. Comparatively recently, around 2mya at the end of the Pliocene, there was further major uplift of approximately 900 m. The land now inside KNP tilted downwards towards the east and 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 (Figure 3.2). Incision flanking the major rivers as they traverse the basalt dates from an even more recent quaternary erosion cycle. These events have resulted in a complex geology. Adding to this complication, many intrusions have resulted in scattered small islands of igneous rock such as gabbros, diabase and dolerite dykes that are surrounded by different types of bedrock.

Drainage patterns in KNP are often related to the geological structure. For example, streams may follow the joints and fractures in granite blocks or preferentially erode along a dyke as opposed to the surrounding, more resistant rock. Whilst rivers established before the Pliocene erosion phase tend to run west-east, younger rivers, formed during this relatively recent period of erosion, tend to run north-south, following the strike of the geology (see Venter, 1990 for a review of the geological history of KNP).

3.2.3. Climate and vegetation

KNP is a semi-arid region, with summer rainfall ranging from 500-700 mm/year in the south to 300-500 mm/year in the north (Zambatis, 2003) (Figure 3.3a). 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 extremely high, with coefficients of variation ranging from 25% in the north to 35% in the south (Schulze 1997, cited in 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). Little water is stored in the system, since potential evaporation almost always exceeds actual levels of evapotranspiration in all areas of the park (Shultz, 1997). In other words, the demand for water by plants always exceeds supply, except during short periods following rainfall. The lack of stored 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 600 km out of a total length of the 31,548 km shown on 1: 50 000 topographical maps) (O'Keefe and Rogers, 2003).

These rainfall differences are reflected in both soils and vegetation. The wetter south has deeper and more diverse soils than the dryer north. In the south, woody vegetation species vary greatly according to hillslope position within geological regions. There is far less variation in the north, where *Colophospermum mopane* dominates in both basalt and granite landscapes. Whereas these differences in species composition may be related to differences in temperature and water availability, the proportion of woody cover is more strongly related to variability in the geological substrate (Figure 3.3).

Temperatures are more predictable, with mild winters and high summer temperatures. 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).

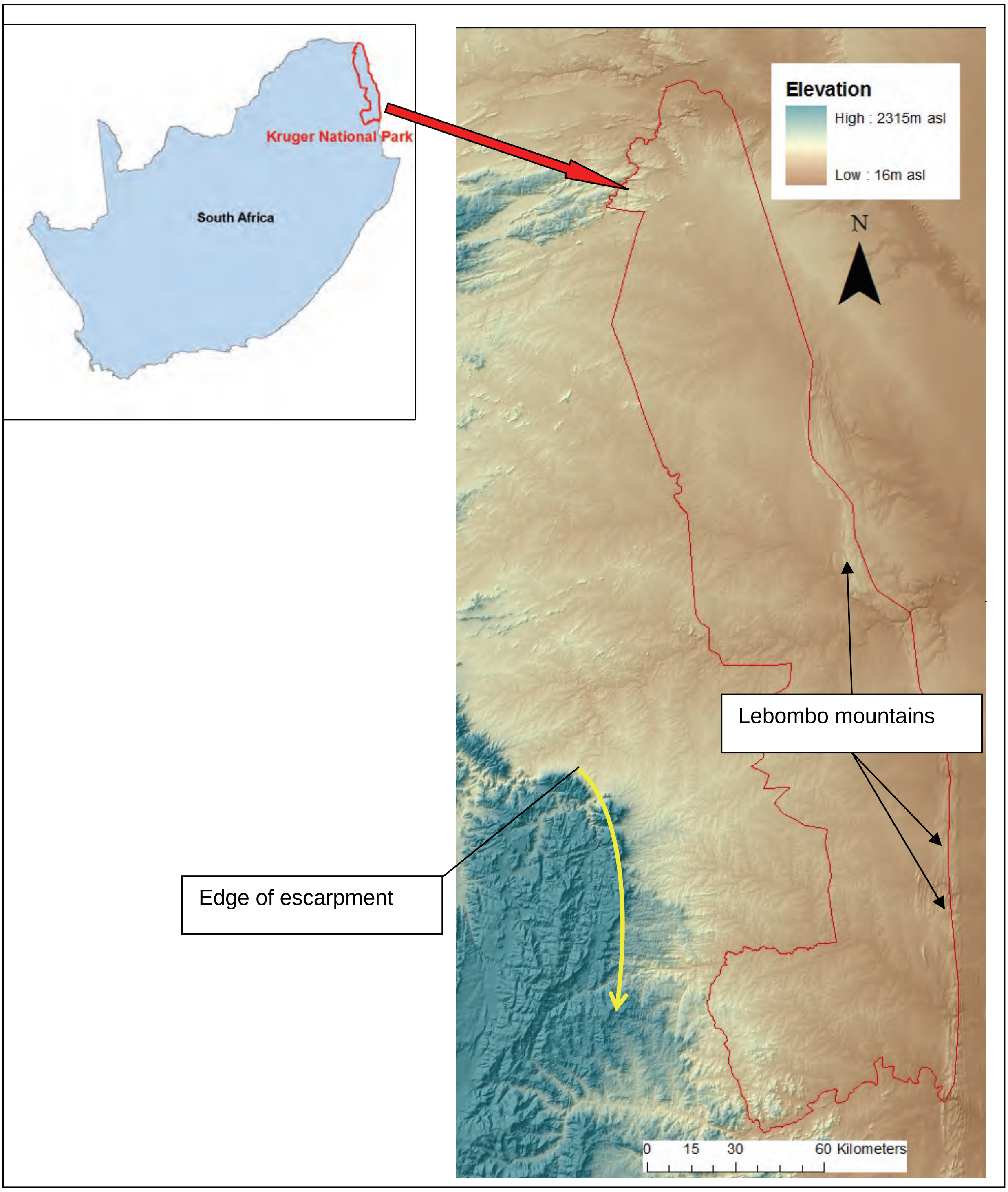


Figure 3.1: Location of Kruger National Park

KNP nestles between the Great Escarpment to the west and the Lebombo mountains to the east. The major west-east rivers can be discerned as areas of lower relief.

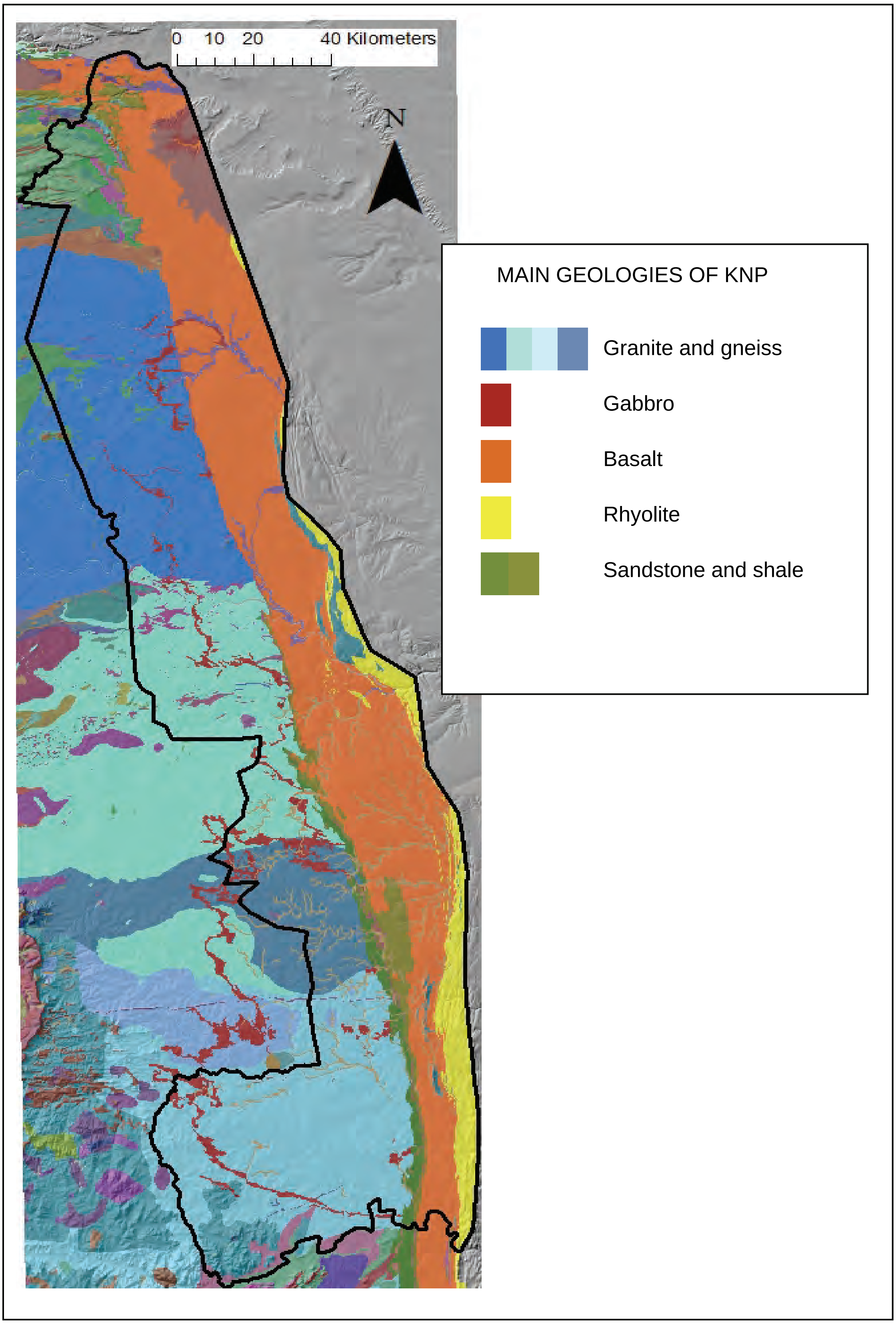


Figure 3.2: Geology of KNP, mapped at a scale of 1:250 000 by the Council for Geoscience in 1981,1985 and 1986

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).

Figure 3.3: a) Mean annual rainfall in KNP (Sanparks-Gis, 2010, Zambatis, 2003) b) % Woody cover in KNP (Bucini et al., 2010) c) % Woody cover overlaid by outline of major geological patterns 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 central areas, where the west is generally drier than the east. The percentage of woody cover appears to vary strongly with geological differences and the position of major rivers rather than with rainfall patterns.

3.3 Previous landscape classifications of KNP

Gertenbach (1983) was one of the first people to construct a functional landscape classification of KNP intended to inform management decisions. He defined a landscapes 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 3.4).

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

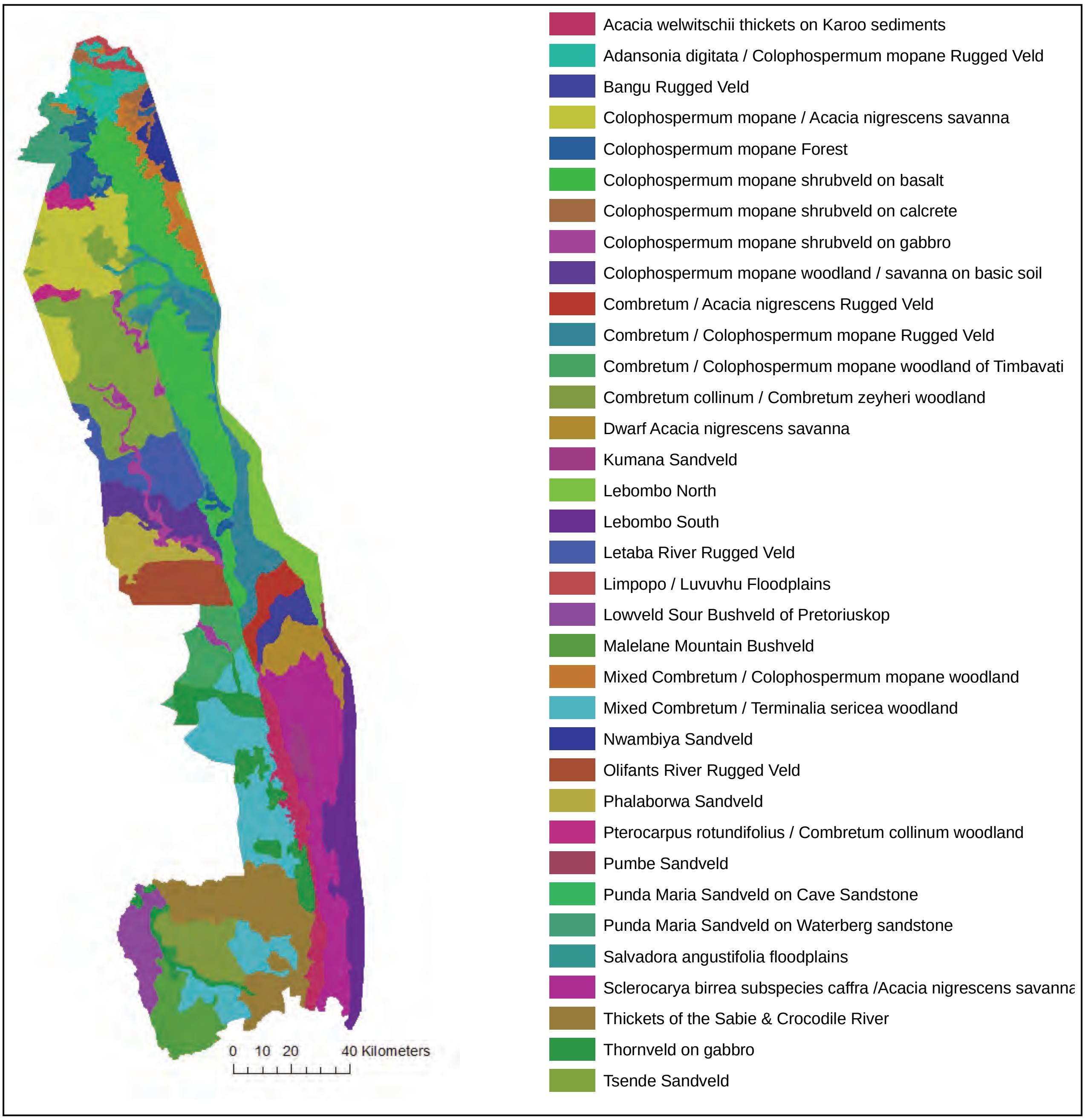


Figure 3.4: Landscapes of KNP (Gertenbach, 1983)

Venter's PhD thesis (1990) presented a new landscape classification (Figure 3.5).

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. Venter proposed four hierarchical levels of landscape classes:

land units, which are specific sections of hillslopes, with distinct morphology (curvature and slope), 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). According to Venter, land units can be mapped at scales of 1: 10 000 or 1: 20 000.

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". This definition was based on a very similar concept of land types used in Australia by Christian and Stewart (1953). The South African Land Type survey also used a very similar concept, but which included climate variables. Since Venter did not have confidence in the somewhat "arbitrary" (sic) boundaries of KNP rainfall data at the 1: 250 000 scale at which he was mapping land types, he adopted the Australian approach.

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 detailed 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.

In most areas the classifications of Gertenbach and Venter are broadly similar (Figure 3.6), which is not surprising, since both classifications are based on similar criteria and tend to follow geological boundaries (see Solomon *et al.*, 1999). In general, Venter's classification is more detailed, and many of Gertenbach's 35 landscape classes are subdivided in Venter's 56 landscape types. Boundaries rarely coincide precisely, as might be expected, given hand delineation of the classes and mapping scales of 1: 250 000.

		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 3.5: Land types of KNP (Venter, 1990)

Land types belonging to the same land system are shown in shades of the same colour

Figure 3.6: 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. In most areas the classifications are broadly similar, which is not surprising, since both classifications follow geological boundaries. In general, Venter's classification is more detailed, with 56 land type classes, as opposed to Gertenbach's 35 landscape classes.

3.4 Building on Venter's classification of KNP

Our framework is founded on similar principles to those used by Venter (1990), but differs in that we invoke the configuration of the drainage network as a structural control on the arrangement of landscape units. We also include the catchment level of organisation, which not only provides naturally defined units that are real spatial entities, but also assists in the description of network position. Our classification also differs from Venter's in taking advantage of the fine scale imagery and sophisticated GIS tools and techniques that are now available, which permit spatially explicit, quantitative analysis of small landscape units such as catenal elements.

3.5 The identification and mapping of hierarchical elements

The identification, classification and mapping of landscape patterns involves choices relating to the

- scales appropriate to the level of organisation that is being described
- variables included
- how these variables are combined to generate distinct patches and
- classes into which patches are grouped

In the following sections we address each of these issues in turn, explaining how these choices are informed by our framework and describing the broad approaches used in constructing classifications of catenal elements, catchments and physiographic zones within KNP.

3.6 Scale

Conceptually, scale represents the ‘window of perception’ or ‘filter’ through which the universe is viewed (Levin, 1992, Marceau, 1999). Scale has many components, including extent, grain, support and the minimum map unit (MMU). The range of scales characteristic of a hierarchal level is called a scale domain, whilst cartographic scale is the ratio between distance on a map and that measured on the ground. Varying any one of these components presents the viewer with a different pattern (Table 3.1).

Geographers refer to the Modifiable Areal Unit Problem (MAUP) which relates to changes in the perception of spatial entities that result from changes in grain and support (Openshaw and Taylor, 1979, Openshaw and Taylor, 1981). Firstly, MAUP acknowledges that even if the extent is constant, the entities that can be seen in a given pattern vary with the grain of perception. Secondly, the shape and size of the support areas within which individual grains are aggregated also changes the perceived pattern. The MAUP cautions care when correlating attributes of spatial entities, since correlation coefficients often change in size, and even direction, when the same entities are viewed at different grains or aggregated in different ways.

Table 3.1: Definitions of the various components of scale
Changes in any one of these components presents the viewer with a different pattern.

Extent	The total area covered by a map. Objects much larger than the extent will not be perceived as individual entities.
Grain	The smallest spatial unit sampled. All properties of this area are treated as homogenous, with internal variations being averaged out. As grain is increased, small objects disappear. Aggregated objects may also differ according to the aggregation method used. In a remotely sensed image, grain is equivalent to the pixel size.
Support	The area over which variables are averaged. Support may be equivalent to grain. Alternatively, support may be the size of a moving window used to derive variables such as curvature or the distance over which gradient is calculated.
Minimum Map Unit (MMU)	The smallest area mapped as a discrete unit. In a vector map, MMU is equivalent to grain, but in a raster image, the MMU may consist of several pixels. Although single-pixel classes can denote the presence or absence of a class, boundaries are unlikely to be accurate. If more precise boundaries are required, the MMU must aggregate many pixels. We consider the MMU for an areal object (e.g. a CASS) to be 3x3 pixels, whilst that for a linear feature (e.g. a stream) is 3 pixels.
Scale Domain	The range of scales that are characteristic of a hierarchical level and over which patterns of the phenomenon of interest change either very little, or change systematically with changes in scale. Scale domains are separated by scale thresholds, which are relatively sharp transitions along the scale continuum where patterns change abruptly, reflecting a change in the relative importance of variables that influence the process producing the pattern of interest.
Cartographic scale	The ratio between distance on a map and that measured on the ground.

One solution to the MAUP is to identify meaningful spatial entities or objects that have an intrinsic scale (Fotheringham, 1989). For example, if the focus is on individual trees, then a suitable grain size, MMU and extent can be determined based on the dimensions of the trees and the required boundary precision. However, if the objects of interest differ greatly in size or shape, it may prove impossible to determine a single appropriate scale of observation.

In our landscape hierarchy, catchments are distinct spatial entities that have intrinsic scales at which they can be mapped. However, the size of catchments and therefore the scale appropriate for mapping them varies with both

> the *stream order* under consideration (and the calculation of stream order itself is dependent on the MMU used for mapping streams)

and

> *landscape texture*, or channel -ridge spacing, a function of stream density.

The landscape hierarchy identifies regions that have very different patterns of landscape dissection as distinct physiographic zones, each of which has a characteristic landscape texture. Where possible, these relationships are used to inform the choice of all scale components for mapping at each of the hierarchical levels of organisation considered in this project.

However, many scale choices are constrained either by data availability or by the purpose for which the map will be used. For example, in this project, the extent of maps of physiographic zones is constrained by the boundary of KNP, our study area, whilst the extent of maps of catenal elements is limited by the availability of data at a fine enough scale to detect topographic variation within catchments.

3.6.1. Cartographic scales at which physiographic zones, catchments and catenal elements are mapped

- The cartographic scale at which physiographic zones, streams and catchments are mapped is also constrained by data availability. The finest resolution DEM currently available that covers the whole park is the 90 m SRTM (Shuttle Radar Topographic Mission) DEM (Farr *et al.*, 2007). Within a few years, fine resolution DEMS are likely to become available in South Africa (Wolfgang Luck, *pers. comm.*). This will allow the classification of catenal elements to be extended over the whole park. The global ASTER DEM at a resolution of 25 m is already available, but horizontal and vertical accuracy are inferior to SRTM, and there are issues with derivative metrics (such as slope, curvature, etc.) which make the DEM unsuitable for terrain analysis (Reuter *et al.*, 2009). Another potential source of fine-scaled DEMs are the 5 m contours produced by NGI (National Geo-spatial Information, formerly CDSM).

The approximate cartographic scale for maps derived from the 90 m SRTM data is 1:90 000. The CASS MMU is 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 (see para. 5.1 below for details). The smallest stream length that is accurately mapped is 270 m (3 pixels).

A larger MMU is used for mapping physiographic zones, where boundary precision is more important than registering the presence or absence of a very small unit. Although the maps are produced at a resolution of 90 m, a notional cartographic scale of 1:250 000 is applied, with a MMU of 60 ha, which is the scale of the geological map that plays an important role in the delineation of different zones (see chapter 6 below). Much larger MMUs (150 $km^{2)}$ apply to the simplified map of physiographic zones, in which classes occupying relatively small areas of the park are merged.

Although the SRTM data can be used to describe large-scale patterns of landscape dissection, the resolution proved to be too coarse to distinguish topographical variation on a single hillslope, particularly in finely dissected landscapes, such as those of the N'waswitshaka granites, where mean hillslope length is about 250 m. This means that the SRTM cannot be used to delineate catenal elements. Instead, we used LiDAR data captured by CAO in April 2008 (Carnegie Airborne Observatory, Asner *et al.*, 2007) at 1.12 m resolution, combined with SPOT5 data captured at 2.5 m (pan) and10 m (red and NIR) resolutions. After processing the LiDAR data to smooth fine-scale elevation differences associated with termite mounds, the data sets were all resampled to 4.48 m resolution, equivalent to a cartographic scale of 1:5 000. This is consistent with an emerging consensus that regards horizontal resolutions of 5-10 m as optimal for describing hillslope terrain units (Zhang and Montgomery, 1994, Kienzle, 2004). In the smoothing and generalisation process, a MMU of 1ha is applied, so the effective scale is approximately 1:10 000.

3.7 Attributes and data sources used to detect landscape units

By definition, each hierarchical element consists of a cluster of many different, interacting environmental attributes, such that there are many combinations of variables that could be used to distinguish between different elements. Furthermore, different attributes are relevant to the detection of the very diverse catenal elements that are found in different physiographic zones. Even when the same attributes are used, they are often calculated over different support areas and/or distances, reflecting the varying hillslope lengths found in areas with different patterns of landscape dissection.

The boundaries of landscape patches defined in terms of different variables may differ slightly, since the processes and feedbacks that determine the pattern for each attribute may have different rates of change across a boundary between two landscape elements. Differences between the boundaries defined in terms of individual variables are likely to be larger in areas where there is a gradual transition between two landscape elements and smaller where there is an abrupt change. The choice of variables used to define landscape components therefore affects the maps that are produced.

In most areas there is unlikely to be an ideal choice of variables that will produce the most accurate map. Although the attributes that define a landscape patch do cluster spatially, we do not expect perfect alignment, precise boundaries or components that nest perfectly within each other. We recognise not only that any map of landscape units is but an approximate representation of reality but also that the reality represented by the map is also imprecise. We merely seek to capture the essence of broad patterns, using imperfect tools.

Although our tools may be imperfect, we nevertheless seek to produce the best maps possible from the available data. To this end, we seek wherever possible to use fuzzy classifications, recognising that landscapes do not fit neatly into mutually exclusive and exhaustive categories. In addition, a basket of variables is used to delineate and classify landscape units, rather than relying on a single indicator to distinguish between patches.

Catenal elements were detected by combining topographical units calculated from the LiDAR DEM with vegetation cover derived from SPOT5 imagery and/or LiDAR canopy height (see Chapter 4). This approach assumes that the topographical and vegetation expressions of catenal elements are spatially aligned with patterns of soils and hydrology. Topographical units were defined using metrics such as relative elevation, slope and curvature, all calculated over distances and areas that are appropriate to the ridge-valley spacing in the physiographic zone under consideration. Although changes in vegetation associated with the boundaries of catenal elements are perhaps best signalled by species changes in both the herbaceous and woody layers, these changes cannot be easily detected in currently available remotely sensed imagery. Instead, we relied on canopy height and cover data to detect vegetation patterns, using imagery captured towards the end of the wet season when trees were fully in leaf (SPOT5 imagery was acquired in March 2006, whilst the CAO LiDAR data were captured in April 2007).

Catchments have been delineated using the 90 m DEM in conjunction with the 1: 50 000 stream layer produced for the national series of topographical maps (see para, 5.1 below). Catchments were characterised in terms of the assemblages and configuration of the catenal elements they contain, so our analysis is restricted to those areas for which LiDAR data are available to describe catenal elements.

Physiographic zones were defined by grouping catchments that share similar slope morphology, within geological boundaries (derived from the 1: 250 000 geological map produced by the Council for Geoscience). Topographical metrics derived from the 90 m SRTM data were chosen that describe the horizontal and vertical variation in landscape dissection.

3.8 How variables are combined to identify distinct landscape elements

Either a top-down or a bottom-up approach can be used to identify physiographic zones and catenal elements. For example, physiographic zones can be indentified either by using morphometrics that describe patterns of landscape dissection (a top-down approach), or by examining catchment-level patterns in the composition and structure of assemblages of catenal elements (a bottom-up approach). However, a bottom-up approach involves a comprehensive description and analysis of all contained elements in at least one lower level of organisation, an enormous task that falls outside the scope of this project. We therefore use a top-down approach to identify and map landscape elements at all levels in the hierarchy.

Furthermore, physiographic zones and catenal elements may be defined *statistically*, clustering attributes in an unsupervised classification, or *heuristically*, translating expert knowledge into classification rules. The heuristic approach is sometimes criticised as being overly subjective. However, although statistical solutions are often presented as objective approaches, the choice of variables to be included and the choice of statistical method are both highly subjective decisions in which different choices usually generate quite different results. Statistical clusters can also be difficult to relate to the processes that generate the pattern and are not necessarily spatially contiguous (Qin *et al.*, 2009, Schmidt and Hewitt, 2004). Given the need to define different classes of hierarchical elements in different contexts, neither method can be generalised to apply to any region. However, the transparency of heuristic rules at least facilitates comparison, since it is easy to see in what respects classes differ.

We use a novel combined approach, in which image objects are first created in eCognition Developer 8.0, using a segmentation routine that statistically groups areas of relative homogeneity with respect to the spatial layers of variables included in the analysis (Baatz and Schape, 2000, Trimble, 1995-2009). A rule-based approach is then used to develop class prototypes, which are idealised representations of the central tendency within each class (see Qin *et al.*, 2009, MacMillan *et al.*, 2000). Membership functions define the similarity between each image object and the prototype for each class. Each object is then assigned to the class for which it has the highest membership value (Figure 3.7).

The prototype and fuzzy classification approach has many advantages over other methods of landscape classification (Woodcock and Gopal, 2000):

- Crisp classifications assume that map categories are mutually exclusive and exhaustive. However, patches in real landscapes may have affinities to two or more classes, or they may not fit well into any of the defined classes. Although our maps assign landscape patches to particular classes, we are able to investigate the relative ambiguity of each classification, identifying alternative classes to which each image object could be assigned. This opens the possibility of identifying transition zones and investigating the extent to which boundaries are abrupt or gradual. This characterisation of boundaries could contribute to an understanding of the nature and extent of connectivity between the neighbouring landscape elements.
- The use of a fuzzy classification also facilitates the assessment of heterogeneity, both in terms of the internal variability of classes and the difference between classes, either by mapping membership values for each class separately, or by mapping the difference in membership values between any two classes.
- The accuracy assessment of a crisp classification assumes that all misclassifications are equally and completely wrong, whilst the evaluation of fuzzy maps acknowledges that there are degrees of inaccuracy as well as several quite different ways of misclassifying a patch.
- Fuzzy classification also reduces the effect of possible inaccuracies in the estimation of thresholds included in the rule sets defining classes, since values near the threshold may be adequate to generate a high enough class membership value to ensure assignment to the correct class. The effect of specifying rigid thresholds is also reduced by inclusion of more than one variable in the definition

of a class prototype. For example, a patch may be very similar to the prototype in terms of one of the variables, but dissimilar to the prototype in another dimension. When the membership values of each function are aggregated to give an overall class membership, the effect of the object failing to meet the class criteria in one dimension is reduced.

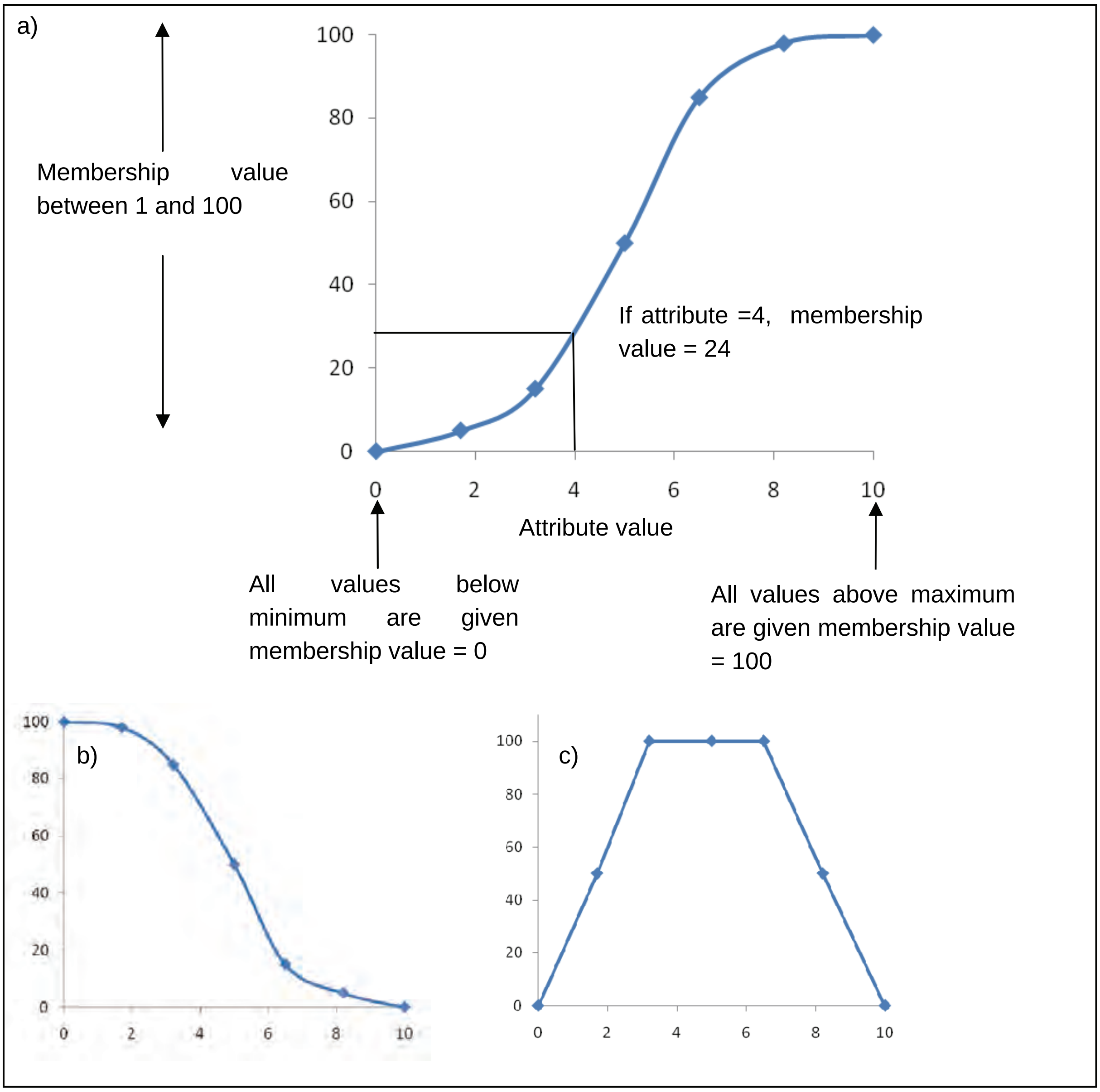


Figure 3.7: Membership function curves

a) Membership value increases with the attribute value until a maximum is reached. All values over the maximum are given a membership value of 100. b) Membership value decreases with the attribute value until a maximum is reached. All values over the maximum are given a membership value of 0. c) Maximum membership value is attributed to a range of attribute values. Outside of this range, membership values fall. Membership values =0 above and below the maximum and minimum attribute values specified.

3.9 How classes are chosen and the rules for prototypes developed

Classes have been chosen and rules developed to define class prototypes based on analysis designed to reveal statistical and spatial relationships between candidate variables. In developing classes for catenal elements, we draw on a database of attributes assigned to individual points regularly sampled at 100 m intervals throughout the study areas. The same database is also used to characterise catchments in these areas.

3.10 Evaluating the classifications

Many choices need to be made when identifying and grouping elements at each organisational level, including: the variables used to define patch identity and class, the scales at which these variables are measured, class definition and how classes are grouped or divided. Thus multiple classifications are possible.

The optimum classifications are those that are both useful and that describe the landscape accurately. Given our aims of helping end users to describe landscapes in terms that capture the variability in processes that control the observed patterns, the utility of the product depends upon user acceptance of the underlying theoretical framework, which must be coherent and credible to both environmental scientists and managers (Cash *et al.*, 2003).

The accuracy of land classifications is traditionally evaluated by groundtruthing, which involves assessing the extent to which patterns observed in the field concur with those predicted by the maps. However, not all discrepancies are equally incorrect or equally unacceptable. Errors in class assignment may be less serious if the discrepancy is between two very similar classes, but unacceptable if the discrepancy is between very dissimilar classes. Similarly, errors arising from the inaccurate mapping of class boundaries are less serious if they occur near the edge of a patch and more serious if they occur in the centre of a patch. For these reasons, we recommend the use of a groundtruthing-approach undertaken by end- users, evaluating each sampled point qualitatively in terms of user acceptability, such as those proposed by Woodcock and Gopal (2000 p. 146):

"(5) *Absolutely right:* No doubt about the match. Perfect.

(4) *Good answer:* Would be happy to find this answer given on the map.

(3) *Reasonable or acceptable answer:* Maybe not the best possible answer but it is acceptable; this answer does not pose a problem to the user if it is seen on the map.

(2) *Understandable but wrong:* Not a good answer. There is something about the site that makes the answer understandable but there is clearly a better answer. This answer is a problem.

(1) *Absolutely wrong*: This answer is absolutely unacceptable and completely wrong."

We envisage that such groundtruthing will take place over time, as the classification products are developed and taken up by end users. As we shall see in Chapter 8, there has already been some uptake of the approach amongst KNP scientists and proposals made to quantify and compare the soils and hydrology found in different landscape elements at scales that reflect the organisational levels of our landscape hierarchy. This project represents but the first step in an ongoing, iterative process of developing, using, and refining the framework and classifications based upon it.

CHAPTER 4 CATENAL ELEMENTS

In the next three chapters we illustrate the application of the framework in the development of classifications that describe study areas in KNP at three organisational levels. This chapter describes our approach to the classification of catenal elements, chapter 5 describes the catchment level of organisation, considering how assemblages of catenal elements change with network position and chapter 6 explains how KNP may be classified into different physiographic zones.

4.1 Catenal elements

Catenal elements are parts of a catchment that have a particular combination of plant cover, soil, slope characteristics and slope position that are proposed to be both cause and consequence of a relatively homogenous water budget.

Our framework suggests that landscapes should partition into these elements, which should also be arranged in a consistent downslope sequence within each physiographic zone. By attempting to classify catenal elements in our study sites we are able to assess the extent to which the defined classes are indeed present in the landscape and systematically arranged down each slope.

In this chapter we first present our approach to the identification and classification of catenal elements. We then illustrate these methods by classifying two very different sites in southern KNP. Lastly, we explore the lessons learned from these classifications in terms of support for the framework principles, potential revisions to the class rule sets, and future avenues for research.

4.2 Identifying catenal elements

Patterns of soil, vegetation and topography within a catchment are all expressions of catenal elements. We used the patterns of vegetation and topography that can be seen in fine-resolution satellite imagery to delineate catenal elements. The assumption that the soil and hydrological expressions of catenal elements are spatially aligned with the described patterns of vegetation and topography could be tested though field measurements in sampled sites, but falls outside the scope of this project.

In theory, catenal elements may be delineated using slope positions (e.g. crests, valley bottoms, etc.) calculated in relation to catchments of any steam order. We use hillslope positions defined in relation to CASSs, since these units offer complete coverage of the landscape at the finest scale at which the drainage network is mapped. In chapter 5 we explore whether or not other sets of catenal elements need to be defined in relation to large order catchments by determining whether or not there are superimposed vegetation patterns associated with 2nd and higher order streams.

Our approach is firstly to demonstrate the existence of relationships between vegetation cover and topography, then to identify easily measurable vegetation and topographical variables that effectively distinguish between different classes of catenal elements. Prototypes of each class are then defined and the landscape evaluated in terms of fuzzy membership to each class in order to map catenal elements (Figure 4.1).

STEP 1.	Delineate areas with similar vegetation cover (e.g. bare, relatively woody, relatively grassy)
STEP 2.	Delineate topographic terrain units (e.g. crest, midslope, channel bed)
STEP 3.	Explore statistical relationships between vegetation and terrain units
STEP 4.	Develop classes of catenal elements and rules that define prototypes for each class, informed both by our conceptual framework and by the relationships described in step 3. Apply fuzzy classification.

Figure 4.1: Procedure for the delineation of catenal elements

This approach is demonstrated in two areas in KNP which have relatively homogenous geology and for which fine resolution imagery is available: granites in the N'waswitshaka basin and the basalts near Lower Sabie (Figure 4.2). The study sites not only differ in geology, but also lie on a west-east rainfall gradient. Whilst the N'waswitshaka site receives 500-600 mm rainfall p.a., the Lower Sabie basalt site only receives 400-450 mm p.a. (Zambatis, 2003) (Figure 4.3).

Although the classification of catenal elements follows the same broad steps in both study areas, some of the detailed methodology was adapted to fit the special needs of each site.

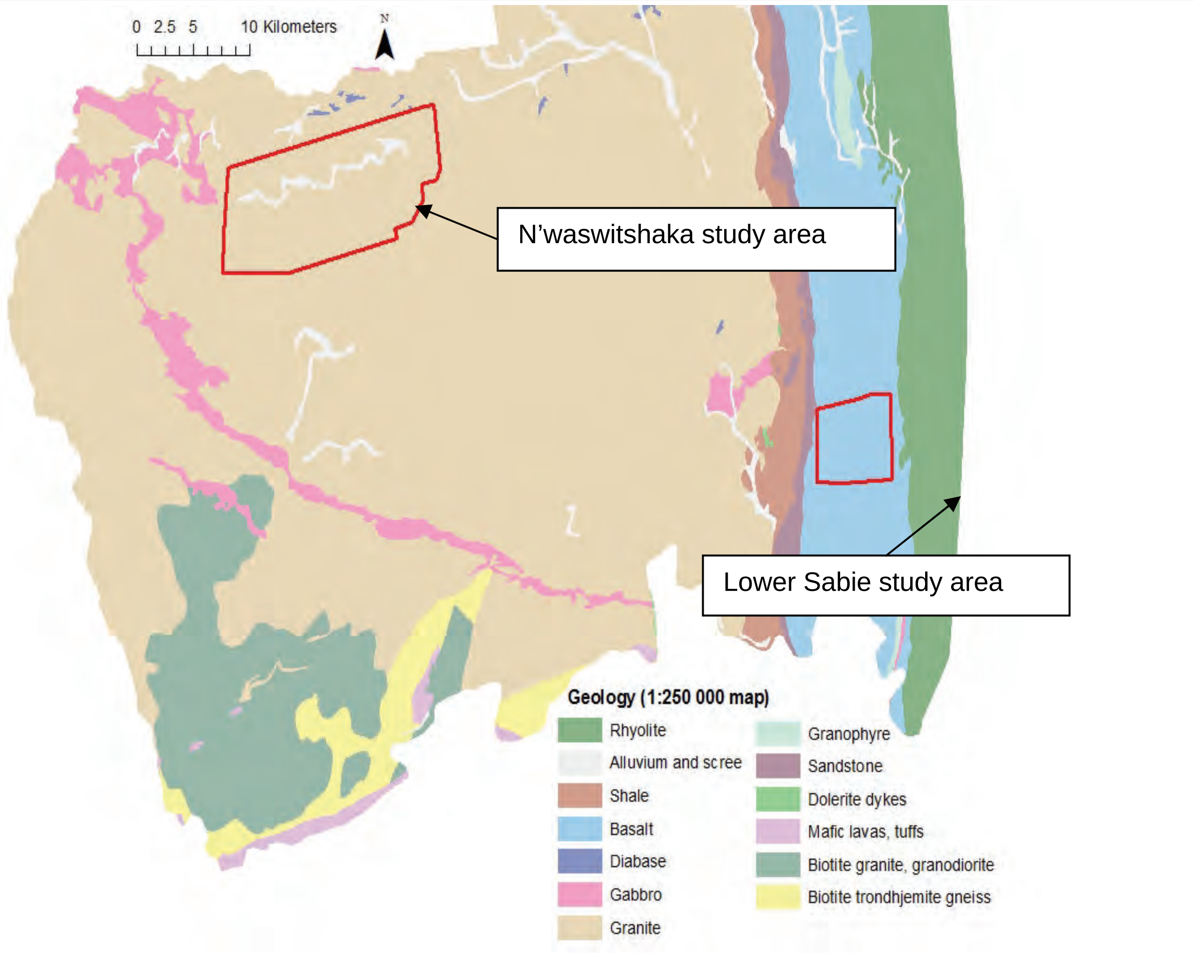


Figure 4.2: The geology of study sites for the delineation of catenal elements

The Pretoriuskop and N'waswitshaka sites are both situated on relatively homogenous granite, whilst the Lower Sabie site lies entirely on basalt. (1:250 000 Geological map, Council for Geoscience)

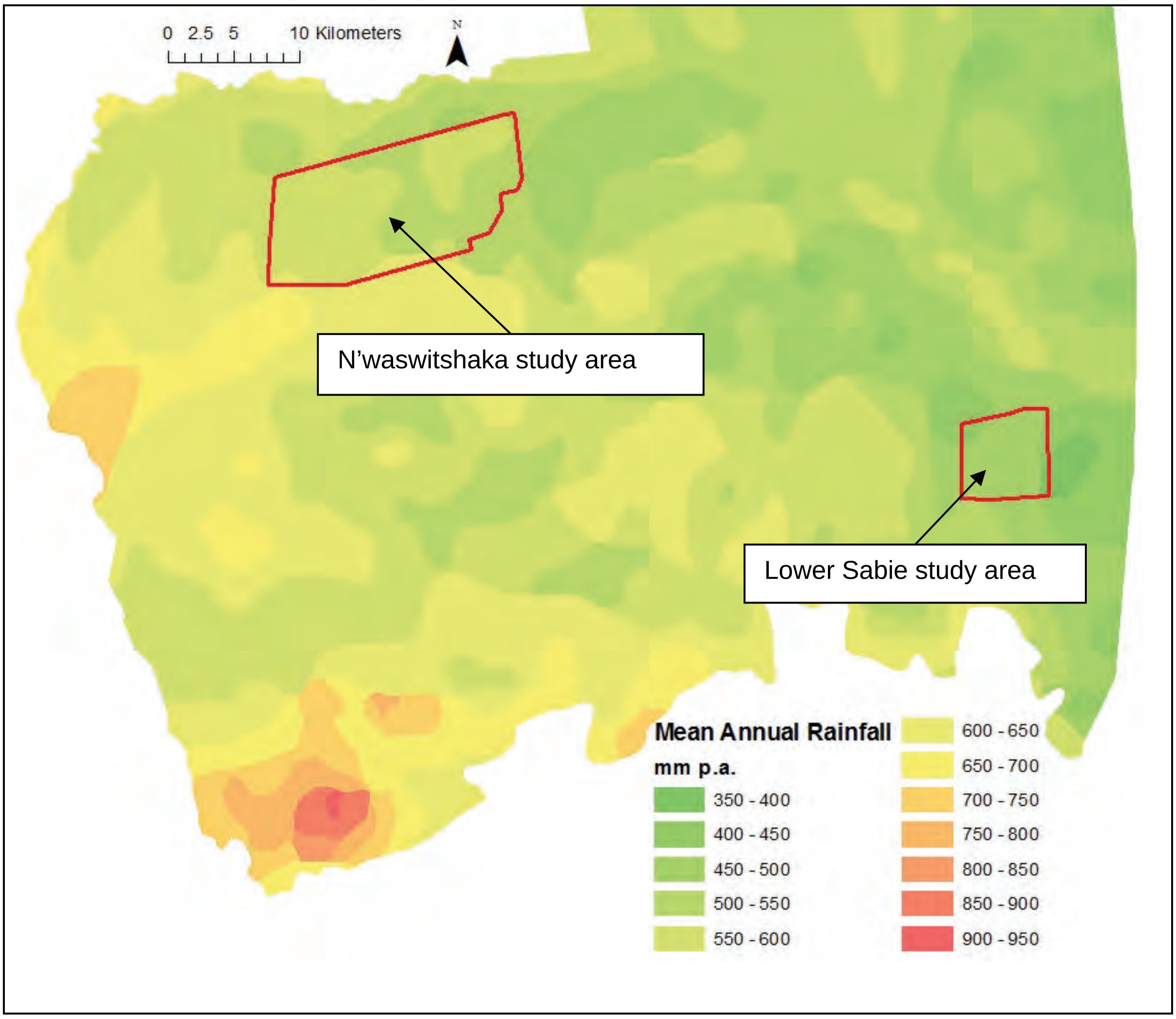


Figure 4.3: Rainfall at study sites in southern KNP (Tarboton et al., 1991, Sanparks-Gis, 2010, Zambatis, 2003)
The Pretoriuskop site has the highest mean annual rainfall (600 mm+ p.a.), whilst the Lower Sabie basalt site only receives 400-450 mm p.a. The intermediate N'waswitshaka site receives 500-600 mm rainfall p.a.

4.3 Catenal elements in the N'waswitshaka study site

4.3.1. Context for the N'waswitshaka study site

The N'waswitshaka site comprises a 6,800 ha (approx 8.2 km x 8.2 km) area of the N'waswitshaka River basin that for the most part lies on relatively homogenous granite. Swarms of dykes and patches of migmatite occur in the north east of the scene.

Assemblages of catenal elements within this area may not only be influenced by local hillslope topography, but also by broader scale changes in geology and climate. The area occupies 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 4.4). The dominant woody vegetation on crests changes over this transition. Although *Combretum apiculatum* is common on crests throughout the scene, in the south west it is found together with *Terminalia sericea*, in the centre of the scene it occurs with *Combretum zeheri,* whilst toward the north east *Combretum apiculatum* dominates on the crest (Venter 1990).

Changes in network position may also affect the types of catenal elements found in this site, which includes the headwaters of the 5th order N'waswitshaka river to the west and an area close to the confluence with the very large Sabie river to the east.

The study area is covered by finer-scaled Carnegie Airborne Observatory (CAO) data that describe ground elevation, canopy height and vegetation patterns (Asner *et al.*, 2007, acquired in April 2008). SPOT5 imagery, (acquired in March 2006) is also available for this area.

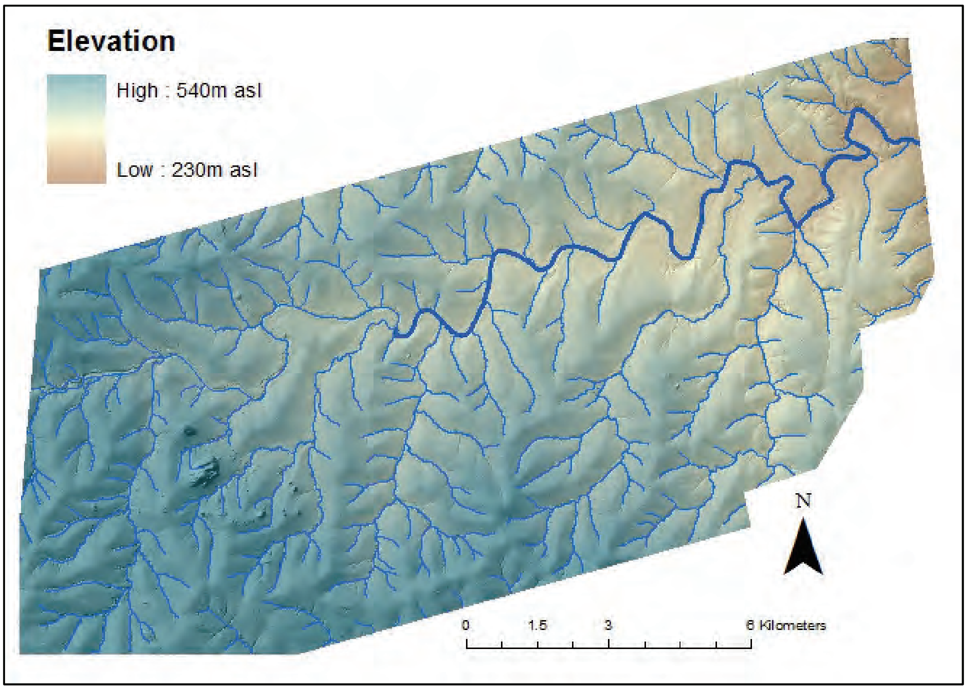


Figure 4.4: Drainage network and elevation in the N'waswitshaka study area

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 scene also includes both headwater areas of the river (to the west) and areas with wider floodplains towards the east. The N'waswitshaka joins the Sabie river some 2km from the north east corner of the scene (6 km along the meandering river course).

Carnegie Airborne Observatory imagery was provided by the Carnegie Institution for Science with support from the Andrew Mellon Foundation, W.M. Keck Foundation and William Hearst III

4.3.2. STEP 1: Classification of vegetation cover in the N'waswitshaka basin

Patterns of vegetation associated with catenal elements in the N'waswitshaka basin are clearly visible to the naked eye in the 2.5 m resolution panchromatic SPOT5 data (Figure 4.5a). Trees show as darker patches, due to their shadows and green colour at the time of the image (March 2006). 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 4.5b).

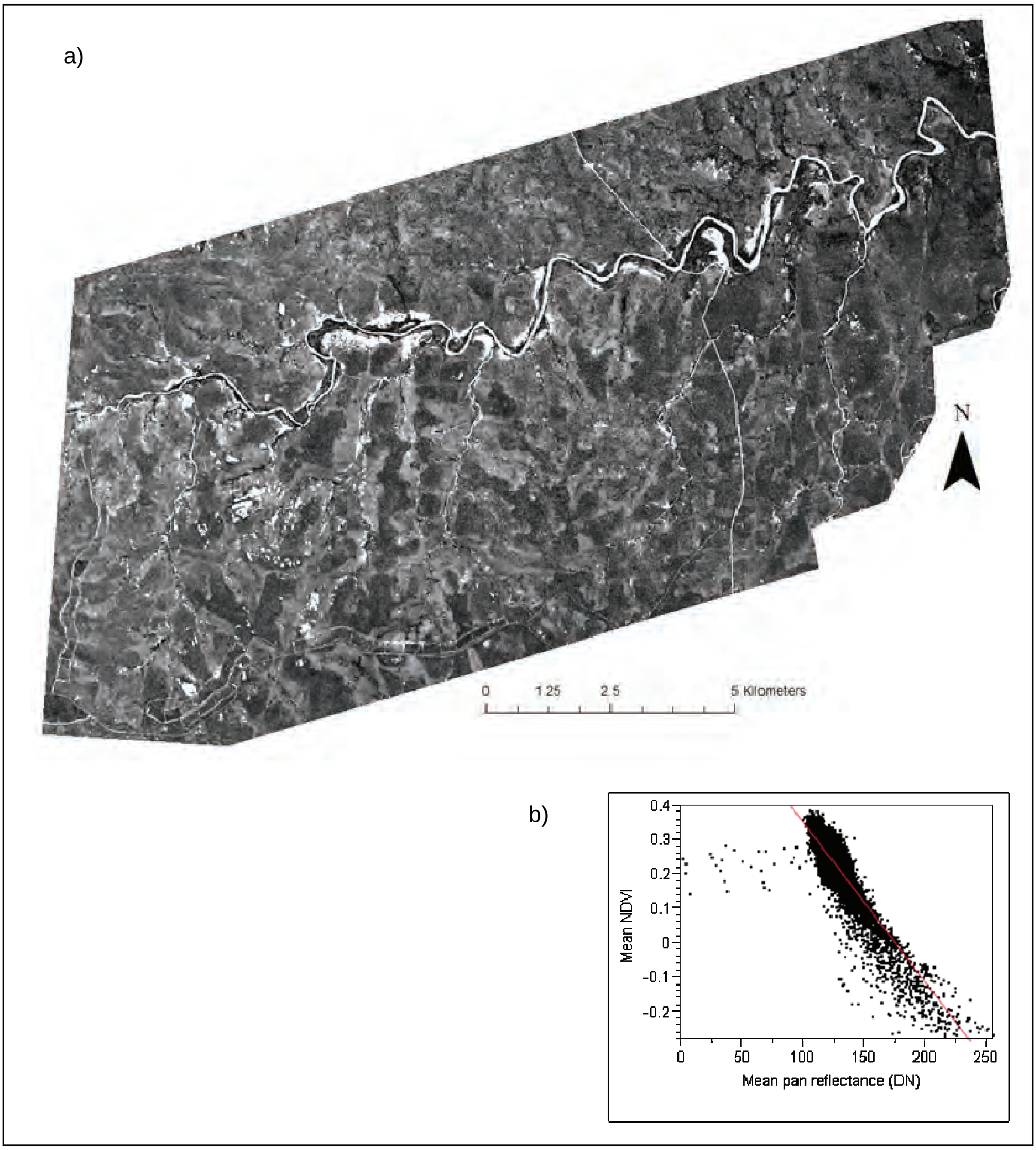


Figure 4.5: Vegetation patterns in the N'waswitshaka basin

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)

However, these patterns are 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 4 km^2) in relation to factors such as species composition, burn history, geology, aspect, etc. A classification procedure has therefore been developed that is based on the *relative* 'woodiness' and 'grassiness' of neighbouring patches.

Vegetation classes are delineated and classified by first segmenting relevant data layers into image objects (using eCognition Developer 8.0) and then classifying these objects. Scale parameters for the segmentation are 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 have 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.

In order to classify the *relative* 'woodiness' and grassiness' of neighbouring patches, we initially classified the extreme ends of the grassy-woody spectrum, using thresholds of pan reflectance that clearly corresponded to areas that are definitely 'woody' and 'grassy'. Unclassified objects were then compared to their neighbours in order to capture relative differences in woody cover (Figure 4.6).

1. Segment into objects based on SPOT5 pan layer aggregated to 4.48 m resolution (Shape 0.1, compactness 0.5), scale parameter =30

2. Initial classification, based on object mean values (DN)

    Bare rock/sand: mean NDVI[1] <=0.15 and mean NIR (SPOT band 3) >=100

    Water: mean NDVI <=0.15 and mean NIR <100

    Woodier: pan >= 129

    Grassier: pan <118

    Dubious: pan 118> <=129

3. Initial contrast with neighbouring objects

    Both: Unclassified and mean difference to neighbouring objects classified as *woodier* >=10 AND mean difference to neighbouring objects classified as *grassier* <= -10

    Possible grass: Unclassified and mean difference to neighbouring objects classified as *woodier* >=10

    Possible trees: Unclassified and mean difference to neighbouring objects classified as *grassier* <= -10

4. Second iteration of neighbourhood contrasts, using smaller mean differences (> =5, <= -5). Note that only as yet unclassified objects are eligible and that comparisons are made with objects originally classified as woodier and grassier, not those classified as such in step 3.

5. Grouping

    possible trees is reclassified as *woodier*

    possible grass is reclassified as grassier

    both is reclassified as *unclassified*

6. Smoothing

    Export to ArcGIS as raster file

    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 4.6: Procedure for vegetation classification in the N'waswitshaka study area

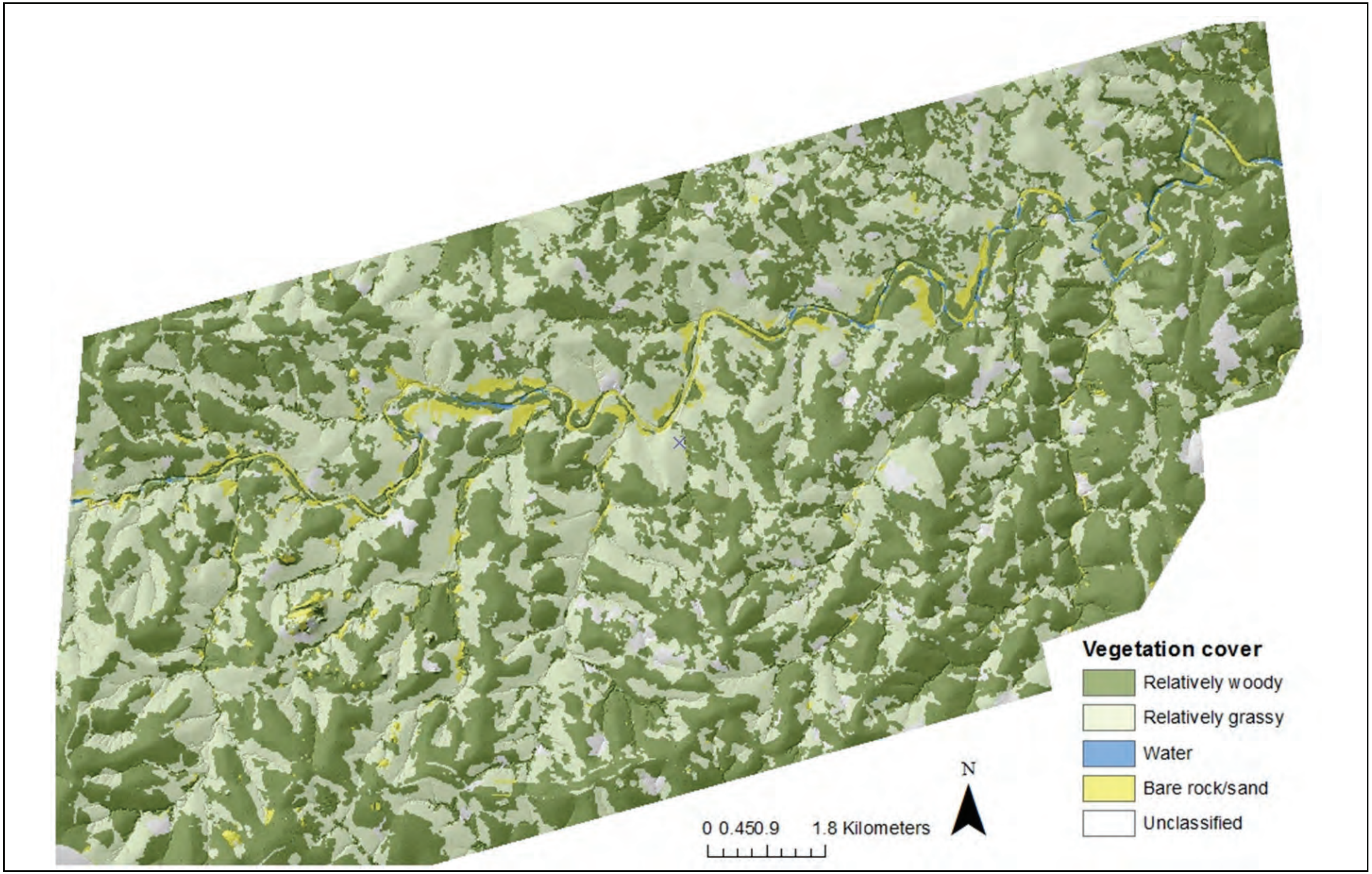


Figure 4.7: Vegetation classification of the N'waswitshaka basin.

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.

In the resulting image (Figure 4.7) some objects remain unclassified that were not bordered by trees or grass with a sharply contrasting pan value. If desired, many of these objects could be classified manually, based on expert judgement.

4.3.3. STEP 2: Classification of hillslope units in the N'waswitshaka basin

Although topographic patterns can be shown using individual variables, such as gradient, relief, curvature and so on, we have chosen to synthesise these variables into 'hillslope units', which are areas of similar topography and hillslope position in relation to channels and divides. This approach not only simplifies outputs, since only one result is obtained, rather than individual findings for a wide range of morphometrics, but has also been shown to improve correlations between soil properties and topographical position (Ziadat, 2005, Herbst *et al.*, 2006).

The classes are based on hillslope position, echoing Conacher and Dalrymple's nine unit model (see chapter 2) and Ruhe's (1956) conceptual model for dividing a hillslope profile into sections corresponding to different elevations above the stream, such as crest, midslope, footslope and valley bottom. These hillslope positions are associated with different soils and a similar approach is used in most other studies relating soils to terrain units, such as the South African Land Types (Macvicar *et al.*, 1974), used by Venter (1990).

All catchments contain a *riparian* zone, which typically comprises the bed and banks of a stream, and a *crest* that straddles catchments across a watershed. *Middle zones* may be subdivided on the basis of slope breaks into toeslopes, footslopes, midslopes, and /or shoulders. In some settings important hydrological differences may also occur between divergent and convergent slopes, and/or between slopes with different aspects. Not all of these components are necessarily present in all settings. In some circumstances, features such as scarps, large rocky outcrops, terraces, local depressions and alluvial fans may be present and of a size and frequency to merit a separate class.

Bearing in mind the large diversity of potential terrain units, as well as the subjective and scale-sensitive nature of landform definition, our approach is to identify topographic units that are strongly associated with vegetation differences. We first conducted statistical analysis to reveal associations between vegetation classes and various topographical metrics including hillslope position, gradient and curvature. The topographical variables that correlated well with vegetation patterns were then used to construct terrain units.

a) Topographic Position Index: A measure of hillslope position

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 mid-slope area where a cell is surrounded by equal areas of high and low elevation. TPI is very scale sensitive, describing different patterns at different scales. Our use of 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 distance between ridges (or channels) in the area of interest. In the N'waswitshaka study area, where the mean CASS width is 534 m, a circular neighbourhood with a 67 cell (300 m) radius was used to calculate TPI (Figure 4.8). Calculated at this scale, TPI effectively captures hillslope position within CASSs in the N'waswitshaka site, distinguishing between:

- *Crests*, which are relatively high in the landscape (red in Figure 4.8)
- *Riparian* areas, which are relatively low in the landscape (blue in Figure 4.8). Note, however, that not all blue areas are riparian zones. For example, the slopes

below the large koppie in the west of the area have low TPI due to the contrast in relief with the outcrop, rather than because they are riparian zones.

- *Koppies* (dark red) and
- *Midslope* areas (beige).

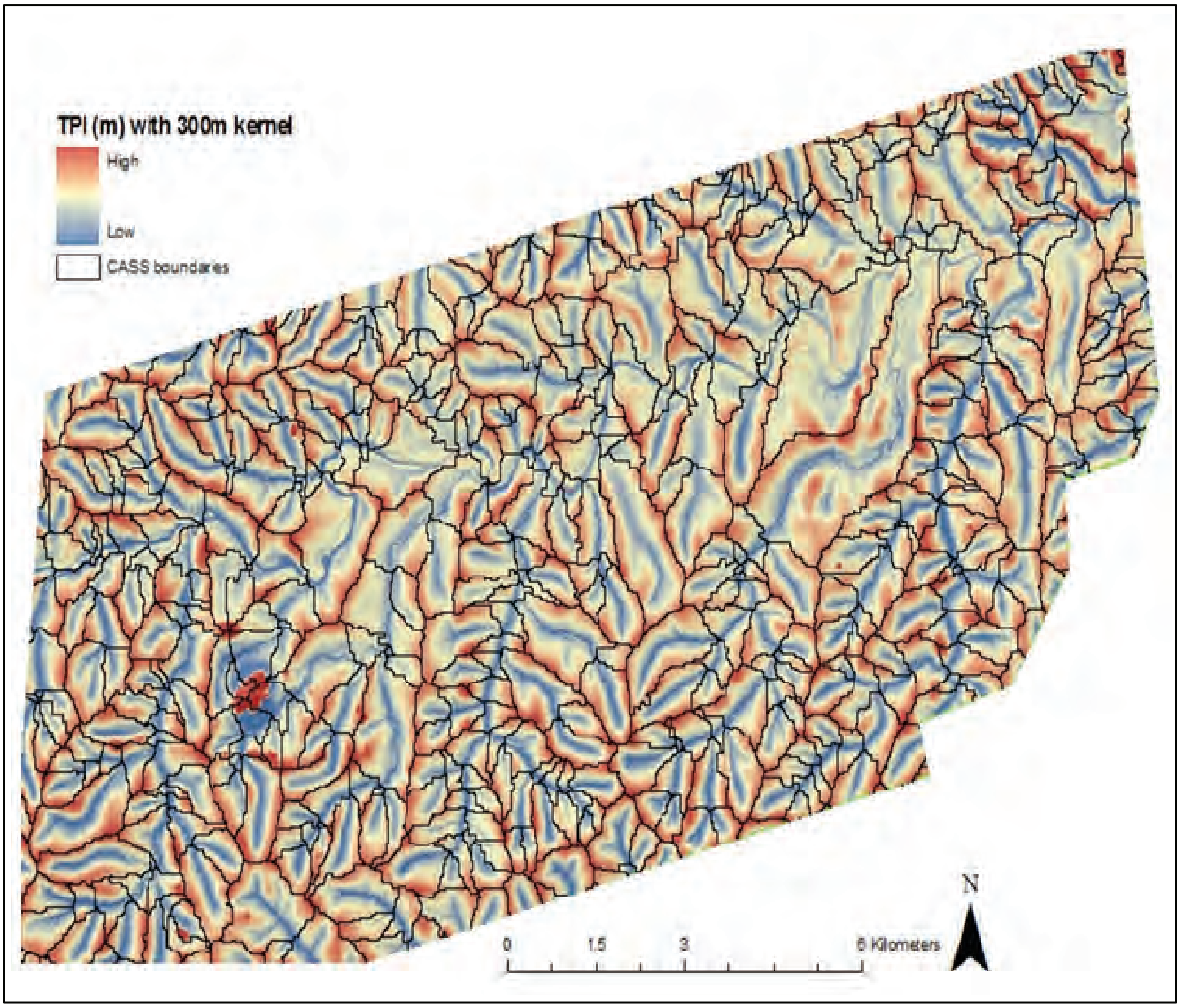
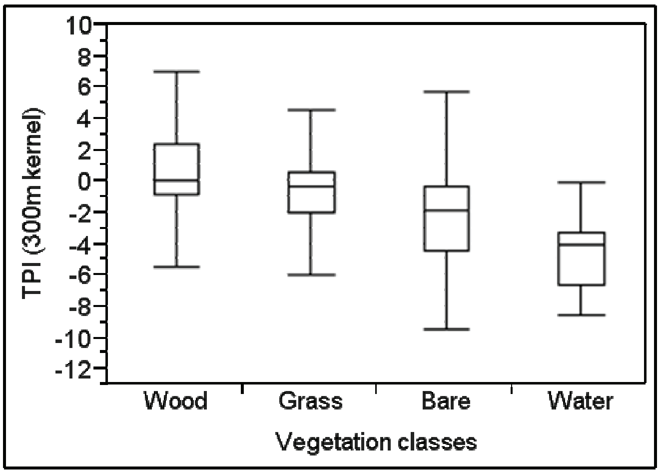


Figure 4.8: TPI (kernel of 300 m) in the N'waswitshaka study area and CASS boundaries.

CASS crests are clearly shown as red areas (high, positive TPI), while riparian zone are blue (low, negative TPI). The koppies in the west are clearly associated with a high TPI, but surrounding slopes have a low TPI, a reminder that TPI alone is not sufficient to indicate riparian zones.

TPI is strongly associated with vegetation class, with significant differences in TPI between all four vegetation classes (Figure 4.9, based on the database of sampled points, n=9,821, Student's t test p <0.05). There is considerable overlap between the 'woodier' and 'grassier' vegetation classes, which 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 1.5 m, suggesting that a threshold of TPI =1.5 m would successfully separate (woodier) crests from (grassier) midslopes.



Vegetation Class	Mean TPI (m) (300 m kernel)	n=
Relatively woody	0.55	13,129
Relatively grassy	-0.60	10,925
Bare	-1.78	686
Water	-4.18	38

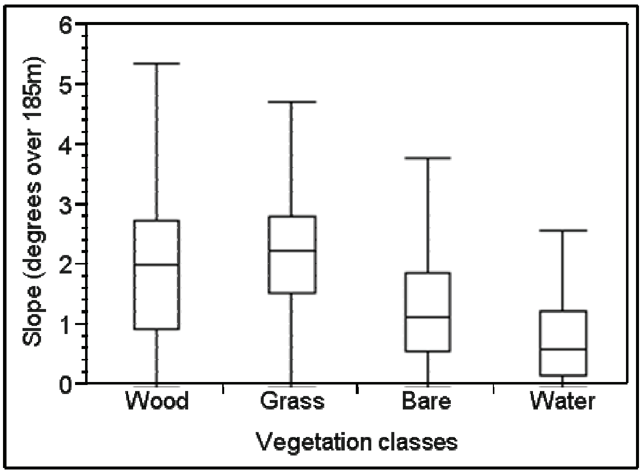
Figure 4.9: Box plot of TPI (m) calculated using a 300 m kernel by vegetation classes for sampled points in the N'waswitshaka study area

Base: Points sampled at regularly spaced 100 m intervals. The box plot shows the median value (line in centre of box), the interquartile vales (edges of box) and the limits within which 90% of the values lie (whiskers).

The means of all vegetation classes are significantly different to each other (Student's t test p <0.05) *b) Gradient*

When 'local' gradient is calculated over a distance of 15 m, the steep and variable slopes associated with incised channels are clearly visible. By contrast, a 'long range' gradient, calculated over 185 m (but still at a pixel resolution of 4.48 m) shows channels and riparian zones as relatively flat (Figure 4.11).

Whilst there is no significant difference between the mean 'local' gradient of vegetation classes, all classes differ significantly in terms of the 'long range' gradient (Figure 4.10, based on the database of sampled points, n=9,821, Student's t test p <0.05). Whilst grass tends to occur on steeper patches than trees, bare and water patches are relatively flat. Despite the significant difference in gradient between grassy and woody patches, there is so much overlap between the classes that 'long range' gradient did not prove useful in separating grassier midslopes from woodier crests.



Vegetation Class	Mean Slope (degrees measured over 185 m)	n
Relatively woody	1.89	13 139
Relatively grassy	2.11	10 925
Bare	1.60	686
Water	0.87	38

Figure 4.10: Box plot of 'long range' gradient by vegetation classes for sampled points in the N'waswitshaka study area

Base: Points sampled at regularly spaced 100 m intervals. The box plot shows the mean value (line in centre of box), the interquartile vales (edges of box) and the limits within which 90% of the values lie (whiskers).

The mean 'long range' gradient of all vegetation classes are significantly different to each other (Student's t test p <0.05). However, there is no significant difference between the mean 'local' slopes associated with the different vegetation classes.

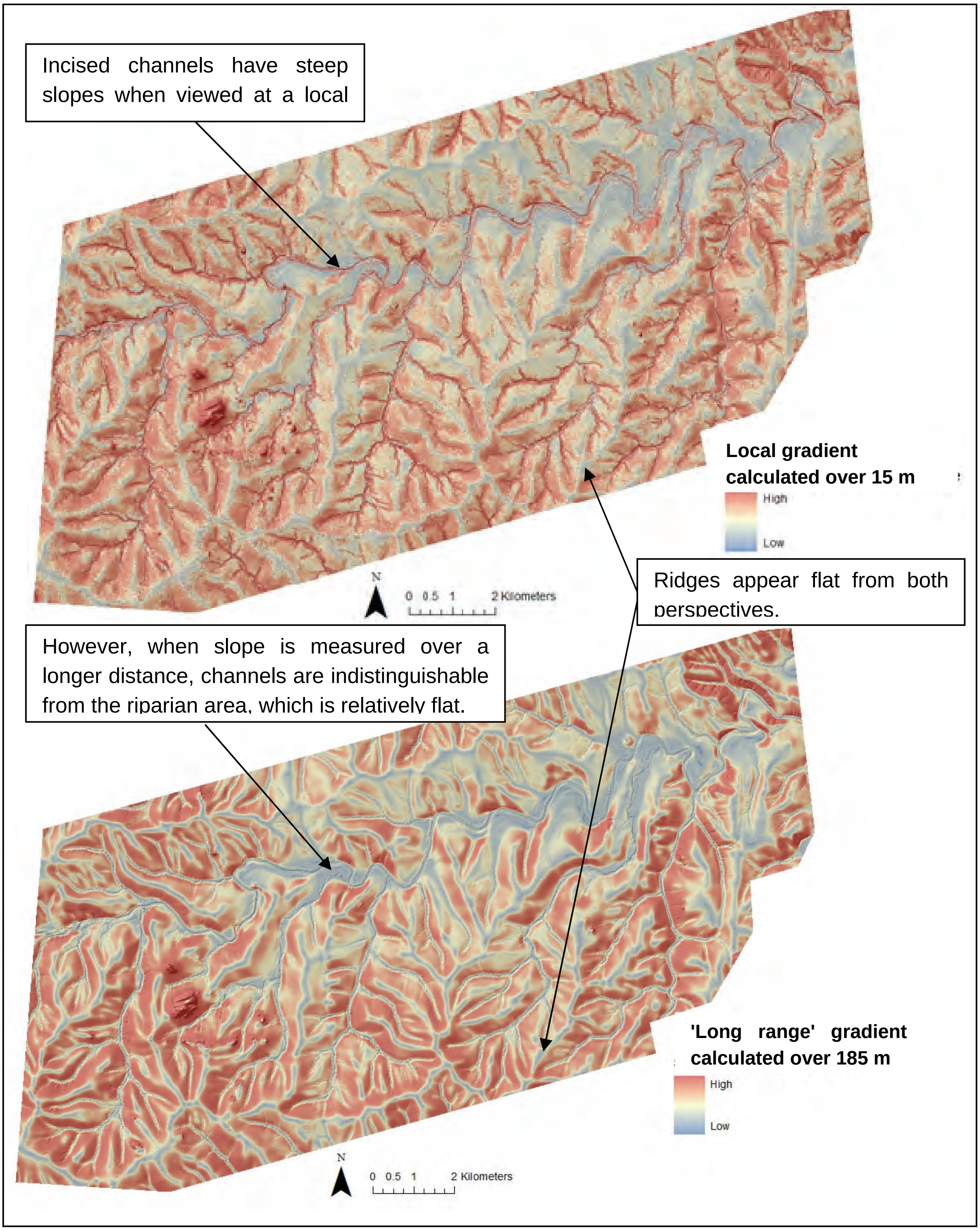


Figure 4.11: 'Local' and 'long range' gradient measured in degrees over 15 m and 185 m in the N'waswitshaka study area.

'Local' gradient shows the steep slopes associated with incised channels (dark red in top image), which contrast with the flat areas on top on the crests and in the lower reaches of the N'waswitshaka floodplain (light blue).

By contrast, 'long range gradient' shows channels as flat (light blue), and only koppies and midslopes appear to have steeper slopes (red).

Each measure of gradient reveals different landscape properties and both are used in the definition of catenal elements.

c) Curvature

Curvature was calculated over a distance of 185 m (the same distance as 'long range' gradient), in order to reveal trends associated with hillslope positions. As might be expected, crests and koppies show convex curvature in both profile and planform directions, while channels are concave in both directions (Figure 4.13). Differences in curvature contribute most to terrain analysis when planform curvature can distinguish between convex midslopes, which are divergent slopes that tend to disperse water, and concave, convergent midslopes, which concentrate water flows.

Restricting the analysis to midslopes only, there is very little difference between the vegetation classes found on divergent and convergent midslopes (Figure 4.12). This result is largely determined by the scale of analysis and classification rules. In our case, divergent slopes that form small ridges between gullies on a hillside are often more wooded than the grassy slopes of the convergent slopes of the gullies. However, the woodier, divergent ridges have generally been classified as part of the crest. This means that there remains little vegetation difference associated with planform variations in the midslope region and there is therefore no need to subdivide midslopes in order to separate convergent and divergent slopes.

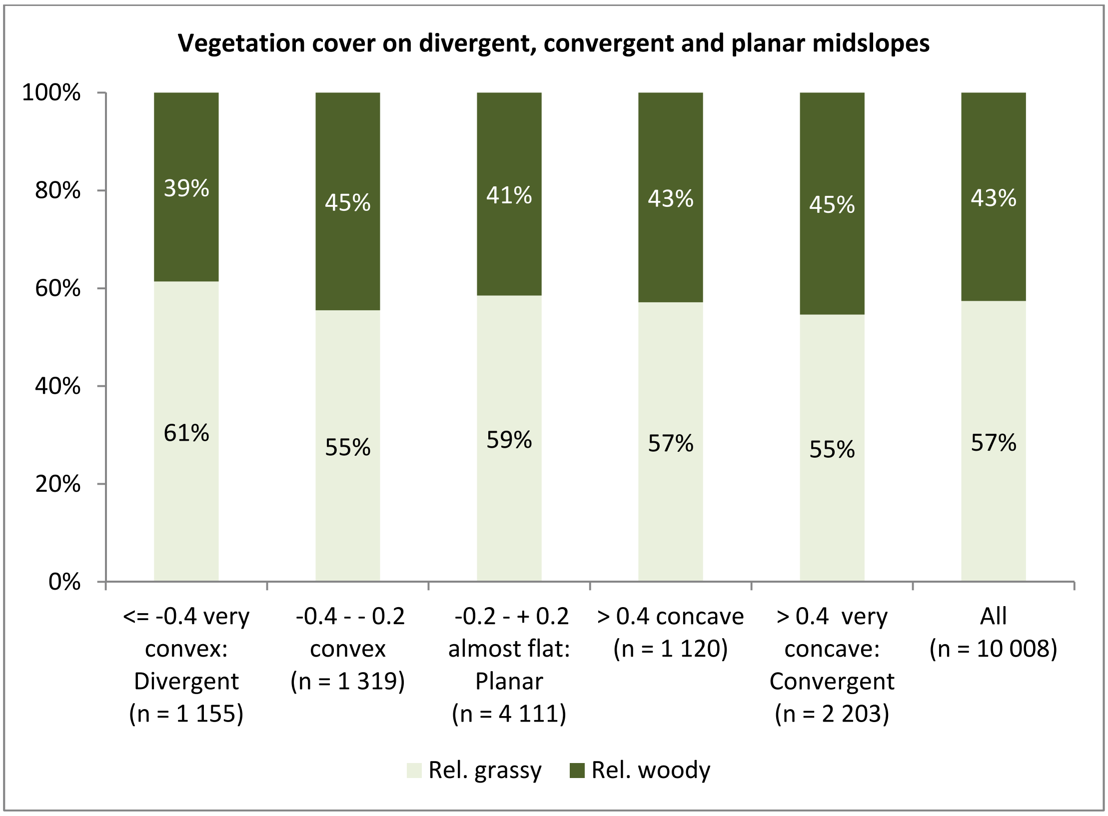


Figure 4.12: Vegetation cover on divergent, convergent and planar midslopes in the N'waswitshaka basin

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

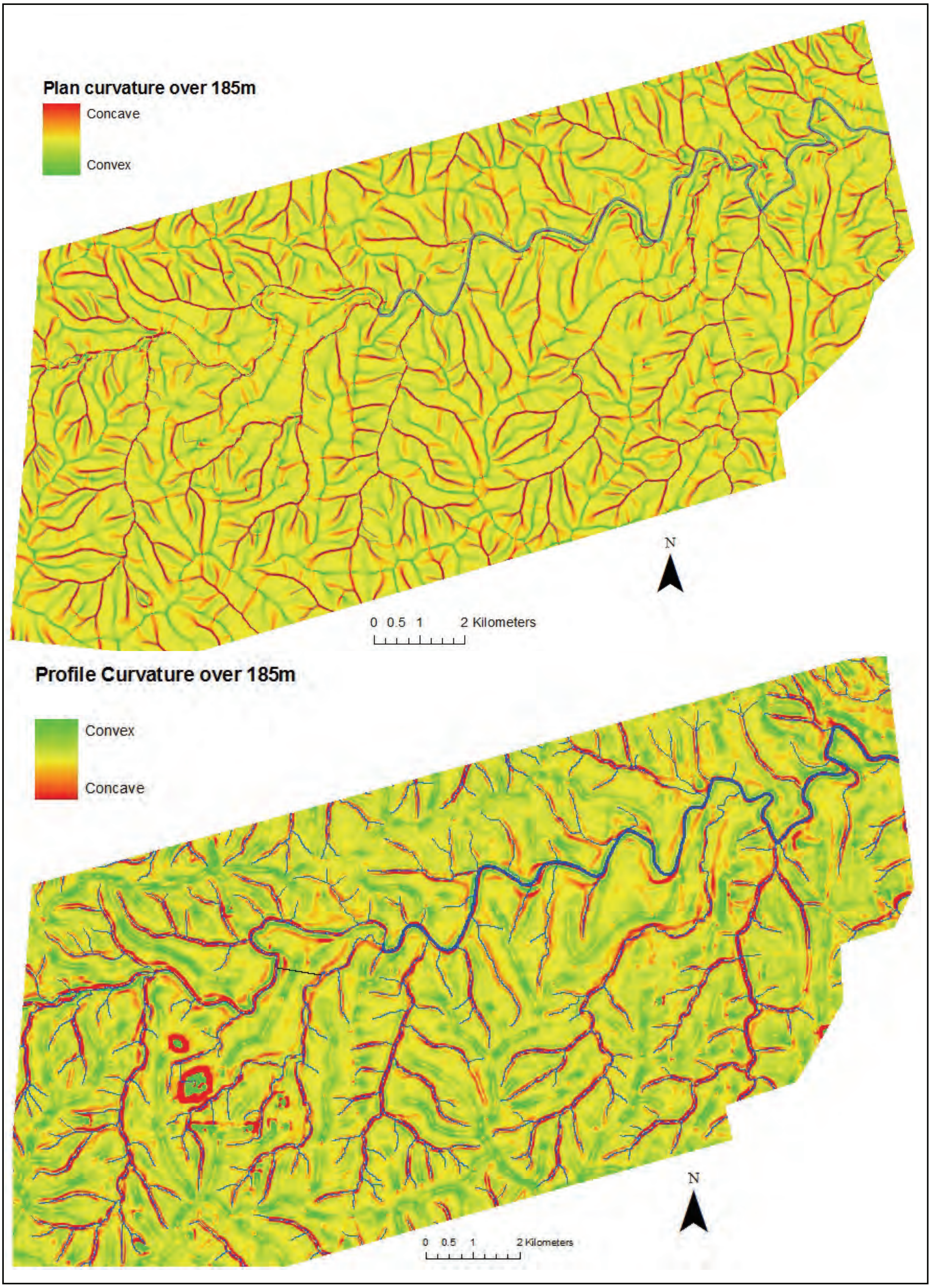


Figure 4.13: Planform and profile curvatures measured over 185 m for the N'waswitshaka study area

In both scenes, drainage lines are also shown, so that the concave channels can be easily distinguished from the convex crests.

4.3.4. Definition of hillslope units for the N'waswitshaka study area

The image objects used for the vegetation classification were further segmented at a smaller scale, using topographical layers describing elevation, local and 'long range' gradient, profile curvature calculated over 15 m and TPI calculated over 300 m, all resampled to a resolution of 4.48 m (Shape 0.1, compactness 0.5, scale parameter =10).

Class prototypes were developed, informed by relationships between topography and vegetation distribution:

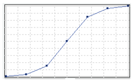
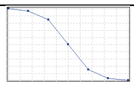
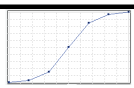
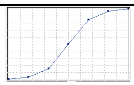
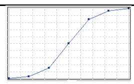
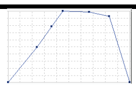
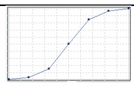
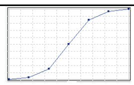
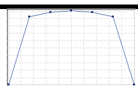
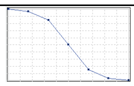
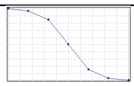
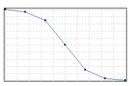
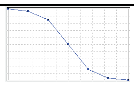
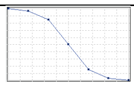
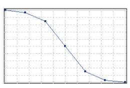
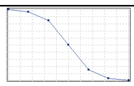
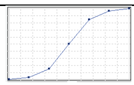
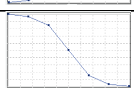
- ***Crests***, which are relatively high in the landscape, often bordered by a tree/grass boundary that occurs at a TPI of about 1.5.
- ***Koppies***, which rise steeply above the surrounding landscape
- ***Midslopes***, which lie between crests and channels and are relatively steep
- ***Flat toeslopes***, which lie low in the landscape and are relatively flat. These are likely to be floodplains)
- ***Channels***, are relatively flat and have concave profile curvature at a 'long range' scale and which lie low in the landscape
- ***Banks***, which lie low in the landscape, are relatively steep and have concave profile curvature at a local scale, but are relatively flat over a longer distance.

A fuzzy classification was used, in which the membership functions for each class define the similarity of each image object to the prototype of each class (Table 4.1). If the rule defining a class prototype includes more than one variable (for example, 'crests' are defined both in terms of TPI and in terms of 'long range' gradient), then the individual membership values for each variable are 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 resulting classification clearly partitions the landscape by hillslope position, as well as identifying koppies and the increasing area occupied by flat flood plains down the course of the N'waswitshaka river (Figure 4.14).

Table 4.1: Rule set used for the fuzzy classification of hillslope units in the N'waswitshaka study area

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

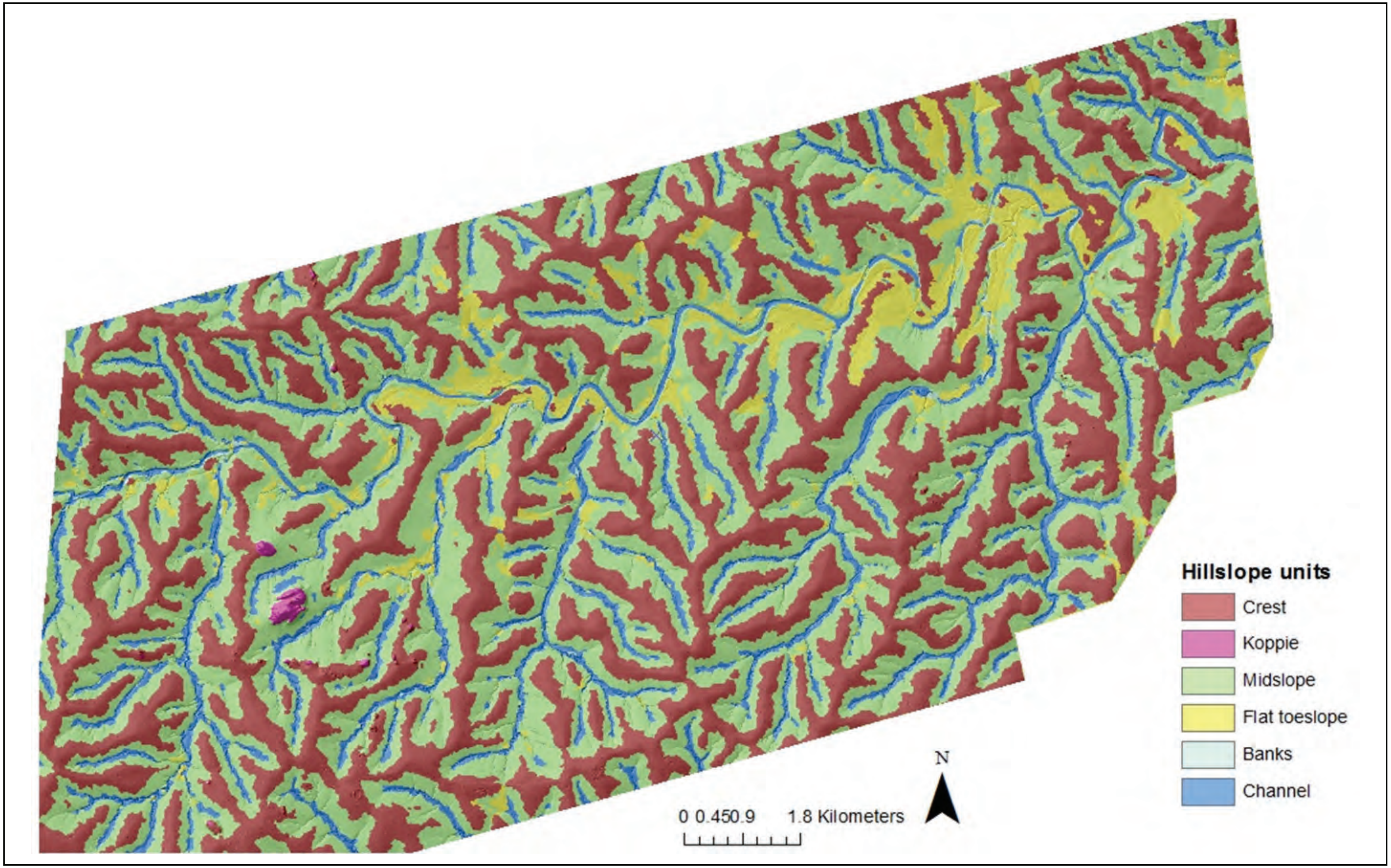


Figure 4.14: Hillslope units in the N'waswitshaka study area.

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

4.3.5. STEP 3: Relationships between vegetation and hillslope units in the N'waswitshaka basin

The relationship between vegetation class and hillslope units was further explored in order to develop rules to define classes of catenal elements.

Relatively woody cover dominates on crests and on river banks (at least on the banks of rivers that have a steep gradient and cover a large enough area to be identified as separate hillslope units). In other hillslope positions, woody cover falls below 50%. Although there is a general pattern of woodier crests and grassier midslopes, it is clear from the vegetation distribution (Figure 4.7 above) that the pattern is far from regular. For example, the woody crests appear to extend much further down the hillslope in the south east of the scene, whilst to the west, the woody crest area is relatively small. Catenal elements combine hillslope position and vegetation cover in a way that allows these spatial differences to be described.

Bare rock and sand was found either on koppies or associated with the riparian zone, occurring in the channel, on banks and on flat toeslopes. Flat toeslopes occupied a position adjacent to larger streams, suggesting that they may be floodplains subject to alluvial deposition and/or vertical movements of stream water through the phreatic zone (Figure 4.15).

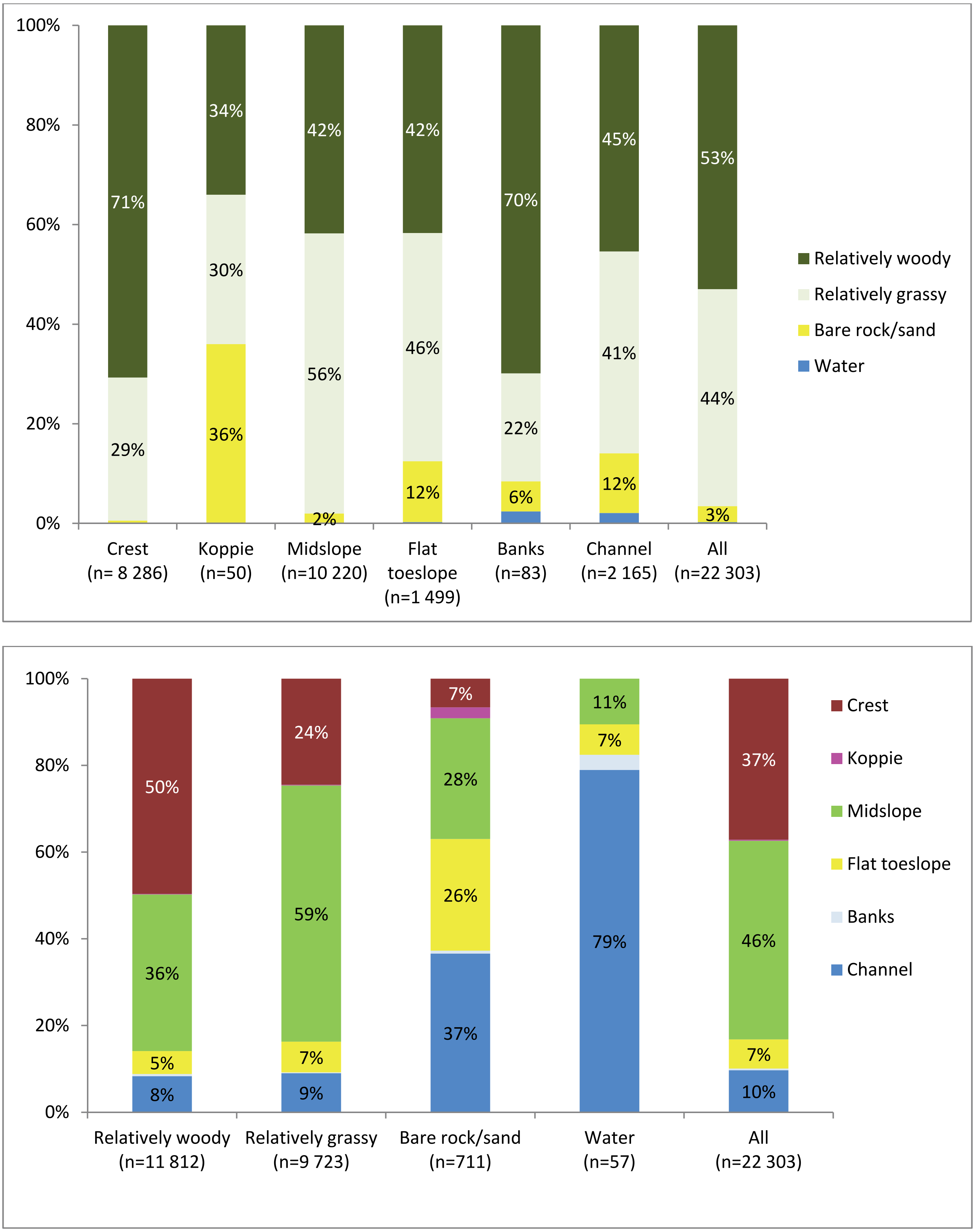


Figure 4.15: Associations between vegetation cover and hillslope units in the in the N'waswitshaka basin

Woodier vegetation is clearly associated with crests, whilst grassier vegetation is more likely to be found on toeslopes or midslopes. Most unvegetated areas (sand, rock or water) are found on koppies or in riparian areas (channels, banks and flat toeslopes).

Based on the classification at points regularly sampled at 100 m intervals throughout the study area.

4.3.6. STEP 4: Define classes of catenal elements and rules that define prototypes for each class. Apply fuzzy classification.

Based on the relationships between terrain units and vegetation cover, prototype classes were defined and a new fuzzy classification applied to the same image objects used for the vegetation and topographical classifications:

> ***Crests***, separated into 'bare', 'relatively woody' and 'relatively grassy'. In all cases, the 'woody' and 'grassy' were extended to include a membership function based on appropriate values in the SPOT5 pan image, so including objects that remained unclassified for vegetation cover.
> ***Midslopes***, separated into 'bare', 'relatively woody' and 'relatively grassy'
> ***Toeslopes***, separated into 'bare', 'relatively woody' and 'relatively grassy'
> Koppies
> Channels and banks

Two of these classes were then enlarged:

> ***Koppies*** were extended to include adjoining objects classified as bare crests or midslopes.
> ***Bare toeslopes*** were extended to included bare crest or midslope objects that were adjacent to the toeslope, channel or banks. These areas are probably sodic sites, areas with soils characterized by a disproportionately high concentration of Sodium (Na) in their cation exchange complex. These soils impede water infiltration, water availability, and ultimately plant growth.

Lastly, the image was smoothed by applying a low-pass filter (majority value in neighbouring circle of 5 cell (25 m) 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 contained only one object each, and these were reclassified manually.

The final image (Figure 4.16) 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 idealised conceptual model of woody crests and grassy midslopes applies best in the centre of the scene.

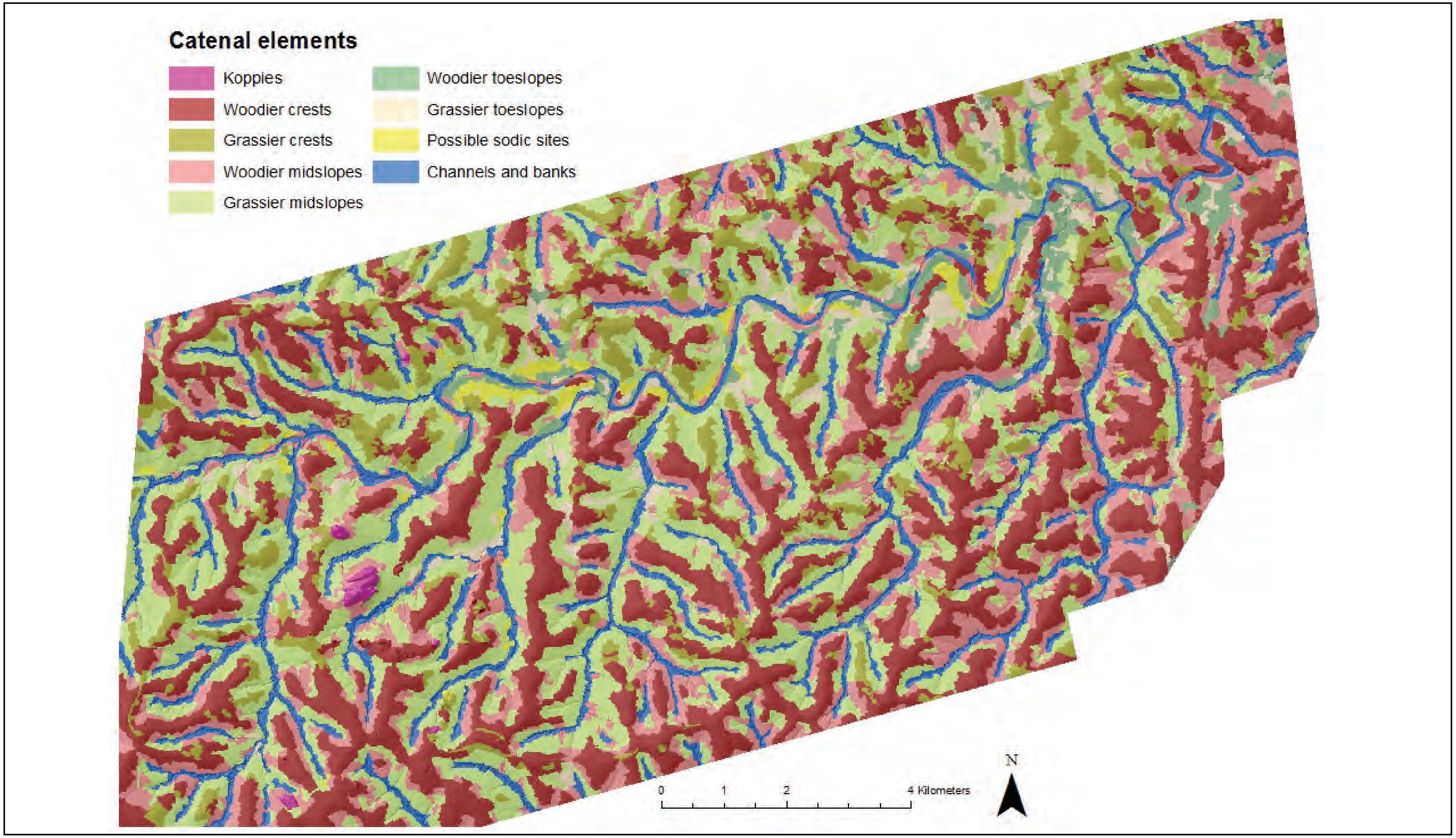


Figure 4.16: Classification of catenal elements in the N'waswitshaka basin.

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.

4.4 Catenal elements in the Lower Sabie basalts

4.4.1. Background

The Lower Sabie study area is 42.2ha (about 6km x 6km) and encompasses the majority of the headwaters of the Nhlowa river. This river rises almost entirely on the basalts included in the study area, before traversing through rhyolites, (where the stream density increases dramatically) and joining the Sabie river about 10km south of Lower Sabie rest camp.

This area is extremely flat, with an elevation range of only about 75 m over the whole area (Figure 4.17). Stream density is far lower than that seen on the N'waswitshaka granites, with a mean CASS width of 1 737 m. This means that metrics designed to capture topographical variation across an entire slope need to be calculated across a longer distance than in the granitic areas. The TPI used for determining hillslope position is measured using an 850 m radius, whilst 'long range' gradient is calculated over 220 m.

The study area falls entirely within the Satara land type described by Venter (1990), which is characterised by red and brown clays of the Shortlands and Swartland forms, which have developed from olivine-poor basaltic lavas. The vegetation is open and *Sclerocarya birrea* and *Acacia nigrescens* are the dominant trees.

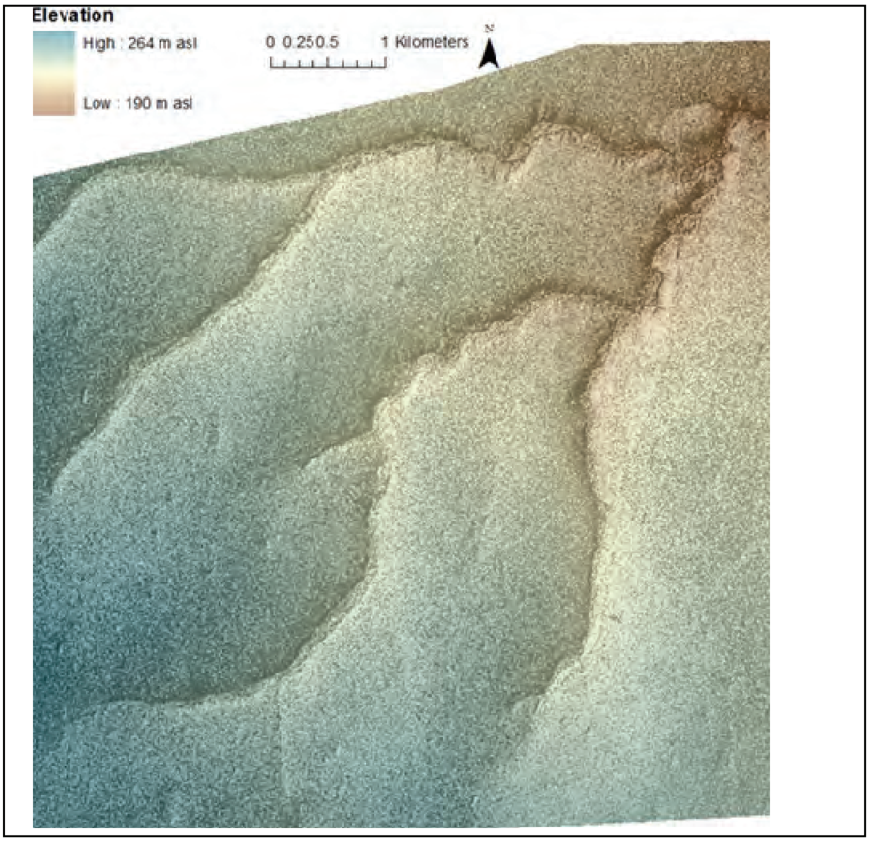


Figure 4.17: Drainage network and elevation in the Lower Sabie basalt study area

The Lower Sabie study area lies entirely on basalt and includes most of the headwaters of the Nhlowa river. The area is extremely flat, with an elevation range of only about 75 m over the whole area. Stream density is far lower than that seen on the N'waswitshaka and Pretoriuskop granites, with a mean CASS width of 1 737 m.

Carnegie Airborne Observatory imagery was provided by the Carnegie Institution for Science with support from the Andrew Mellon Foundation, W.M. Keck Foundation and William Hearst III.

4.4.2. STEP 1: Classification of vegetation cover in the Lower Sabie basalts

Patterns of woody vegetation are not easily discernable from SPOT5 imagery in the Lower Sabie basalts (Figure 4.18), so we incorporated LiDAR canopy height data to separate trees from grass (Figure 4.19). Many tall trees appear to be located near rivers, whilst there appears to be no systematic pattern for shorter trees, so we also separated woody cover into two height classes in order to test these relationships more thoroughly (Figure 4.20).

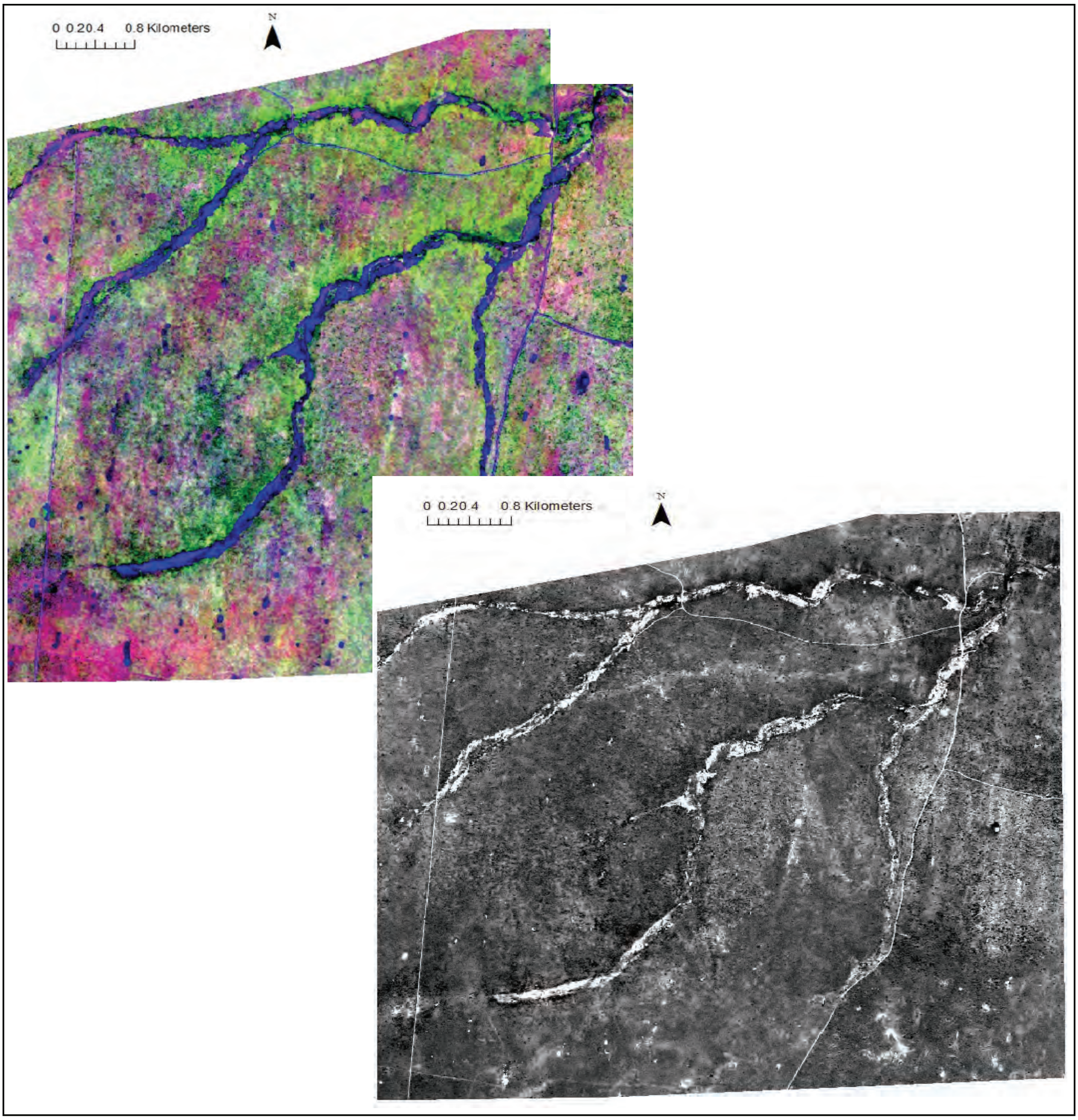


Figure 4.18: SPOT5 images of the Lower Sabie basalt study area

This image, acquired in March 2006, towards the end of the wet season, shows channels that contain water for most of their length. Isolated pans also contain water. However, vegetation patterns are unclear in both images False colour RGB is SWIR, NIR, Red bands

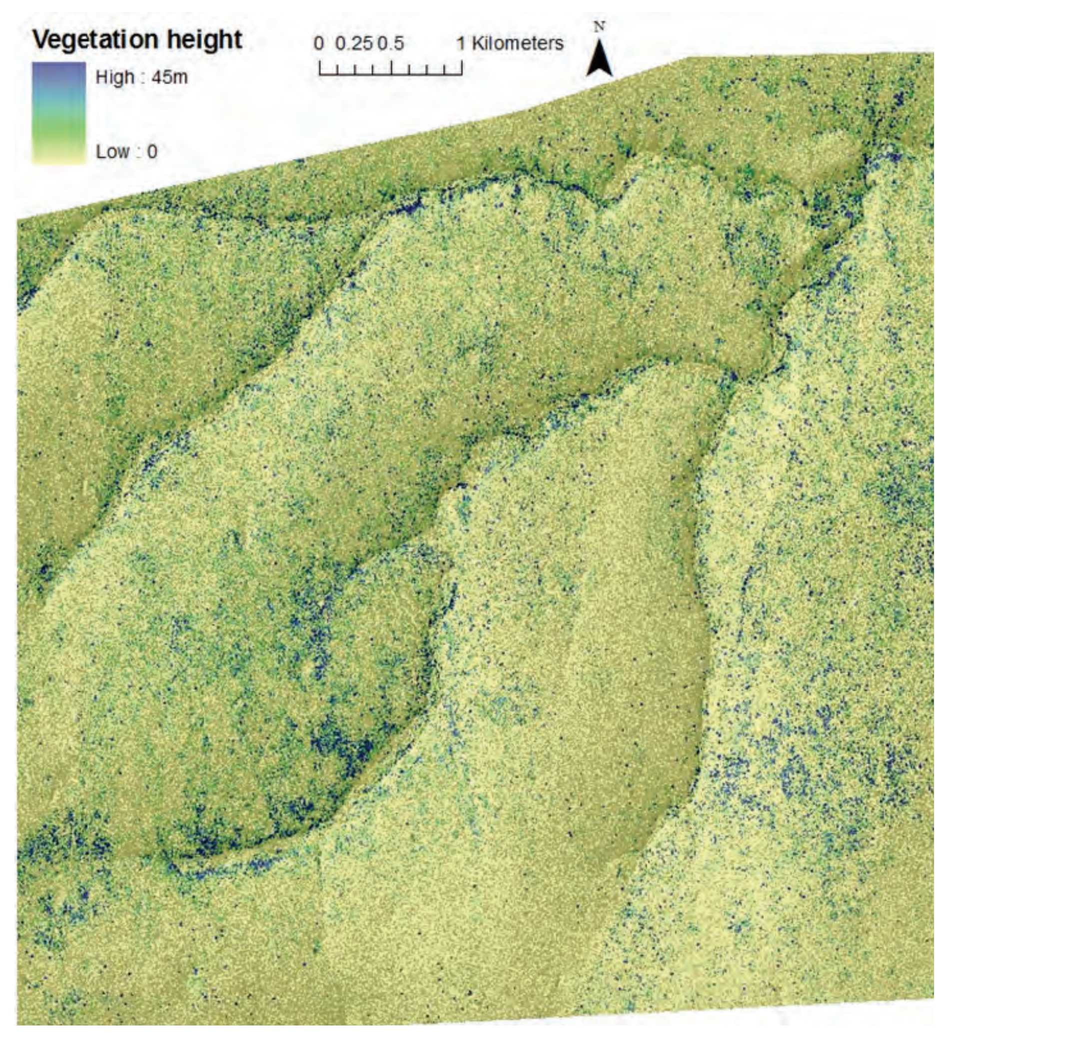


Figure 4.19: Vegetation height in the Lower Sabie basalts
Many tall trees appear to be located near rivers, whilst there appears to be no systematic pattern for shorter trees

- Segment into objects based on
  - SPOT5 pan, NIR and red layers resampled to 4.48 m resolution
  - canopy height CAO LiDAR data
  - TPI, profile and plan curvatures, and slope, – all calculated within 11 cell (49 m) kernels
  - TPI calculated within a 190 cell (851 m) kernel
  - Shape 0.1, compactness 0.5, scale parameter =3
- Class definitions:
  - Unvegetated: mean NDVI <=0.22 and mean NIR (SPOT band 3) > 120
  - Water: mean NDVI <=0.22 and mean NIR ≤ 120
  - Tall trees: > 10% cover over 5 m high
  - Grass: < 5% cover over 0.5 m high
  - Intermediate trees: remainder of scene
- Smoothed

Figure 4.20: Procedure for vegetation classification in the Lower Sabie basalts

The vegetation classification reveals only a loose relationship between woody cover and distance to a channel. More distinct vegetation boundaries seem to be associated with the roads that run north-south to the west and east of the scene and are probably related to fire history (Figure 4.21).

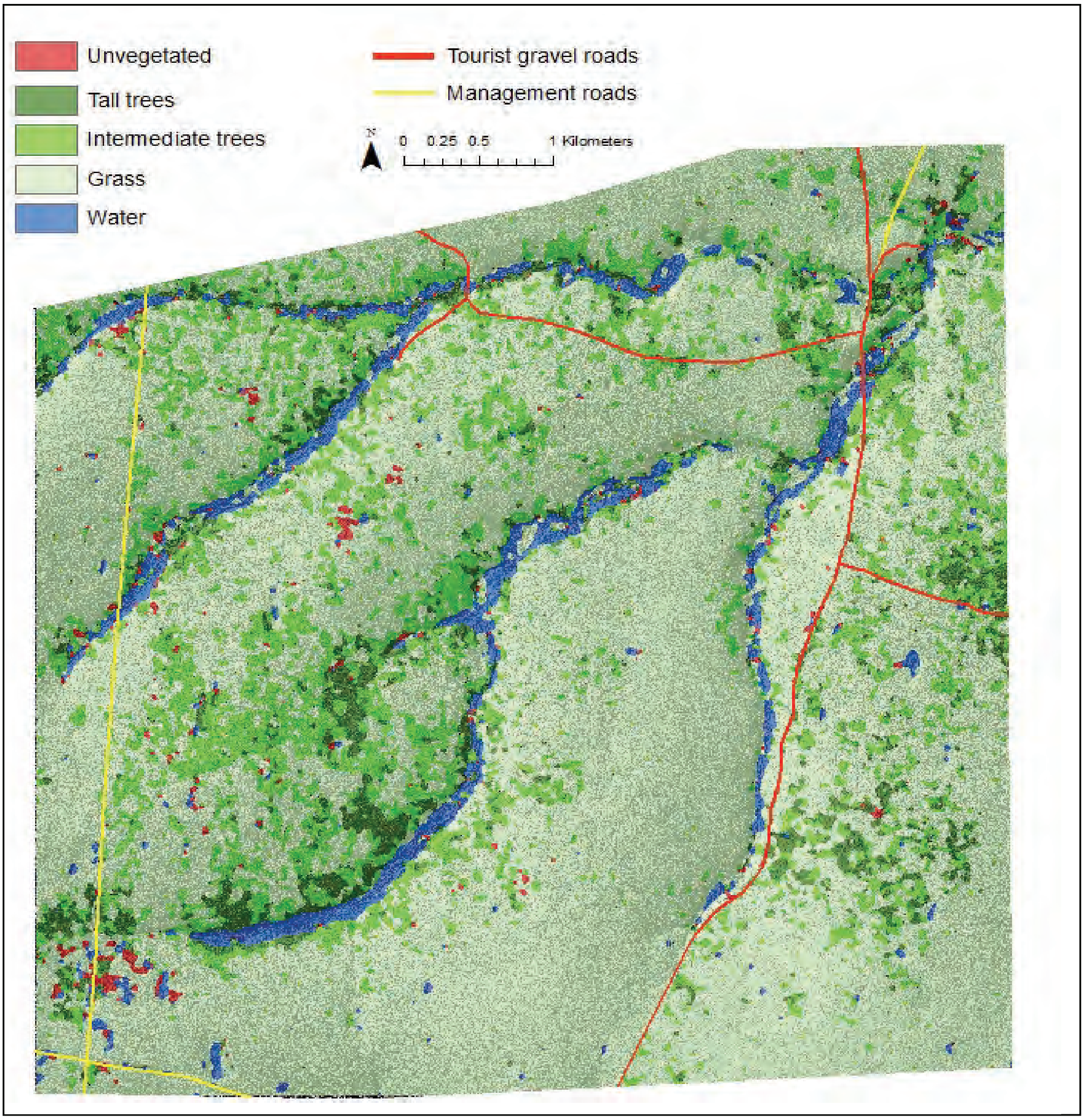


Figure 4.21: Vegetation classes in the Lower Sabie basalts

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.

Carnegie Airborne Observatory imagery was provided by the Carnegie Institution for Science with support from the Andrew Mellon Foundation, W.M. Keck Foundation and William Hearst III

4.4.3. STEP 2: Classification of hillslope units in the Lower Sabie basalts

Although TPI remains our main tool to describe hillslope position, the wide valley spacing in the Lower Sabie basalts means that TPI needs to be measured over a much larger distance than is needed in the southern granites of N'waswitshaka and Pretoriuskop. The mean CASS width in the Lower Sabie basalt study area is 1 737 m, so a circular kernel of 850 m (190 cells) radius was used to calculate TPI in this region in order to capture variation over a complete hillslope (Figure 4.22).

In order to capture details of channel topography, TPI is also measured over a much smaller distance of 49 m (11 cells), a distance which captures variation across the width of the channel bed, distinguishing between incised channels, lateral gullies and the channel bed itself (Figure 4.23).

Profile curvature over the same distance also helps distinguish the incised channels, whilst plan curvature shows the incised channels and banks of the river bed, planform curvature distinguishes gullies that flow into the main stem (Figure 4.23).

Calculated over 220 m, gradient shows broad differences between the crests and the channel. There is some suggestion of slope breaks dividing midslopes from crests. When calculated over 49 m, gradient clearly shows the relatively steep banks that bound the channel, as well as the depressed pans scattered throughout the landscape (Figure 4.24).

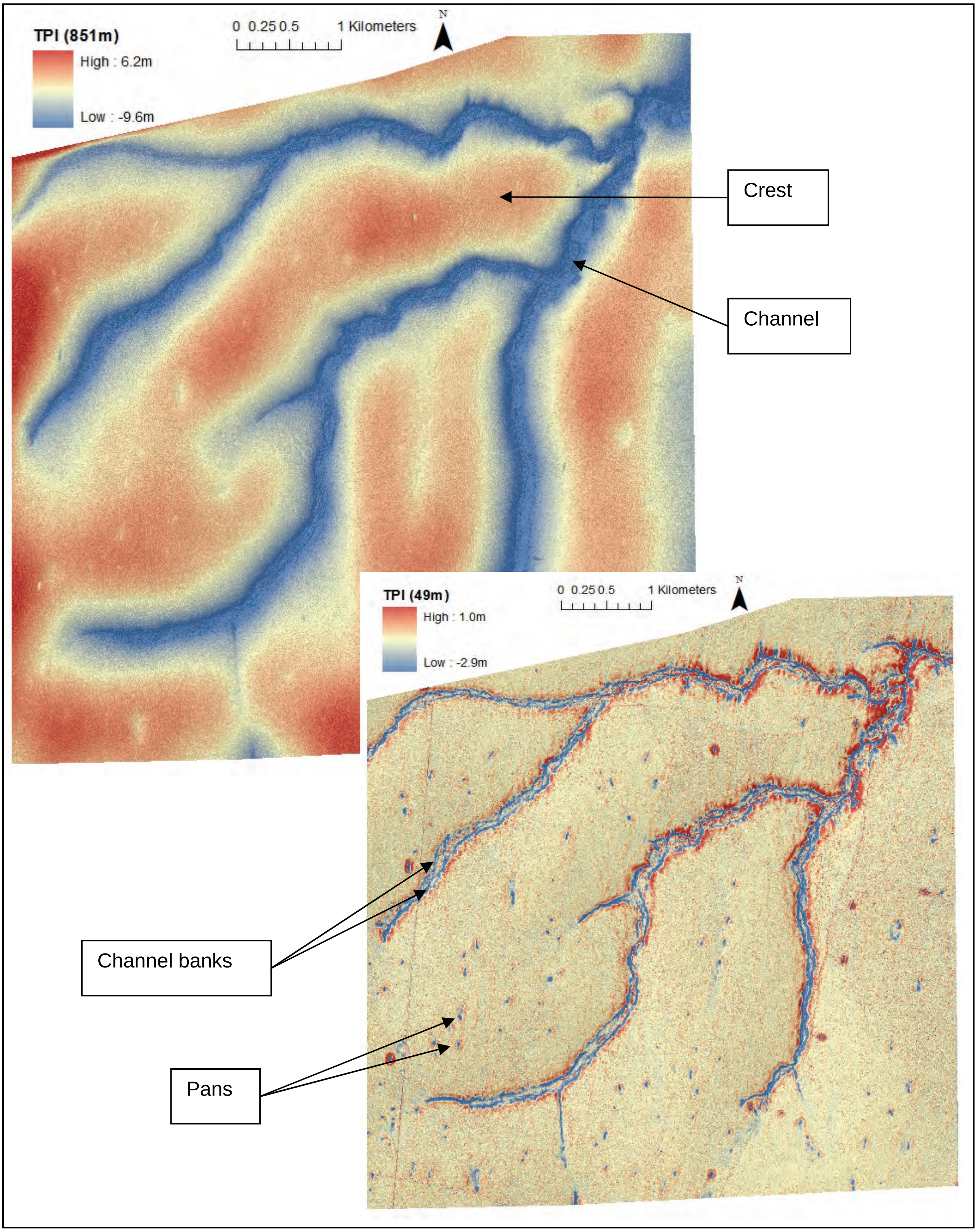


Figure 4.22: TPI calculated over 851 m and 49 m within the Lower Sabie basalt study area

TPI calculated over 851 m clearly distinguishes between crest and channel regions. The same measure calculated over 49 m shows fine detail of the sloping channel banks and pans.

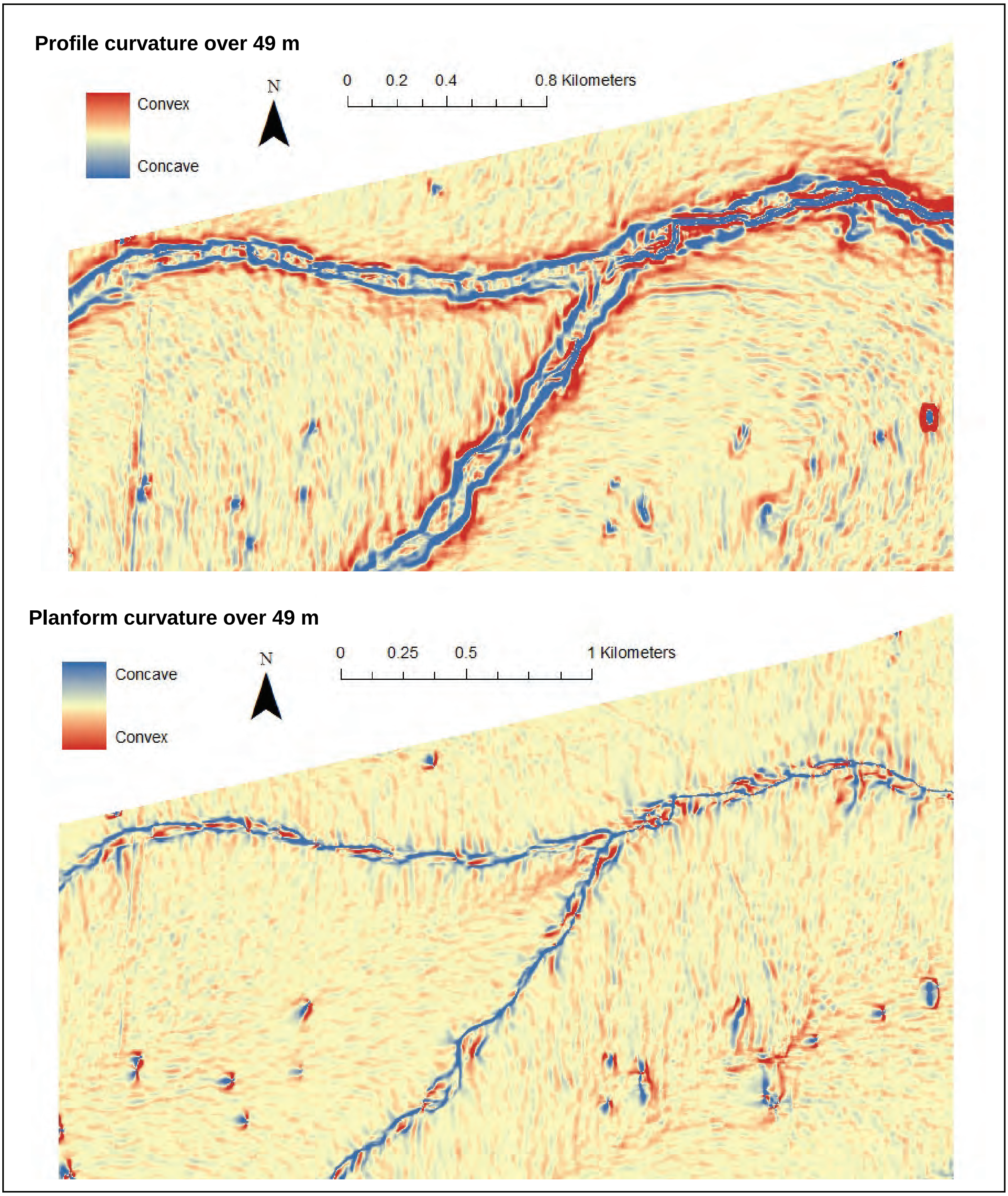


Figure 4.23: Curvature over 49 m in channels on the Lower Sabie basalts

Whilst profile curvature measured over approximately half the channel width reveals the incised channels and banks of the river bed, planform curvature distinguishes gullies that flow into the main stem.

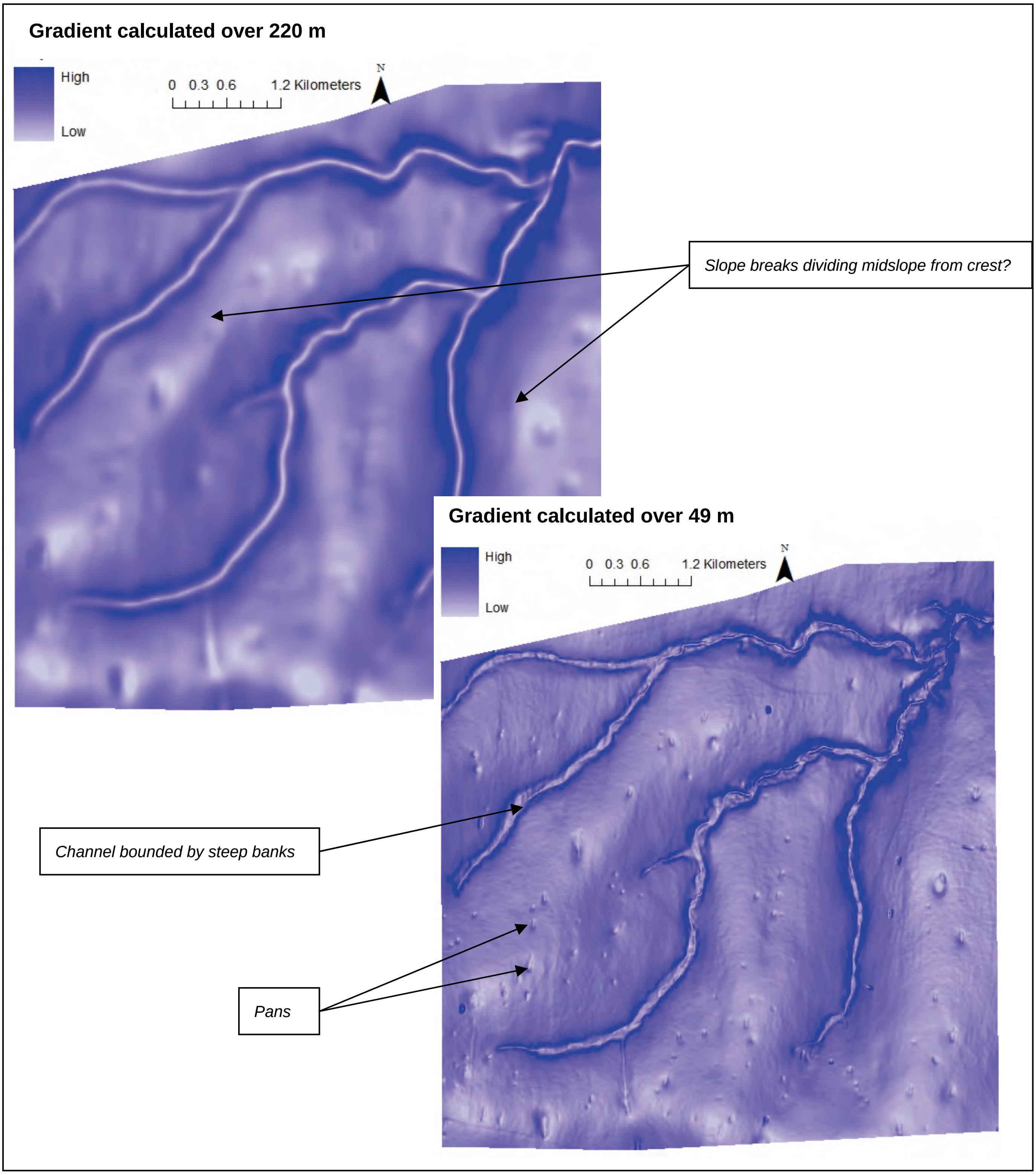


Figure 4.24: Gradient calculated over 220 m and 49 m in the Lower Sabie basalt study area

Calculated over 220 m, gradient shows broad differences between the crests and the channel. There is some suggestion of slope breaks dividing midslopes from crests. Gradient calculated over 49 m clearly shows the relatively steep banks that bound the channel, as well as the depressed pans scattered throughout the landscape.

Based on the variation in these topographic variables, class prototypes were developed for:

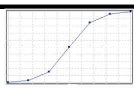
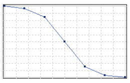
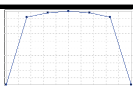
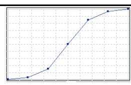
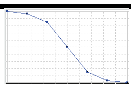
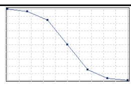
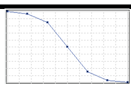
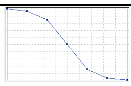
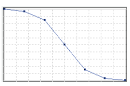
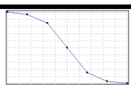
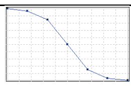
- ***Crests***: high in the landscape and very flat
- ***Midslopes***: steeper 'long-range' gradient than crests, and medium-high in the landscape
- ***Footslopes:*** steeper 'long-range' gradient than midslopes, and medium-low in the landscape
- ***Banks***: Very low in landscape and highly concave curvature (11 m)
- ***Channel floor***: Very low in landscape and flat

Pans were then added:

- ***Pans***: on crests or midslopes and mean TPI (11 M) <= -0.1

A fuzzy classification was applied to the same image objects used for the vegetation classification (Table 4.2).

Table 4.2: Rule set used for the fuzzy classification of hillslope units in the N'waswitshaka study area

Class	Variable	Membership function curve	Minimum value	Maximum value	Comments
Crest MIN OF	Mean TPI (851 m)		0.5	1.0	high in the landscape
	Mean 'long range' gradient (220 m)		0.7	1.5	Flat
Midslope AND	Mean TPI (851 m)		-2	2	
	Mean 'long range' gradient		0	0.7	
Footslopes AND	Mean 'long range' gradient		0.7	0.9	Quite steep
	Mean TPI (851 m)		-1	-0.8	Low in landscape
Channel Floor AND	Mean TPI (851 m)		-3	-2	Very low in landscape
	Mean local gradient (49 m)		1	1.2	Flat locally...
	Mean 'long range' gradient (220 m)		0.8	1	...and/or over 'long range'
Banks AND	Mean profile curv (49 m)		-0.0003	-0.0002	Concave over (49 m)
	Mean TPI (851 m)		-3	-2	Very low in landscape

The final classification shows a discontinuous incised channel lies within a larger channel, which is bounded by sloping banks (Figure 25). Slope breaks defining boundaries between footslopes, midslopes and crests are extremely subtle and often ill defined, therefore these boundaries are indicative only.

Pans on the crests and midslopes sometimes form chains of ponds, which suggest the possible development of a new channel. However pans are also seen on crests, where they appear to be disconnected from the drainage network.

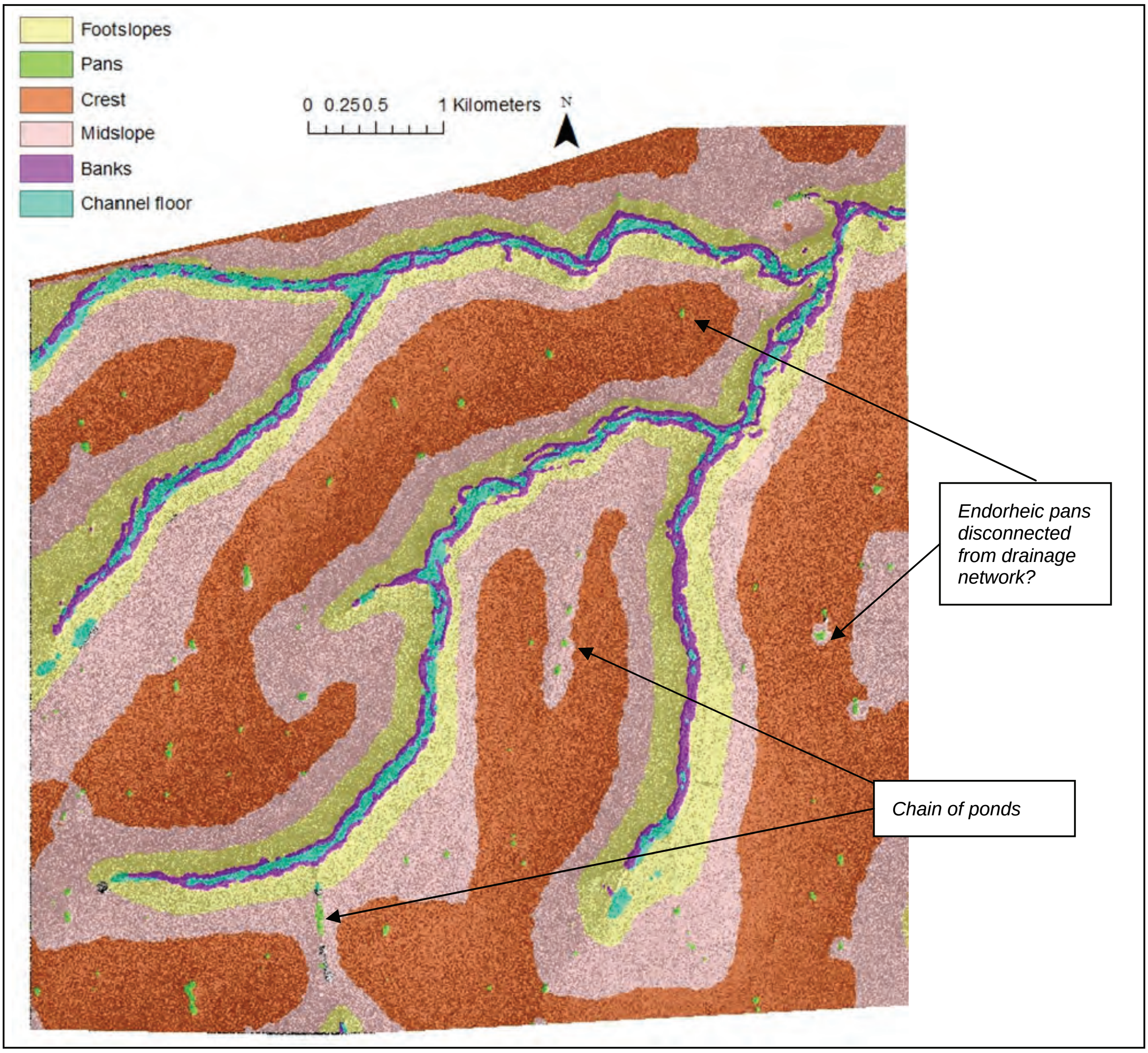


Figure 4.25: Hillslope units in the Lower Sabie basalts.

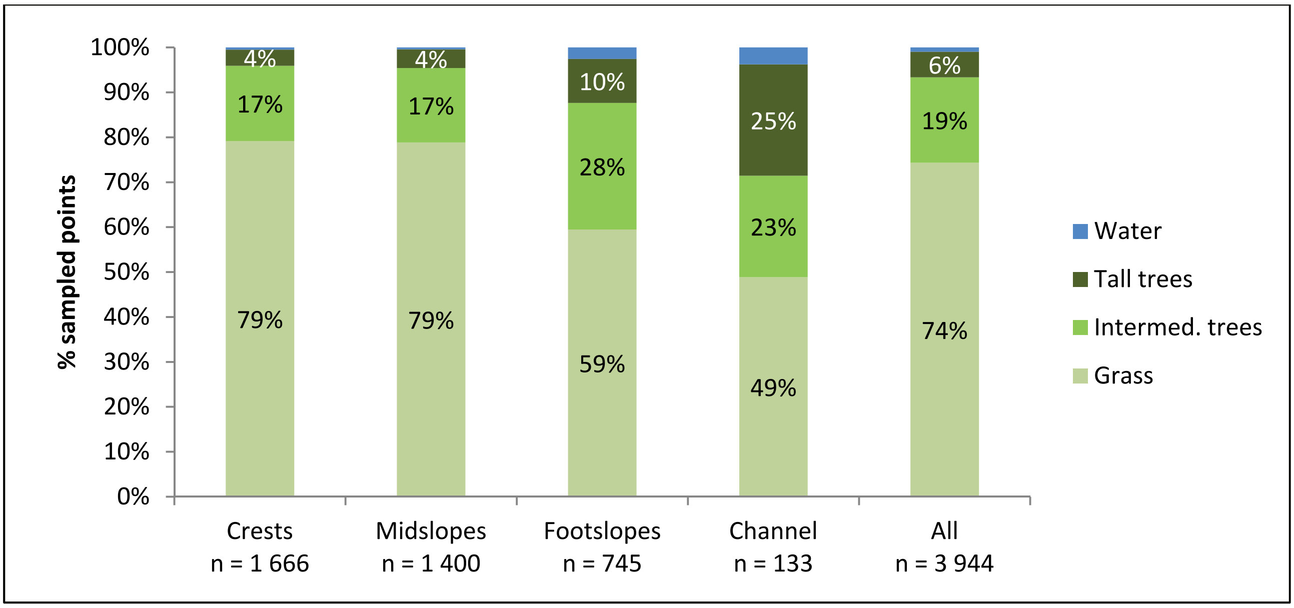
A discontinuous incised channel lies within a larger channel, which is bounded by sloping banks. Pans on the crests and midslopes are sometimes chains of ponds that suggest the possible development of a new channel, but are also seen in positions, where they appear to be disconnected from the drainage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

Slope breaks defining boundaries between footslopes, midslopes and crests are extremely subtle and often ill defined, therefore these boundaries are indicative only.

4.4.4. STEP 3: Relationships between vegetation and hillslope units on the Lower Sabie basalts

Both vegetation cover and height classes show relationships with broad-scale TPI (calculated over 851 m), suggesting that trees are more likely to establish and to grow taller in areas relatively low-lying areas near the channel.

Whereas almost half the vegetation cover on the banks and beds of channels falls into classes of 'tall' and 'intermediate' trees, crests are dominated by grass. However, woody vegetation is sparse in all areas – it is not the case that all low-lying areas are wooded. Furthermore, the association between woody cover and elevation above a stream is quite loose and there are no distinct vegetation boundaries that related to topographical variations.



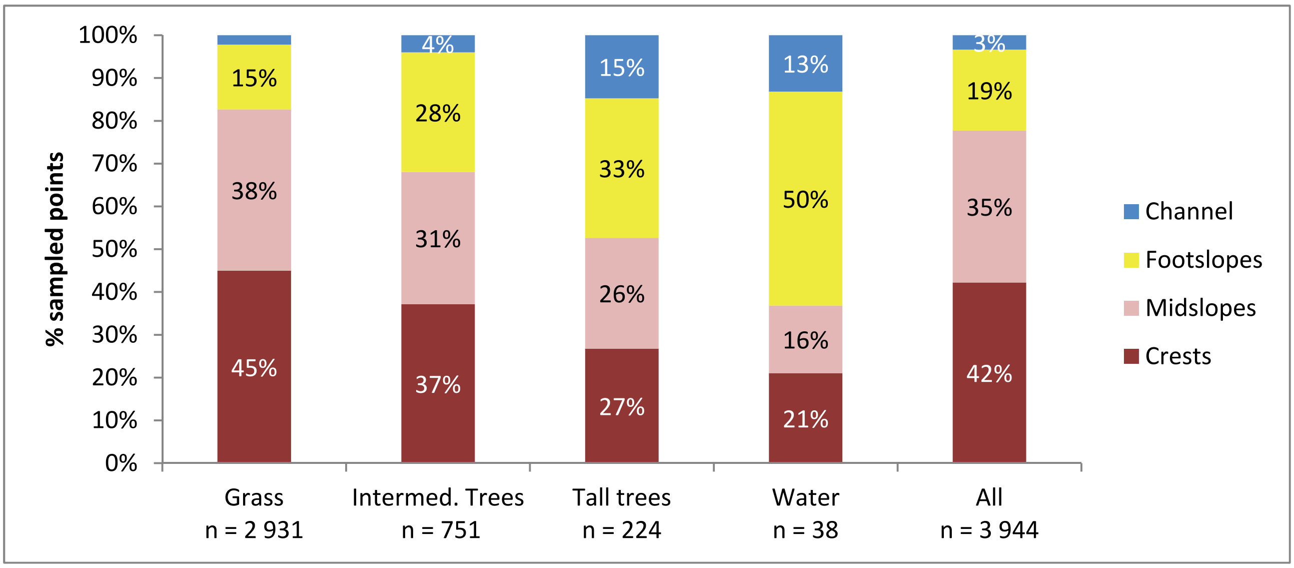


Figure 4.26: Relationships between vegetation and hillslope units on the Lower Sabie basalts

The proportion of hillslope units covered by intermediate and tall trees increases steadily downslope. Based on points sampled at 100 m intervals.

4.4.5. STEP 4: Catenal elements in the Lower Sabie basalts

We defined only two catenal elements for the Lower Sabie basalts: a *channel*, bounded by distinct banks, and a large *interfluve* area. We noted that a subtle gradient exists between the lower and upper slopes, with decreasing woody vegetation found further away from the channel. However, we also noted that surface topography is not the dominant control on woody vegetation patterns in crestal positions and therefore infer that there are no differences in hydrology in these areas that are systematically related to slope position. This means that the interfluve areas are not subdivided into different catenal elements (e.g. crest, midslope, footslope).

Most pans are small, under the 1ha MMU for catenal elements, and are hence considered as microfeatures typical of interfluves.

Channels are defined by aggregating the riverine features identified in the topographical classification (banks and channel floor), whilst interfluves form the remainder of the landscape.

The Lower Sabie basalts are dominated by these interfluves, which occupy some 94% of the area (Figure 4.27). Whilst channels are characterised by the presence of water and relatively tall trees, the vegetation on 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.

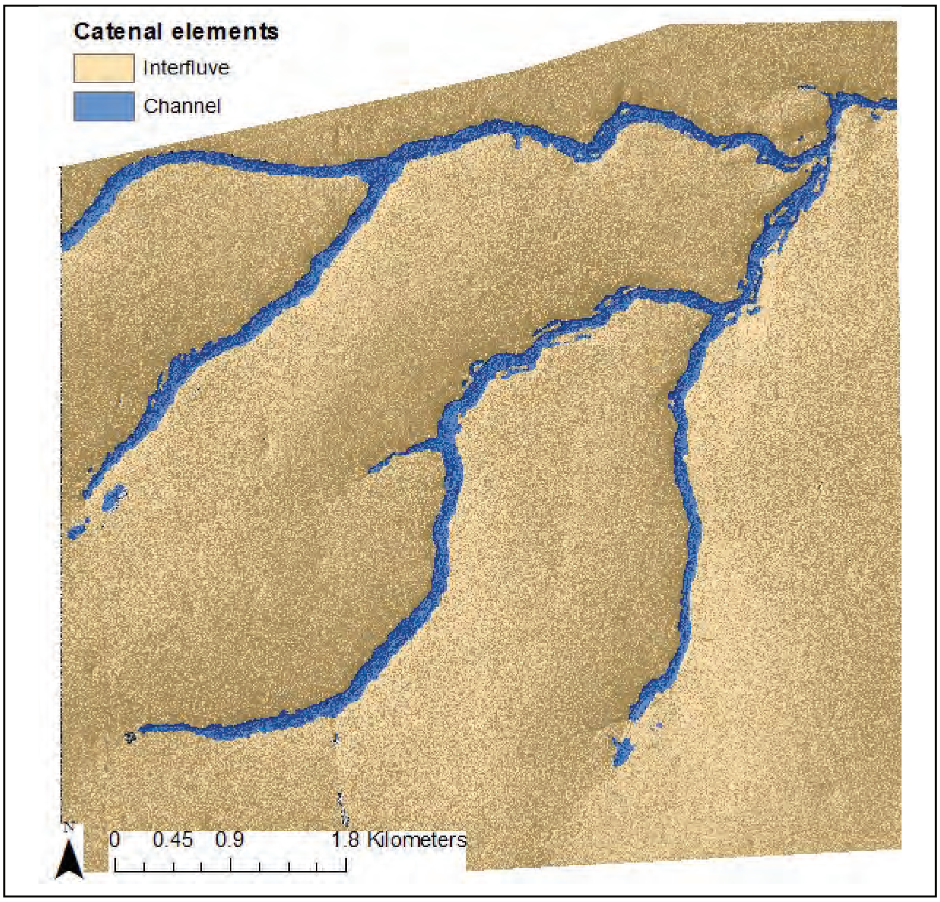


Figure 4.27: Catenal elements in the Lower Sabie basalts

This region is dominated by interfluves, which occupy some 94% of the area. Whilst channels are characterised by the presence of water and relatively tall trees, the vegetation on interfluves is heterogeneous and is likely to be influenced by patterns of subsurface water storage, fire and herbivory, rather than the very slight topographical variations seen in this very flat landscape.

4.5 Lessons learned from the delineation of catenal elements in the N'waswitshaka and Lower Sabie study areas

The two study areas in which our approach to the delineation and classification of catenal elements has been illustrated occur in very different physiographic zones. Whilst the N'waswitshaka study area is situated in the finely dissected southern granites, the Lower Sabie site lies within basalts that have much larger catchments and CASSs.

Not only are different suites of catenal elements needed to describe landscapes in the two settings, but the scales at which the variables used to define these elements also differ. For example, in order to describe hillslope position in a way that captured variation across the entire hillslope, from crest to valley bottoms, TPI had to be calculated using different kernels in the two study areas. In each case, the landscape wavelength, or ridge-valley spacing was used to set a kernel appropriate to the setting. The landscape wavelength also influenced the distance over which gradient and curvature was measured. Furthermore, within each setting, several different kernels were used to describe different landscape features. For example, whilst large kernels were used to describe landscape position, small kernels were used to describe channel banks.

The typical areas covered by catenal elements in each study site also differ greatly. For example, interfluves occupy much larger areas within the basalt site than do crests in the granite site. This variation in the size of catenal elements has important implications for the way in which we parcel land for either scientific investigation or conservation management. Whilst large areas of the basalts can be considered to be relatively homogenous at the level of catenal elements, differences between relatively small tracts of land within the granites are likely to demand separate treatments by both managers and scientists. It simply does not make sense to use the same sized grids or areas for either managerial or scientific applications in the two settings. Furthermore, features of the same size may be elements at two different organisational levels in the two settings and therefore demand different perspectives for their investigation or management. For example, whilst a hectare of land forming a patch with vegetation cover and soils that are distinct from its neighbours' may form an entire catenal element within a granitic setting, the same sized patch is better perceived as a contingent feature within a much larger catenal element in a basalt setting. In the first instance, the patch would be treated as different to its neighbours in a sample design or in a fire management policy, but in the second instance, the patch would more appropriately be treated as similar to its neighbours.

It is only by meeting the challenge of identifying appropriate scales to describe catenal elements within each physiographic zone, that it becomes possible to describe the repeating patterns that characterise the landscapes of each zone. However, a full description of these repeating patterns also demands consideration of how assemblages of catenal elements change with network position, the subject of our next chapter.

CHAPTER 5 CATCHMENTS

5.1 Introduction

The focus of the last chapter was the identification of catenal elements, patches of the riverine and terrestrial landscape with distinct combinations of hydrology, soil and vegetation that are associated with characteristic hillslope positions. We now consider how the configuration of a drainage network constrains the composition and arrangement of these patches, creating repeating patterns that differ between physiographic zones.

These patterns are analysed in terms of catchments and CASSs that drain into different order streams. We use the term 'catchment' to refer to the total area that drains into the whole length stream of a particular order, whilst CASSs are areas that drain into a stream segment. Whilst the entire landscape can be partitioned into CASSs, only partial coverage is gained when the landscape is viewed from the perspective of catchments associated with each stream order (see p.15 ff for an explanation of how catchments and CASSs are defined and ordered). Catchments and CASSs are natural units, in which both channels and watershed impose boundaries for many ecological processes. Catchments and CASSs are real spatial entities, with definite boundaries that can easily be mapped from a DEM.

The mapping of catchments and CASSs, as well as the assignment of stream order, is extremely scale sensitive. Furthermore, stream orders are not directly comparable in different physiographic settings where different processes lead to stream initiation. In one area, streams may start with the joining of many small 'fingertip' streams, such that a stream becomes a second order stream very high in the catchment. In another setting, streams may start from a wetland, from which a single channel emanates. In such a setting, second order streams are found much further down in the network and drain a much larger area than in the first example.

In this project, streams are defined as shown on the 1:50 000 topographical maps (National Geo-spatial Information) and CASSs and catchments delineated using this layer in conjunction with the SRTM 90 m DEM (see para. 5.2 below for details). Streams and CASSs have then been assigned stream orders using the Horton-Strahler method (Horton, 1945, Strahler, 1957).

Catchments and CASSs can be characterised in many ways, including morphology (size, shape, gradient, stream length, etc.), patterns of contained soils and vegetation or in terms of a catchment water budget. We characterise catchments and CASSs in terms of the composition and arrangement of the catenal elements they contain. This approach synthesises morphological, vegetation and soil patterns. Furthermore, since the nature of catenal elements and their connectivity are major determinants of the overall catchment/CASS water budget, the approach also captures the variation most likely to be associated with hydrological differences between catchments and CASSs.

Our framework suggests that the configuration of a drainage network imposes a structure on the composition and arrangement of catenal elements, such that different assemblages of catenal elements are associated with catchments and CASSs in different network positions within a particular physiographic zone. Therefore, rather than classifying catchments and CASSs into types, we explored their systematic variation with network position. We used stream order as a convenient indicator of stream size and hence network position, examining differences in the assemblages of catenal elements contained within catchments and CASSs of different stream orders in each of our two study areas.

We then consider landscape patterns associated with catchments of different stream orders. As explained in chapter 2 (p15ff), it is likely that different patterns of soil and vegetation are found within catchments of different stream orders and that these patterns are superimposed upon each other

(Figure 2.8 above). For example, we could expect that the crests of 3rd order catchments have denser woody cover than that found on the midslopes, such that first order crests located near the 3rd order river are less woody than those located high in the catchment, near the 3rd order watershed. If such superimposed patterns are evident, then it is necessary to expand the landscape hierarchy to include nested subsets of catchments, each with their own characteristic assemblages of catenal elements.

The implications of the structure and arrangement of catenal elements on the water budget for an entire catchment are considered in chapter 7, which draws together the various classifications produced in southern KNP and suggests some of the processes that may be responsible for the observed patterns.

5.2 Stream and catchment delineation in KNP

In order to delineate catchments and CASSs, 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, but 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 (see Figure 6.1 below), such that it is inappropriate to apply a single threshold for the whole park. For example, using the SRTM 90 m 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 basin and a 37% overestimation of links in basaltic areas, compared to streams shown on the 1:50 000 topographical map.

Even within an area with relatively homogenous geology and soil, there may not be a sharp threshold between hillslope and channel processes in semi-arid landscapes such as those found in KNP, and some drainage lines may not be channelized. Since the purpose of this project is to link water distribution to patterns of soil, vegetation and topography, 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 and connected into a drainage network can be identified by changes in vegetation, sometimes accompanied by changes in curvature. In preparing the 1:50 000 topographical maps covering KNP, these indicators have been used by the South African NGI (National Geo-spatial Information) to delineate streams from high resolution aerial photography. 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. The mapped scale of 1:50 000 is more than adequate for our purposes, since it is a much finer than 1:90 000, the equivalent cartographic scale of the 90 m SRTM data that is used to delineate the catchments associated with this stream network.

However, the GIS layer produced by digitising the blue lines representing streams on 1:50 000 topological maps is not hydrologically correct, since streams are not always digitised in the correct flow direction and tiny breaks in the lines mean that the network is not fully connected. In order to produce a hydrologically correct stream layer, stream locations are ‘burnt’ into the 90 m 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 are then modified to force flow along the ‘burned-in’ flow paths (Table 5.1).

Once streams have been delineated (Figure 5.1), CASSs are then delineated using an ArcHydro function that identifies the area draining into each stream segment (Figure 5.2). Lastly, 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.

Table 5.1: Procedure used for stream and catchment delineation in KNP

DEM pre-processing	Identify endorheic depressions, appearing on a DEM grid as 'pits', or 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 10 m resolution. Construct a grid raster (Stream cell =1, other cells =0) from stream vector layer, snapped to the 10 m DEM grid. The10 m resolution of this grid preserves tributaries and their junctions that are lost at the original 90 m resolution of the DEM. Lower the elevation of stream cells by 750 m, 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 10 m resolution, snapping to the DEM layer (source cell =1, other calls =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.

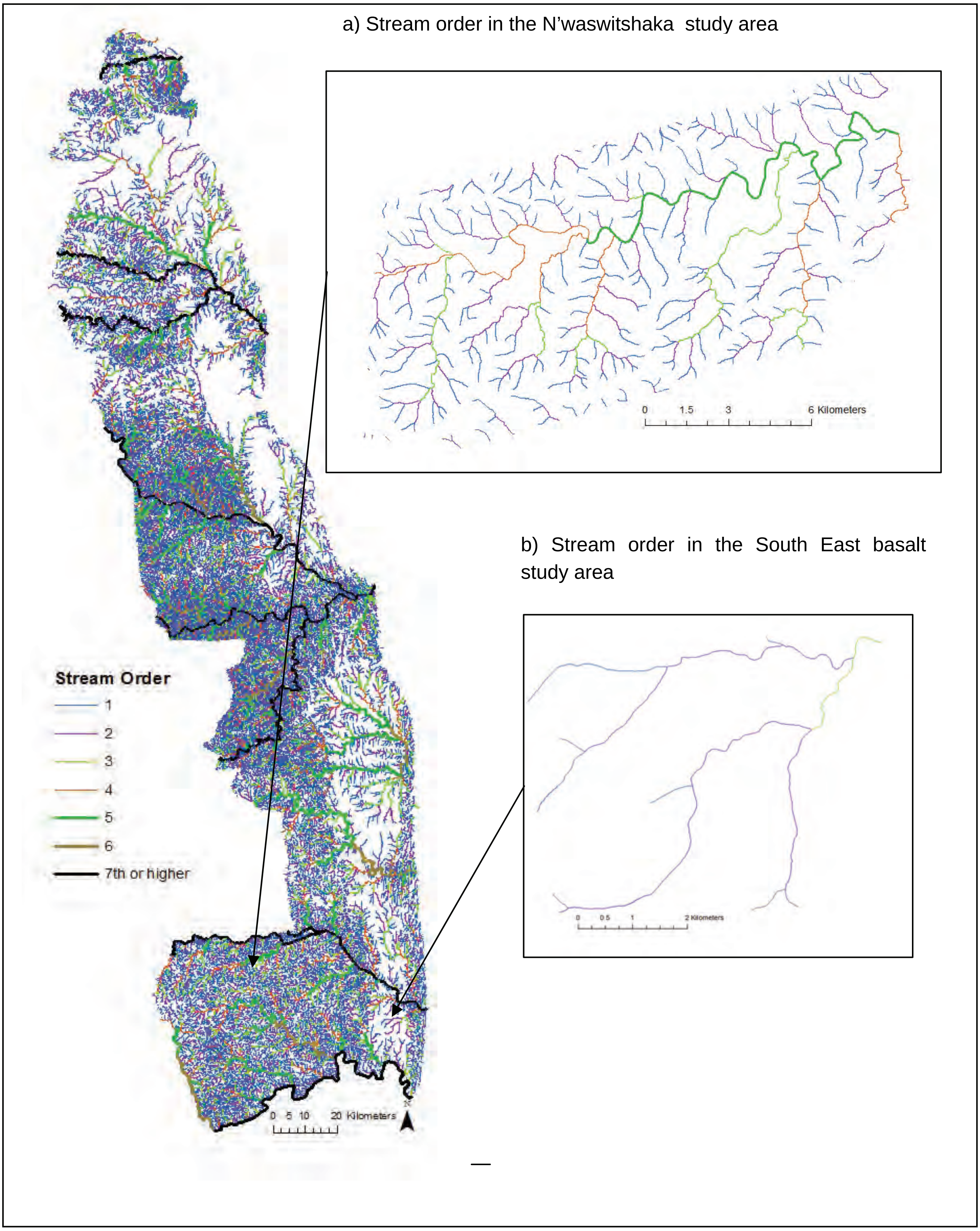


Figure 5.1: Steams in KNP, delineated from the 1 50 000 topographical map and ordered using the Strahler-Horton method Insets show stream order in the two study areas

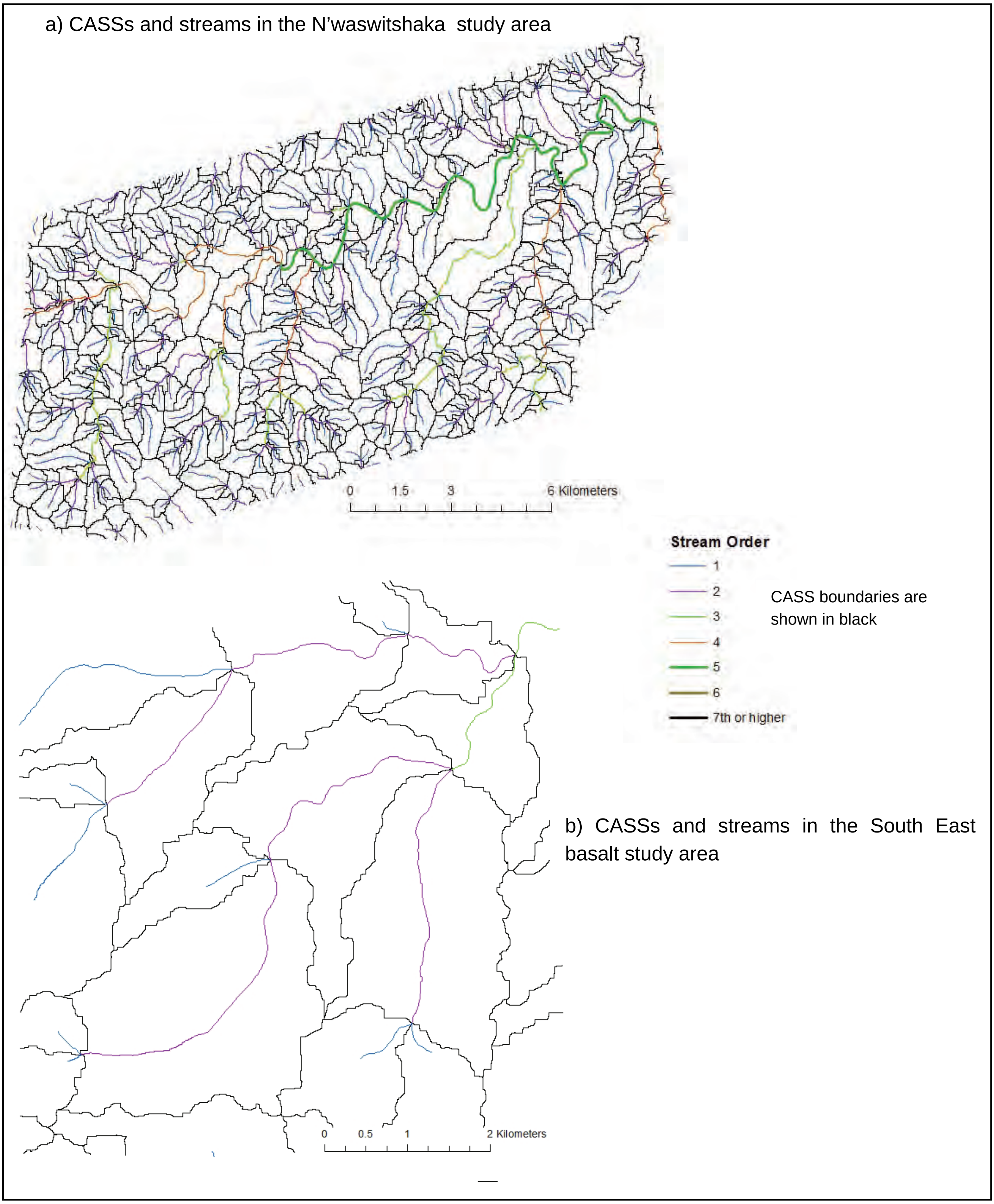
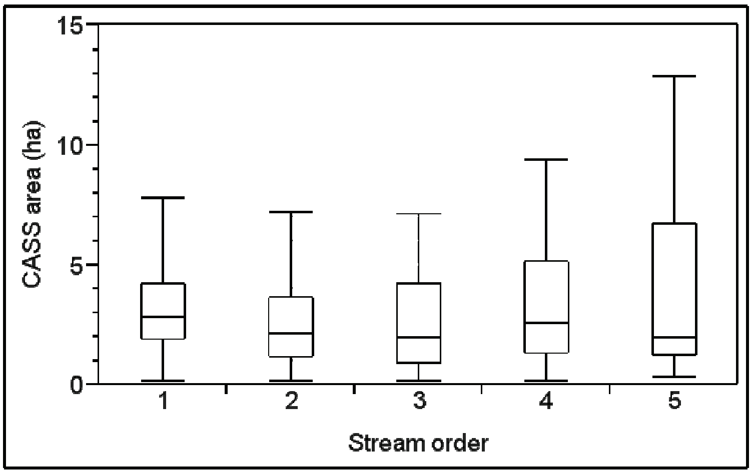


Figure 5.2: CASSs within the N'waswitshaka and Lower Sabie basalt study areas

5.3 Characteristics of CASSs in different network positions within the N'waswitshaka study area

In order to understand how assemblages of catenal elements change with network position, we examined the composition and downslope sequences of catenal elements contained within different order CASSs. We used a database of the characteristics of points regularly sampled at 100 m intervals throughout the study area to describe the distribution of catenal elements. We assumed that the number of points contained in a catenal element is proportional to the area it occupies. Furthermore, since CASSs of all stream orders are of a similar size (Figure 5.3), the area occupied by a catenal element accounts for a similar proportion of the total CASS area, irrespective of stream order. Thus the mean area of land occupied by an element accounting for an average of 25% of all 1st order CASSs is similar to the mean area of land occupied by an average of 25% of all 3rd order CASSs.



Stream order	Mean CASS area (ha)	in
1	3.50	345
2	3.00	163
3	3.47	76
4	3.58	58

Figure 5.3: Area of CASSs draining into different order stream segments in the N'waswitshaka study areas

The centre line in the box plots shows the median area (ha) of different order CASSs, while the box is bounded by the inter quartile ranges and the 'whiskers' show the boundaries within which 90% of the sample falls.

In the N'waswitshaka basin, all CASS are of a similar size. The only significant difference was between the mean size of 2nd and 5th order CASSs (Student's t test, α = 0.05).

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 5.4). 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 39% of the CASS, compared to only 31-33% of 2nd -3rd order CASSs and 27% of the area of 5th order CASSs. Indeed, 59% of the area of all crests occur within 1st order CASSs.

Thus the major difference between assemblages of catenal elements in different network positions 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.

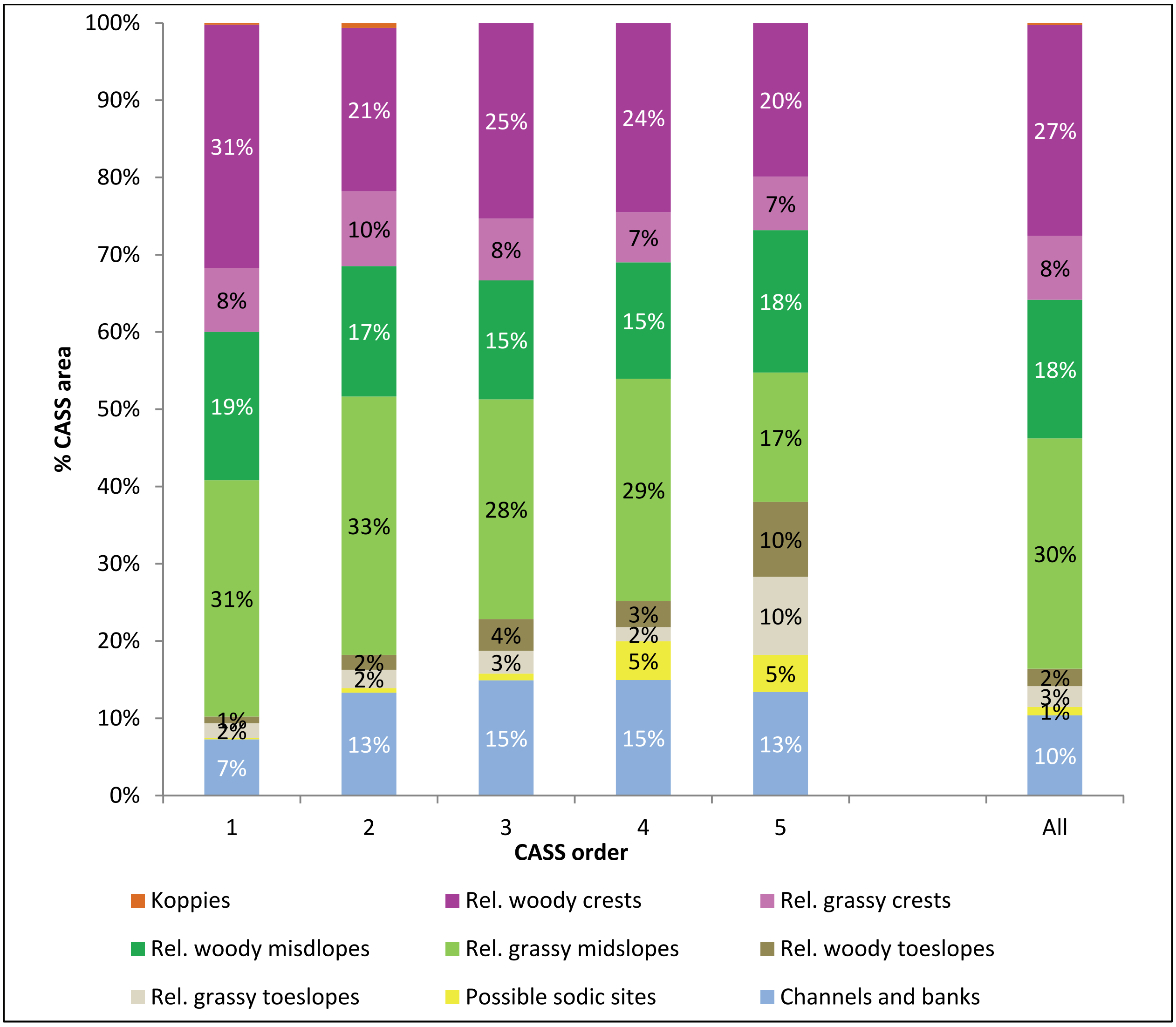


Figure 5.4: Terrain units and CASS order in the N'waswitshaka study area

Based on sampled points, where n=25 504 for all points in the N'waswitshaka study area, 13 685 of which are in 1st order CASSs, 5 276 in 2nd order, 2 434 in 3rd order, 2 275 in 4th order and 1 834 in 5th order CASSs. Catenal elements are defined in chapter 4.

For second order CASSs and above, the area occupied by channels, banks, possible sodic sites and toeslopes increases steadily with stream order. The areal proportions of crests are very similar between 2nd,3rd, 4th and 5th order catchments

5.4 Do systematic landscape patterns exist within high order catchments in the N'waswitshaka basin?

So far, we have only described landscape patterns associated with individual stream segments. We now consider whether or not other patterns exist that are associated with each stream orders (as described in para. 2.3 above). If, for example, distinct vegetation gradients existed from the channel to the divide of high order catchments, then we would expect to find this pattern superimposed on the vegetation characteristics of contained CASSs (as illustrated in Figure 2.8 above). So, if woody cover increased from the lower slopes up to the divide in a high order catchment, then the crests of CASSs located high in the headwaters would be more woody than CASS crests located at lower elevations, nearer to the main river. If such patterns exist, then it becomes necessary to expand the landscape hierarchy, incorporating sublevels that describe these patterns in terms of new series of catenal elements associated with each catchment order (see para, 2.3 above).

We tested this proposition using our sample of points. For each point, we calculated:

- The *percentage cover over 0.5 m high* found in a circle of 3.4 m radius, a proxy for the density of woody cover. This metric was derived from the canopy height LiDAR data. Pixels with vegetation over 0.5 m 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 (3.36 m at the original LiDAR resolution of 1.12 m)).
- *Hillslope position* as defined in Chapter 4. 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, we found no cases in which strong relationships were present and all correlation coefficients were below 0.07 (Table 5.2). We therefore found 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. Although we have only examined the distribution of woody cover in relation to the wider network position, we infer that the findings also apply to soil distribution, given the tight coupling of soils and vegetation in this area.

This means that the repeating patterns of soil, vegetation and topography found within this area can be adequately described by considering the character of CASSs alone. It is not necessary to consider the position of these CASSs within the wider stream network or to invoke additional sub levels within the landscape hierarchy in order to describe or explain landscape patterns (see para. 2.3 above).

	All **1st order** catchments	All **2nd order** catchments	All **3rd order** catchments	All **4th order** catchments
n (catchments)	*237*	*178*	*7*	*2*
Points on crests				
Correlation coefficient of dist to stream vs. % woody cover (>0.5 m 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 dist to stream vs. % woody cover (>0.5 m high)	0.015	-0.004	-0.059	-0.043
n (points)	*5596*	*4 324*	*2 743*	*2 179*

Table 5.2: Relationships between canopy cover and distance to stream for terrain units in different order catchments within the N'waswitshaka basin

All correlation coefficients < 0.07

5.5 Characteristics of CASSs and catchments in different network positions within the Lower Sabie basalt study area

CASSs in the Lower Sabie basalts are very large and only five CASSs are wholly within the study area, preventing a formal analysis of assemblages of catenal elements. Nevertheless, we can make some observations:

- With only two distinct catenal elements in the whole area, there are no changes in the composition of catenal elements by stream order.

- Morphological differences associated with changing stream order are limited to subtle variations in the channel profile. Along the course of each stream, channel banks become wider. However this happens mainly at the expense of the channel bed, such that there is only a marginal increase in the combined width of the channel and banks (see Figure 4.24 above).
- There is no evidence for different patterns associated with different order catchments that are superimposed on each other.

This landscape consists almost entirely of large interfluves, which show no systematic pattern of topography or vegetation. Away from the channel, variations in vegetation (and therefore, we infer, hydrology) and the presence of pans do not appear to be related to either hillslope or network position. We suggest that these patterns are randomly distributed, and are most likely the result of interactions between fire, herbivory, animal diggings and very local geological differences.

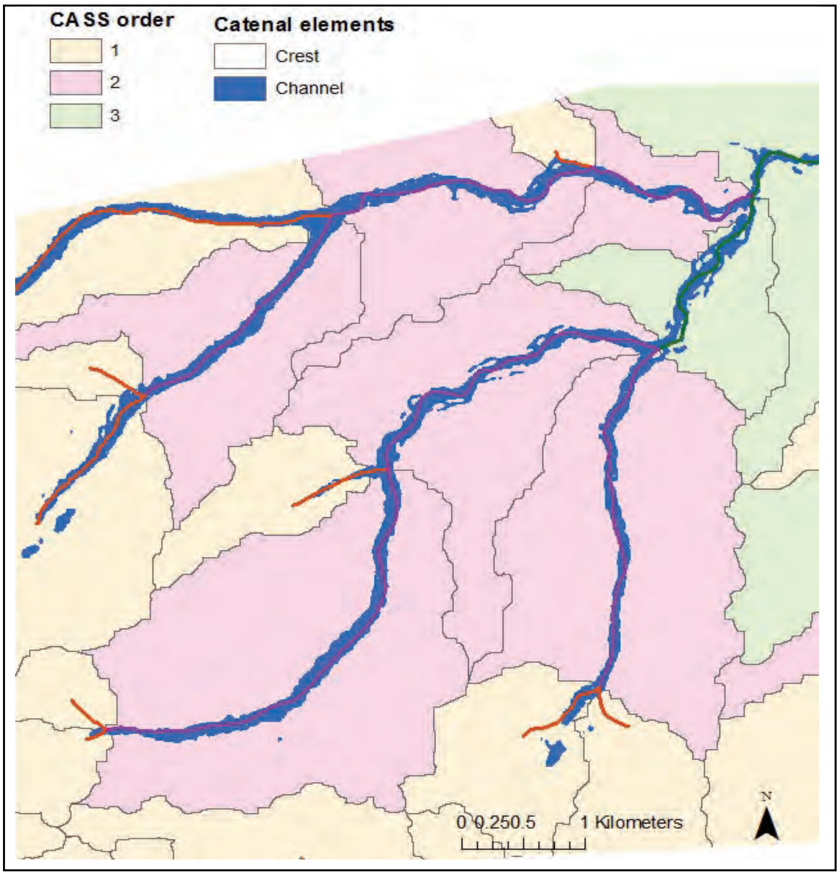


Figure 5.5: CASS and catenal elements in the Lower Sabie basalt study area
Streams derived from the 1:50 000 topographical map and their CASSs are superimposed upon the channel catenal element.

5.6 Summary

We characterised catchments in our two study areas in terms of the catenal elements they contain. Rather than developing a typology of different classes of catchment, we examined how assemblages of catenal elements change in structure and composition between catchments located in different network positions. This approach meets the challenge of quantitatively describing the repeating patterns of vegetation, topography and the associated soil and hydrological patterns that characterise each physiographic zone.

Although catchments can be defined in different ways (i.e. either as CASSs that drain individual stream segment or as areas drained by entire streams of different orders) we found that in both our study areas landscape patterns could be adequately described by considering CASSs alone. In neither study area was there evidence to suggest that different vegetation patterns are associated with different order catchments and superimposed upon each other. This means that no additional sublevels within the catchment level of organisation need to be invoked to fully describe these landscapes.

In each study area we found that catchments can be characterised by quite different assemblages of catenal elements, forming very different repeating patterns throughout the drainage networks.

In the N'waswitshaka basin area, the pattern of relatively woody crests lying upslope of relatively grassy midslopes is repeated throughout almost the entire study area. The only difference associated with network position is that a larger proportion of the area of higher order CASSs is occupied by fluvial elements such as toeslope, channels and banks.

In the Lower Sabie basalts, all CASSs contained only interfluves and channels. The only evidence of changes in the assemblages of catenal elements associated with different positions in the drainage network was a slight change in channel morphology as streams increased in size.

Our approach to the characterisation of catchments in terms of the structure and composition of the catenal elements they contain provides a new way to describe the distinct landscape patterns associated with each physiographic zone. The delineation of these zones forms the subject of the next chapter.

CHAPTER 6 PHYSIOGRAPHIC ZONES

6.1 Introduction

Physiographic zones are areas with distinct patterns of geology and landscape dissection, defined in terms of catchment, hillslope and stream network morphology. Patterns of landscape dissection and the configuration of the network limit the potential energy available to move water across the surface of the landscape and control the speed and direction of any such movement. Thus the patterns of landscape dissection impose constraints on the possible assemblages of catenal elements that can occur within a physiographic zone. For example, a finely dissected physiographic zone with short steep slopes cannot support the same catenal sequences of vegetation and soils as a zone that has long slopes and little relief.

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, not only do we currently lack the fine scale DEMs that are needed to fully characterise small-scale elements in the whole KNP, it is also an enormous task to undertake. We therefore use a ‘top-down’ approach in which physiographic zones are delineated in terms of differences in landscape dissection and geology.

The conductivity and porosity of bedrock and its weathered products, as well as structural features such as fissures, cracks and joints all influence rainfall partitioning and therefore are controls on seasonal flow patterns, stormflow, subsurface flow and, water quality as well as the processes of erosion and sedimentation. Thus the geological and climatic history is encoded within the drainage network pattern (Luo and Stepinski, 2008). For example, impermeable bedrock tends to generate more runoff than more permeable bedrock, leading to a more finely dissected landscape, with higher drainage density and steeper, shorter slopes than is found in areas with more permeable bedrock (Figure 6.1). In areas receiving more rainfall, the landscape is likely to be more finely dissected and be eroded more deeply than in more arid areas. Patterns of stream branching are also largely determined by geology. For example, rectangular patterns are typical of the right-angled joints and faults often found on granitic bedrock, whilst dendritic patterns occur in areas where there is little variation in the resistance to the flow of water, such that streams run in all directions without a definite directional preference (Howard, 1967).

	Stream density (km/km²)	Area (km²)	Length of streams (km)
All KNP	**1.86**	**19,006**	**35,308**
Malvernia sandstone, conglomerate	4.23	74	313
Biotite gneiss	2.67	4,717	12,574
Biotite granite, granodiorite	2.45	333	816
Potassic granite, gneiss	2.43	871	2,119
Other	2.25	396	890
Biotite trondhjemite gneiss	2.24	107	239
Granite	2.10	3,039	6,371
Gabbro	2.07	550	1,140
Rhyolite	1.65	966	1,596
Shale	1.59	478	762
Basalt	1.22	5,783	7,051
Clarens sandstone	1.13	591	670
Dolerite dyke	0.91	21	19
Granophyre	0.86	198	171
Andesites and basalts with interbedded tuff	0.81	196	159
Diabase	0.77	33	26
Waterberg sandstone, conglomerate	0.76	372	282
Aeolian sand	0.39	281	110

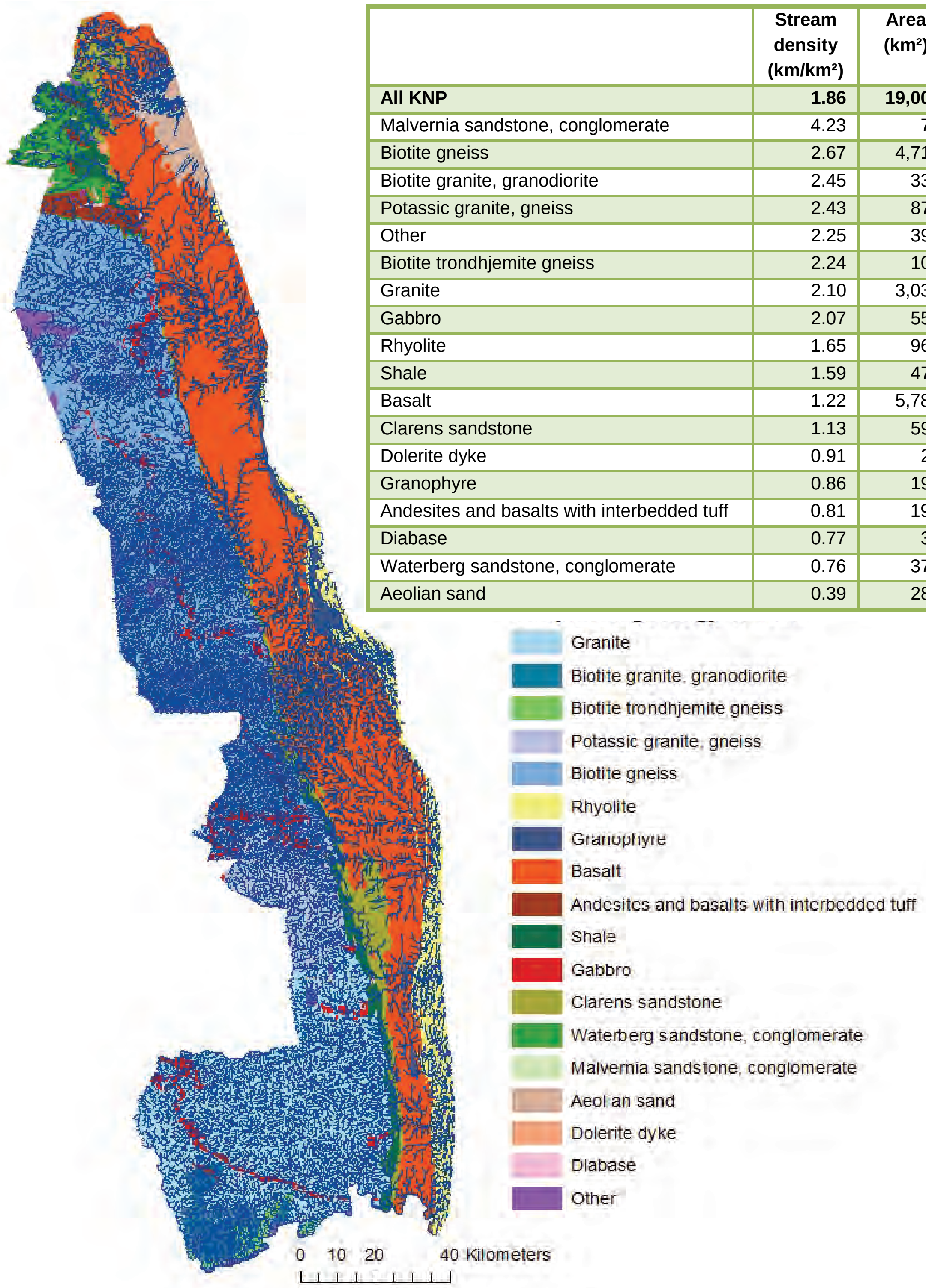


Figure 6.1: Stream density and geology in KNP

Geology is simplified from 1:250 000 CGS map. Within KNP, stream density varies from over 4.2 km/km² to less than 0.4 km/km².

Boundaries between physiographic zones are thus closely related to geological and climatic boundaries. However, patterns of dissection may also be shaped by the behaviour of large rivers controlled by historical events and forces external to the region. For example, a finely dissected region is associated with the passage of the Letaba river across the basaltic plains in KNP (Figure 6.2). Here, quaternary erosion by the river has created a topography that is quite different to that found in surrounding earlier erosion surface (Venter, 1990), a substrate that is typically associated with flat plains and a very low stream density.

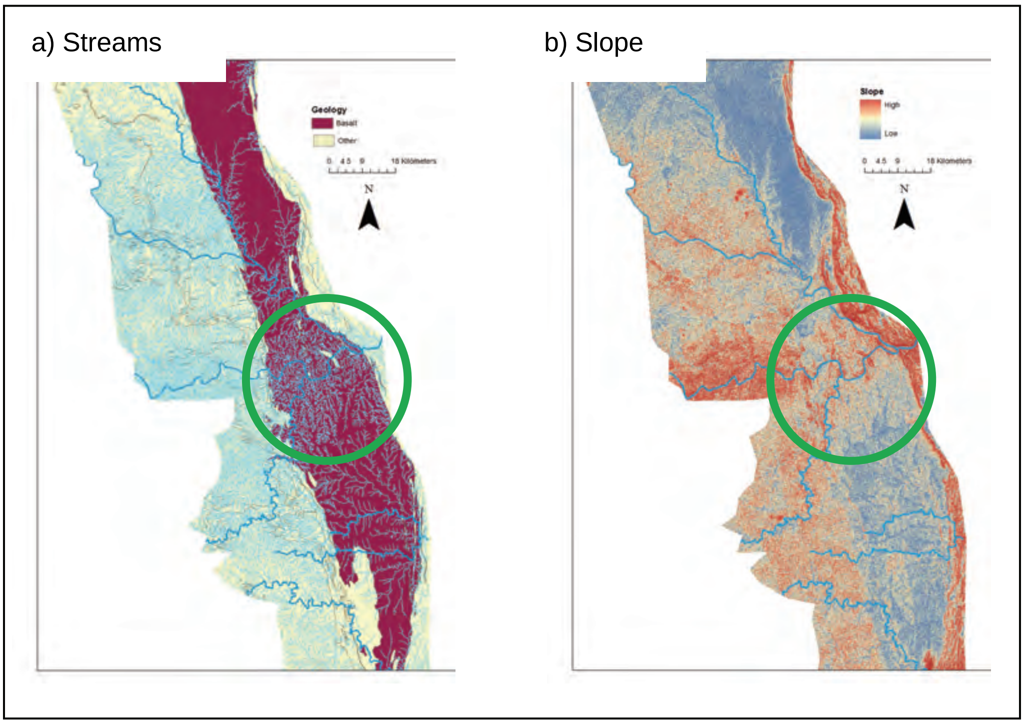


Figure 6.2: High stream density (a) and steeper slopes(b) associated with quaternary erosion by the Letaba river

The constraints that hillslope and channel morphology impose on the vegetation, soils and biota of a region has underpinned many land and river classifications. For example, Partridge defines 'geomorphic provinces' as:

> *"similar land areas containing a limited range of recurring landforms that reflect comparable erosion, climatic and tectonic influences, and impose broad constraints on lower levels of organisation, e.g. drainage basins, macroreaches, channel types" (Partridge et al., 2010 p.2)*

Regional scale terrain units also form a key element in SOTER (World SOil and TERrain Digital Database), a programme initiated by the International Society of Soil Science (ISSS) and supported by FAO and other international organisations, in collaboration with a wide range of national soil institutes (ISRIC, 2010). In order to aid coarse-scale predictive soil mapping, terrain units with distinctive lithology and geomorphic patterns of landscape dissection are being prepared throughout the world (Dobos *et al.*, 2005).

These approaches to landscape and riverscape classification all seek to identify what Pike *et al.* described as the

> *"geometric signature' of a landscape, a set of measurements from a DEM that describe topographic form well enough to distinguish geomorphologically disparate landscapes." (Pike et al., 1989 p.128).*

6.2 Identifying patterns of landscape dissection

Despite the widespread use of morphological differences to underpin the delineation of physiographic zones, there is no standard approach to the detection of patterns of landscape dissection. Different practitioners use different morphological variables that are combined in different ways and at different scales. However, these variables are highly correlated. For example, vertical relief and gradient are both related to slope length. Thus most methods of delineating physiographic zones involve just three or four attributes that represent the key dimensions of hillslope and network morphology:

- the horizontal spacing of channels and ridges (landscape wavelength)
- vertical relief (landscape amplitude)
- gradient and
- elevation (this variable is sometimes omitted when small extents are considered).

However, these attributes do not only vary between physiographic zones, but within each physiographic zone the attributes also vary by network position. Indeed, the morphology of high order CASSs may be very similar across several physiographic zones, with large, relatively flat channels and floodplains bounded by relatively gentle slopes. We therefore adopted a stratified approach, considering the morphology of low (1st and 2nd order), medium (3rd and 4th order) and high (5th or higher) order CASSs separately.

We use CASSs as the basic unit of analysis for detecting physiographic patterns, rather than using raster layers or a point sample. This approach not only facilitates the stratification described above, but also resolves many of the issues surrounding the choice of scales of analysis. Basing the classification on real spatial entities not only resolves many aspects of the MAUP (see para. 3.6 above), but also follows from our framework, which suggests that catchments and CASSs in the same physiographic zone have similar morphology.

In order to capture the horizontal and vertical dimensions of the landscape dissection pattern associated with CASSs of each stream order, we measured the *area* of each CASS, the *elevation range* (maximum vertical relief) and the *mean slope* (maximum gradient in a 3x3 cell of the 90 m SRTM DEM).

We then detected spatial clusters of these attributes (ISOCLUSTER in ArcGIS (ESRI, 1999-2008)) for CASSs within each of the three groups (low, medium and high stream orders). The characteristic of these clusters were then used to define prototypes for nine 'morphological zones', each of which has a characteristic distinct landscape dissection pattern (Figure 6.3).

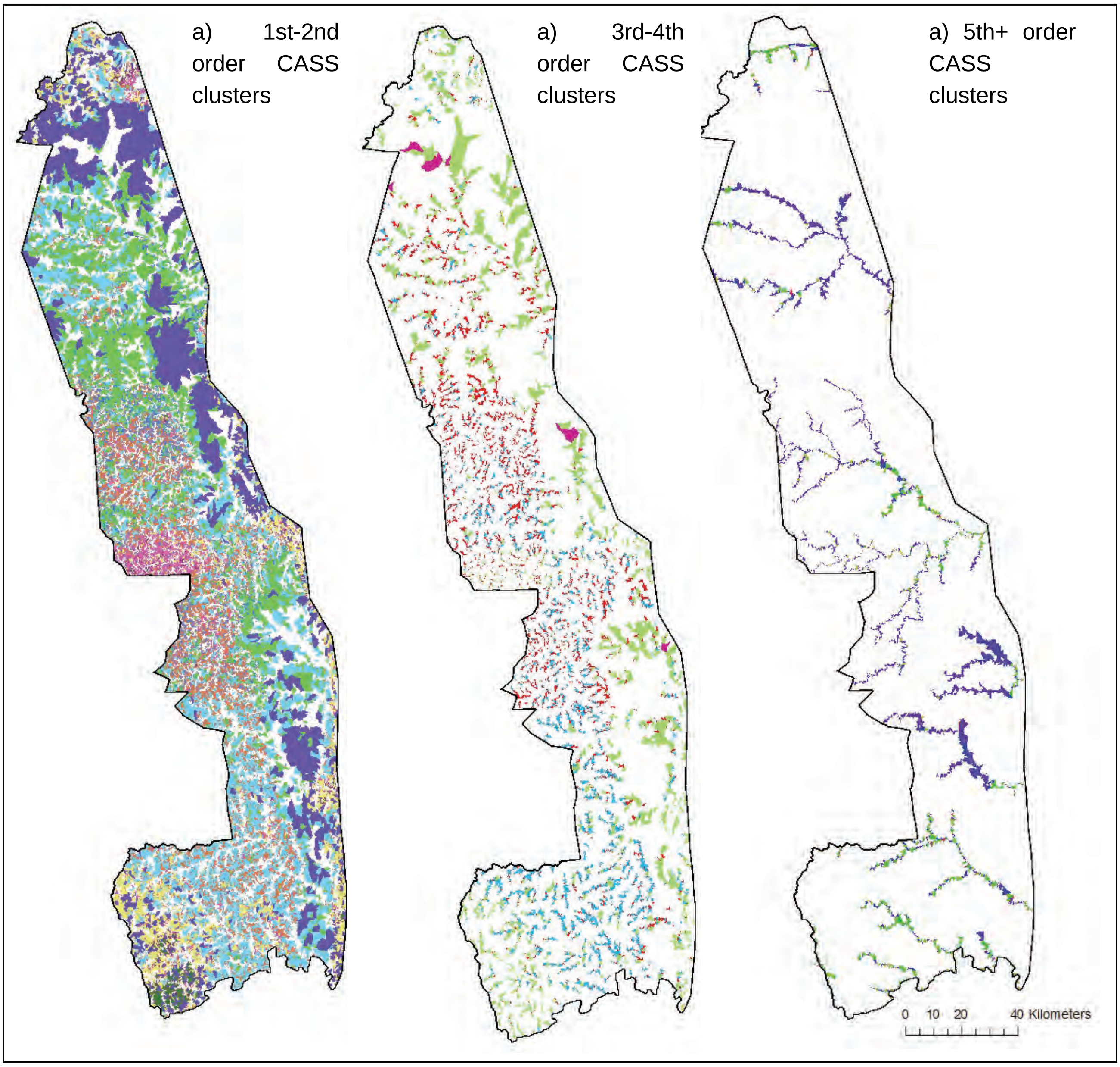


Figure 6.3: Spatial clusters for 1st-2nd, 3rd-4th and 5th + order CASSs in KNP
a) 9 classes of 1st-2nd order CASSs b) 5 classes of 3rd-4th order CASSs c) 4 classes of 5th+ order CASSs

6.3 Prototypes for morphological classes

We identified eight morphological classes from the CASS clusters, each with a distinct pattern of landscape dissection. Since the morphology of 3rd and higher order CASSs varies little between zones, we focussed on the morphological differences between 1st-2nd order CASSs to define a rule set for the fuzzy classification of landscape dissection, basing definitions on the characteristics of each cluster (Figure 6.4 and Table 6.1).

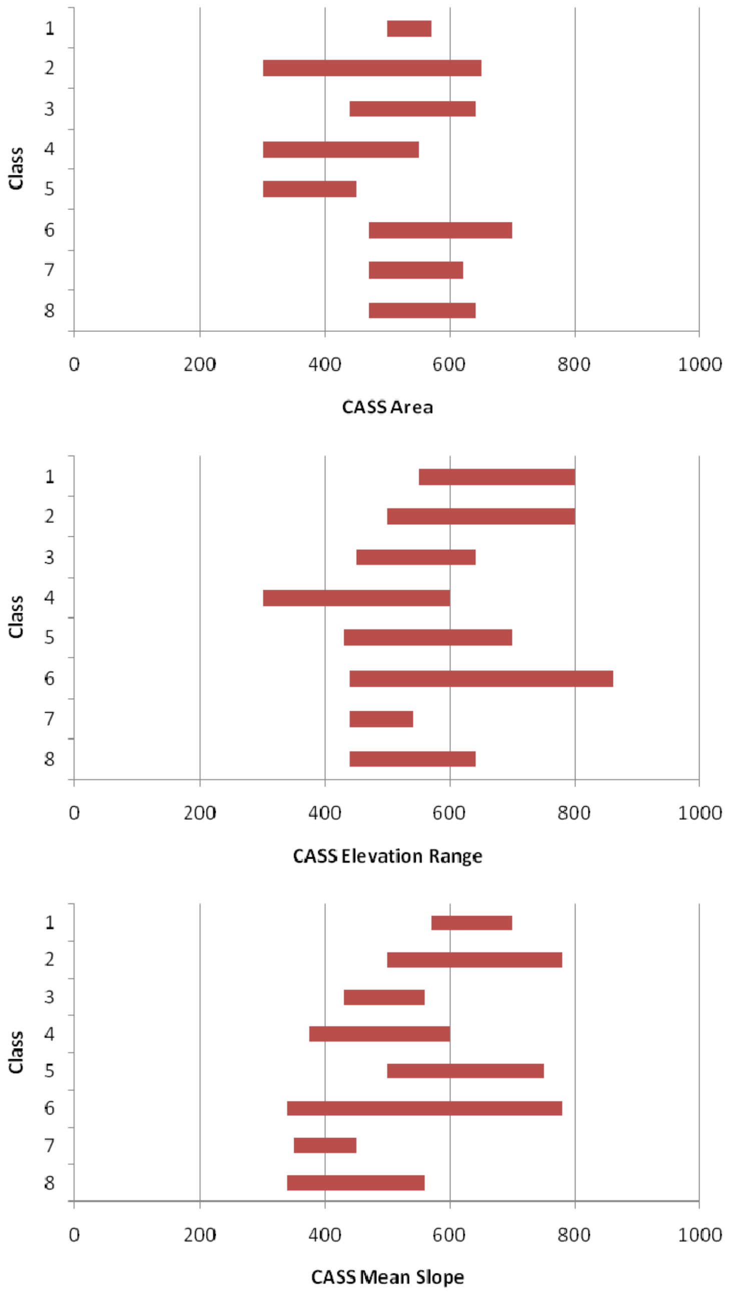
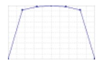


Figure 6.4: Characteristics of 1st-2nd order CASSs in morphological classes of KNP

Values for area, elevation range and slope were first log transformed, then standardised on a scale of 1-1000. Graphs show the range containing 90% of the values for CASSs in each class

Table 6.1: Rule set for the definition of morphological classes in KNP

Characteristics of clusters of 1st-2nd order CASSs were used to guide the development of the rule set. Values for area, elevation range and slope were first log transformed, then standardised on a scale of 1-1000

Class		**Area**			**Elevation range**			**Mean Slope**		
	CLUSTER	Shape	Low	High	Shape	Low	High	Shape	Low	High
1	789		500	570		550	800		570	700
2	76(10)		300	650		500	800		500	780
3	54		440	640		450	640		430	560
4	42		300	550		300	600		375	600
5	68		300	450		430	700		500	750
6	3 10		470	700		440	860		340	780
7	3		470	620		440	540		350	450
8	35		470	640		440	640		340	560

6.4 Landscape dissection patterns in KNP

The initial map of morphological classes (Figure 6.5a) shows high levels of heterogeneity within each zone, reminding us that ecological zones are never homogeneous. However, to make the map more usable, we smoothed the image by applying a focal majority filter with a neighbourhood of 5 cells (equivalent to 450 m radius at 90 m resolution) and then eliminating zones under 1 km^2 by merging them with those neighbours with which they shared the longest border (Figure 6.5b, Table 6.2).

Table 6.2: Characteristics of morphological classes in KNP

Morphological classes are best characterised in terms of the first and second order CASSs they contain

Class	**% area occupied by 1st/2nd order CASSs**	**Mean area of 1st-2nd order CASS (ha)**	**Mean elevation range of 1st-2nd order CASS (m)**	**Mean slope of 1st-2nd order CASS (deg)**
1	4%	33.53	101.47	8.13
2	20%	23.82	20.42	1.90
3	11%	18.05	13.93	1.68
4	1%	6.93	19.26	3.49
5	14%	24.08	34.61	3.30
6	36%	139.41	29.08	1.31
7	13%	30.90	15.74	1.29
8	2%	39.09	10.75	0.75
ALL 1st/2nd order CASS	100%	33.72	24.67	2.26

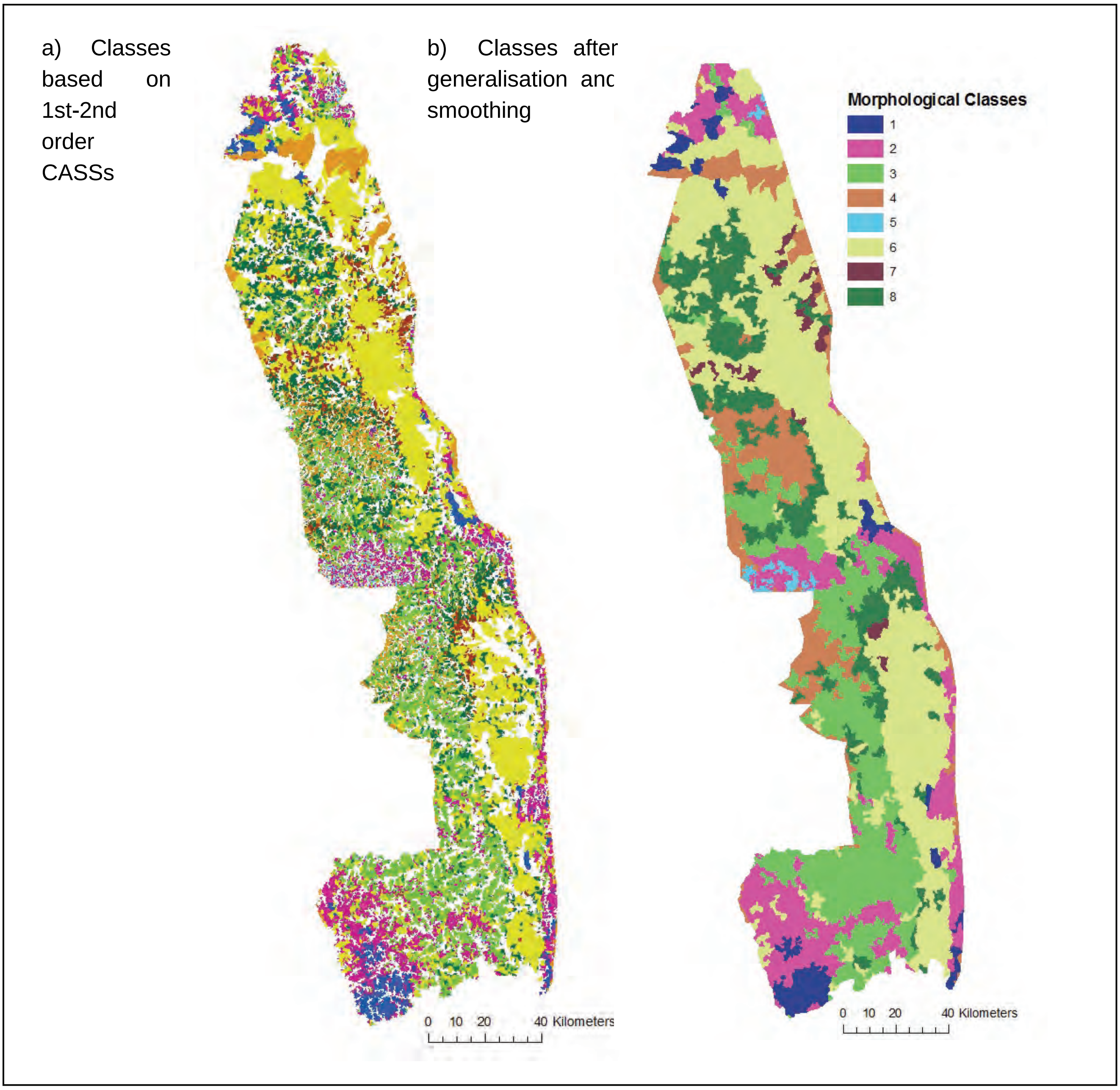


Figure 6.5: Landscape dissection patterns in KNP

The fuzzy classification of 1st-2nd order CASSs (a) is simplified in b) by applying a majority filter and then eliminating all polygons <1 km^2.

6.5 Incorporating geological boundaries

Although transitions between the morphologically based classes of landscape dissection often reflect geological boundaries, some ecologically important geological 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 6.6), 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.

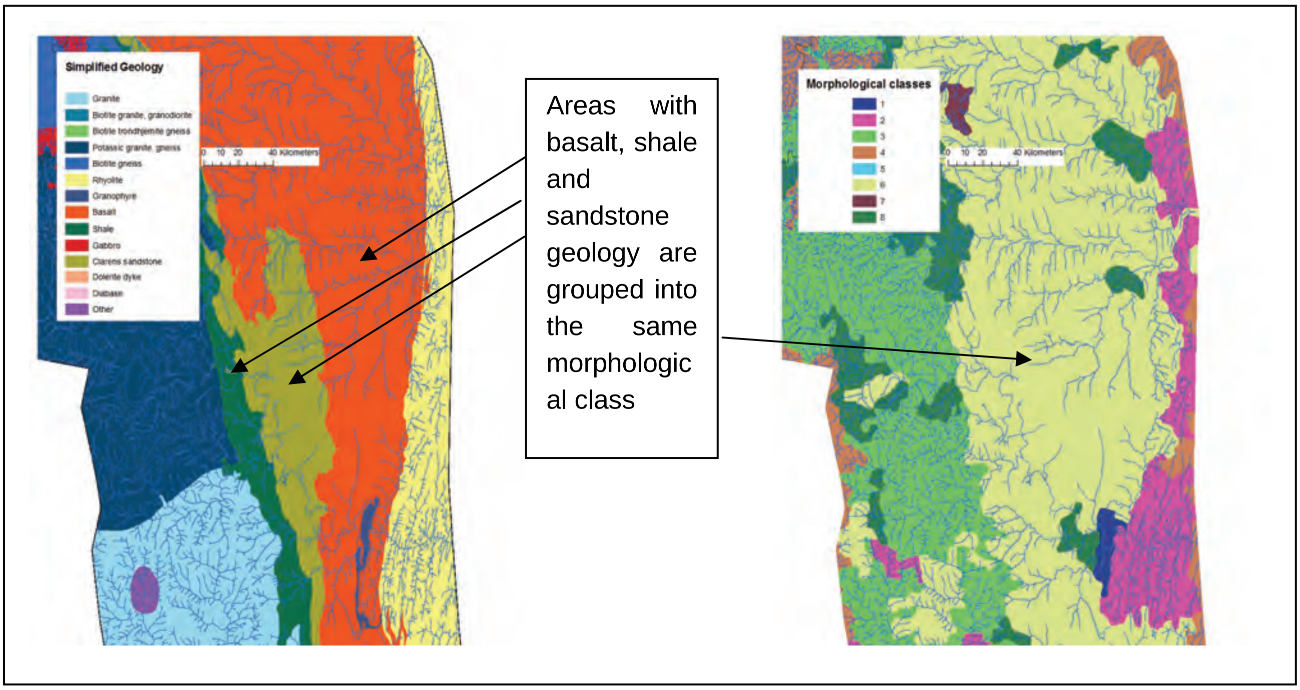


Figure 6.6: Morphological similarity between shale, sandstone and basalt geologies

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 our map. For example, the gabbro strip in southern KNP is represented only by a few relatively flat patches (Class 6).

6.6 Physiographic zones of KNP

In order to derive the physiographic zones of KNP we therefore overlaid our map of morphological classes with a simplified geological map. This procedure generated a total of 87 separate classes, many of which occupy very small areas (Figure 6.7). We then consolidated these classes, merging classes occupying less than 150 km^2 across the whole park with their most similar neighbours, resulting in 27 physiographic zones (Figure 6.8). The zone associated with basaltic geology occupies the largest area of the park (21%). All other zones occupy less than 10% of the area of KNP.

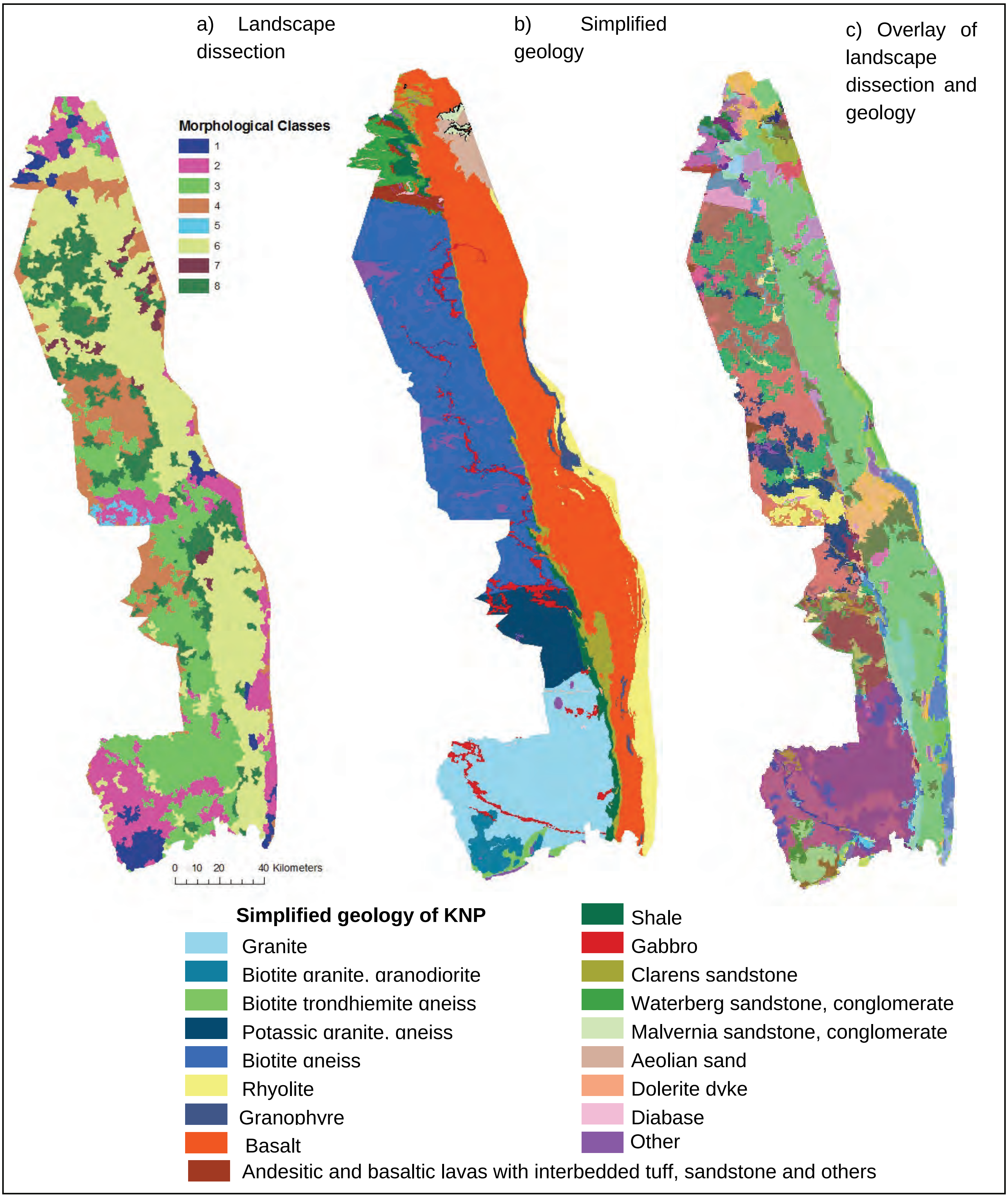
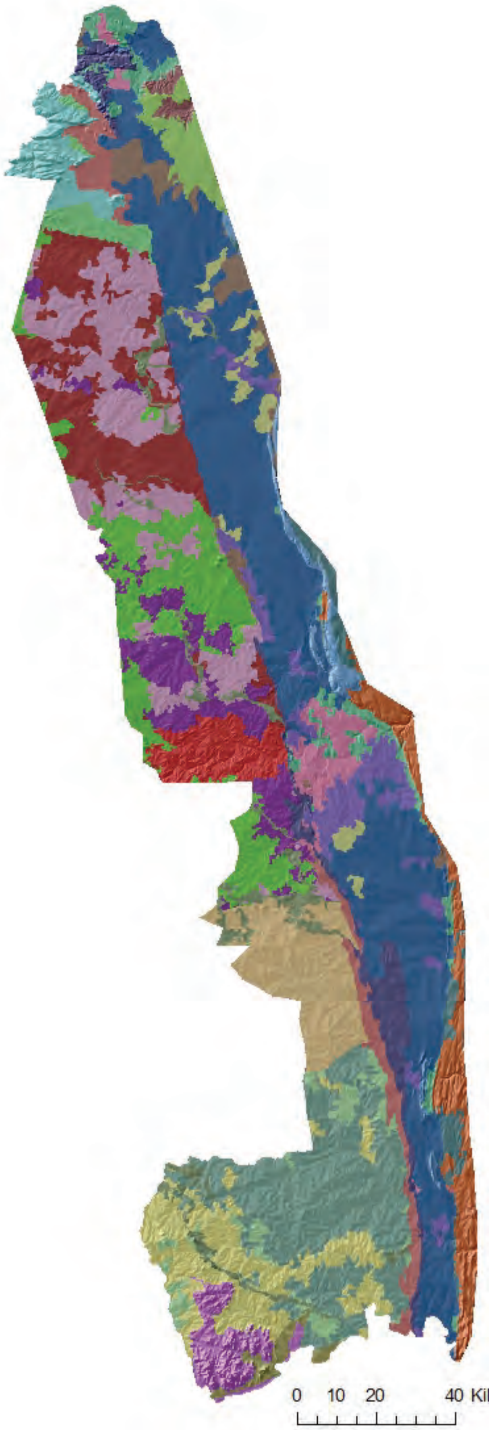


Figure 6.7: Zones of landscape dissection overlaid on geology

a) Morphological classes of landscape dissection b) simplified geology derived by combining similar geologies shown in the 1:1250 000 geological map c) the result of overlaying a) and b), producing 87 separate classes, many of which occupy very small areas.



ZONE		% area KNP	Area (ha)	Characteristics of 1st and 2nd order CASSs		
				Mean Slope (deg)	Mean range elev (m)	Mean area (ha)
1		2%	469	1.7	21	29
2		2%	358	8.1	89	21
3		3%	496	1.5	26	69
4		1%	210	4.2	80	77
5		3%	571	2.6	34	59
6		1%	269	2.1	31	132
7		2%	395	4.9	90	114
8		5%	874	1.7	18	23
9		4%	674	4.1	48	32
10		1%	248	2.1	41	81
11		2%	329	1.8	20	24
12		2%	321	1.5	21	87
13		2%	384	3.1	37	27
14		21%	3 971	1.1	27	173
15		3%	611	1.2	15	29
16		1%	230	0.7	10	36
17		4%	798	1.9	17	17
18		7%	1246	1.6	12	12
19		2%	443	3.3	22	9
20		6%	1 176	1.1	20	90
21		8%	1 427	1.3	16	31
22		1%	204	1.7	36	153
23		9%	1 769	2.0	24	30
24		5%	1 005	2.8	37	34
25		2%	311	1.9	36	76
26		0%	79	4.0	26	10
27		1%	118	3.7	60	39
ALL		100%	18 986	2.3	25	34

Figure 6.8: Physiographic zones in KNP
Classes occupying less than 150 km^2 across the whole park have been merged with their most similar neighbours
The zone associated with basalt (14) occupies the largest area of the park (21%). All other zones occupy <10% of KNP.

6.7 Summary

We have defined physiographic zones in KNP by marrying a fuzzy classification of landscape dissection with geological boundaries. Our framework proposes that within each physiographic zone, catchments and CASSs of each stream order have similar morphology. We therefore based our derivation of landscape dissection classes on the morphological similarity of CASSs, calculating these separately for different stream orders.

It was necessary to include a geological layer in order to derive physiographic zones that not only contain catchments with similar morphology, but that also contain similar assemblages of catenal elements within their catchments that generate similar water budgets. Some geologies have similar morphology, but produce soils that support very different vegetation and hence have very different hydrological characteristics and catchment water budgets.

Ideally, our 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. We hope that such validation will be undertaken as more fine-resolution DEM data become available that permit mapping of catenal elements in wide areas of the park.

In the next chapter, we will use our studies in southern KNP to relate our maps of different hierarchical levels to each other, drawing out some of the hydrological, geomorphological and ecological implications of the diversity and spatial arrangement of elements at each organisational level in the landscape hierarchy.

CHAPTER 7 SYNTHESIS OF CLASSIFICATIONS IN THE STUDY AREAS

7.1 Introduction

In this chapter, we review the classifications for our study areas, relating the observed patterns to likely causal processes and drawing out some of the hydrological, geomorphological and ecological implications of the diversity and spatial arrangement of elements at each level of organisation.

The synthesis is intended to illustrate not only how the various levels of the hierarchy come together to describe a landscape, but also to show how knowledge from diverse disciplines may be integrated within the framework. The descriptions of each landscape element given below are not intended to be comprehensive, but merely to illustrate how holistic descriptions are facilitated by our framework and the classifications derived from it, with knowledge organised around the classes of elements at each level in the hierarchy. To these ends, we draw on field observations and existing knowledge, relying heavily on Venter's (1990) description of our study areas. Much of this knowledge is qualitative and needs to be confirmed through rigorous surveys and studies, similar to those proposed for the ‘super sites' (see para. 8.5 below).

7.2 N’waswitshaka study area

7.2.1. Physiographic zone

Most of the N'waswitshaka study area has been classified as falling within the southern granites physiographic zone, in an area characterised by a finely dissected landscape, with high stream density, high relief intensity and medium slope. However, the south west corner of the scene falls within a different physiographic zone. Although still on granite, low order catchments in this zone tend to have steeper slopes and greater relief than those in the remainder of the scene (Figure 7.1). This is consistent with Venter's (1990) classification that puts this corner of the study area in a transition zone between the Skukuza and Pretoriuskop land types (Figure 3.5 above).

As in the whole of KNP, summer rainfall often falls in intense thunderstorms, such that the system is pulsed, driven by episodic events. In granitic areas, high overland flow is often seen, particularly over exposed rock surfaces. Streams are flashy, flowing infrequently, but then often carrying large volumes of water that have a large potential for erosion, producing the finely dissected landscape that we see today.

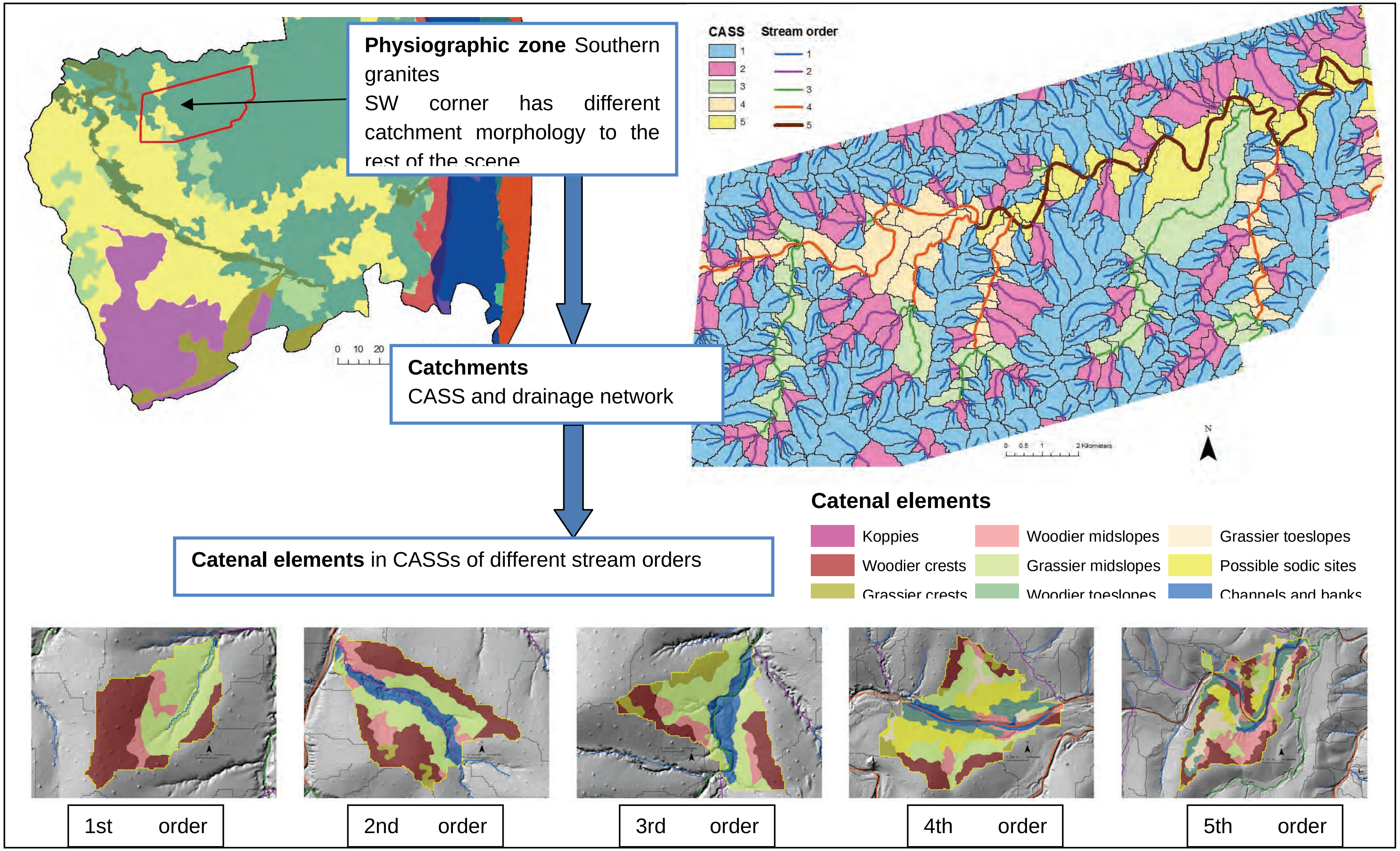


Figure 7.1: Physiographic zone, catchments and catenal elements in the N'waswitshaka study site.

*N'waswitshaka lies within the southern granites **physiographic zone** and includes the majority of a 5th order **catchment**. **Catenal elements** area arranged in repeating downslope sequences, with a tendency towards relatively woody crests and relatively grassy midslopes. The floodplain that develops along the main river stems is manifest in additional catenal elements found in high order CASSs, including woody and grassy toeslopes and possible sodic sites*

7.2.2. Catchments

The study area covers most of the fifth order catchment of the N'waswitshaka river. A pattern of relatively woody crests lying upslope of relatively grassy midslopes is repeated throughout almost the entire study area. The only difference associated with network position is that a larger proportion of the area of higher order CASSs is occupied by fluvial elements such as toeslope, channels and banks.

The implications of the composition and arrangement of catenal elements within CASSs are drawn out below in a section considering the downslope sequence of catenal elements in typical CASSs of this area (p 99 ff).

7.2.3. Catenal elements

Relatively woody crests

Crests are very flat, becoming slightly convex towards the midslope. Soils tend to consist of medium to coarse sand (Hutton, Clovelly, Glenrosa), with rapid infiltration and little water storage capacity. The underlying granites weather very slowly and fine particles are quickly leached and moved downslope. There is much bioturbation, both from termites and burrowing animals such as aardvark, which is likely to further increase infiltration rates. Water is thus likely to drain quickly down through the surface soil and then move downslope under the surface, over and through saprolite and bedrock. Overland flow is likely to be minimal over most of the sandy crest.

The soils are low in nutrients, supporting sourveld grasses and woody cover dominated by *Combretum apiculatum*, and *Grewia bicolor*, with *Combretum zeyheri* becoming more common on crests towards the south of the site.

Relatively grassy midslopes

Relatively grassy midslopes are dominated by duplex soils (e.g. Sterkspruit, Escourt), in which a sandy/loamy surface horizon overlies a clay rich B horizon. In the B horizon, fine clay particles that have been transported either from upslope crest areas or by eluviation from the surface join local material to form a layer that is quite distinct from the A horizon above. The clay forms a wedge-shaped plug that rests upon the saprolite layer and builds upslope overtime (Khomo, 2008).

Water penetrates the clay layer very slowly, but once the clays are saturated, water is held for some time, since the clays are slow to drain and have a high water storage capacity. These midslopes support dense stands of hydrophilic grasses such as *Eragrostis gummiflua* and relatively few trees.

Subsurface water moving downslope from the sandy crests is often forced to the surface when it encounters the clay layer of these soils, forming a seepline. The seepline is saturated for much of the rainy season, when pools and wetlands may form along its length. The seepline is also characterised by *Terminalia sericea*, which in many CASSs are established along a distinct line that follows the contour that separates the crest from grassy midslopes.

This catenal element potentially receives water from the crest areas as well as supplying water to downslope elements. As well as these lateral fluxes, some water may also infiltrate vertically and be stored locally in the clays for a short period between the clays being saturated and the water being lost through evapotranspiration.

Streams usually start to be channelised in midslope areas. In this physiographic zone streams often start at small wetland area, proceeding downhill, initially forming a series of step-pools and a discontinuous channel. Steep banks develop a short distance from the area where a continuously incised channel begins.

Toeslopes

Toeslopes are associated with higher order streams. Whilst they are generally absent in low order catchments, toeslopes increase in size as stream order increases. Toeslopes are relatively flat and may receive alluvial deposits when the stream floods. These areas may be woody, grassy or bare. It is likely that grassy areas form a continuum with the grassy midslopes described above, whilst the trees in woody toeslopes may form part of a riparian zone where roots can access relatively plentiful groundwater. Wooded toeslopes to the north of the study area are likely to contain dense thickets of thorny shrubs such as *Acacia grandicornuta*. Woody areas may also be associated with riparian zones, with undeveloped soils (e.g. Oakleaf) formed from alluvial deposits and organic inputs that support a large variety of tall trees such as *Xanthocercis zambesiaca* and *Ficus sycomorus*. These areas are not generally wide enough in the study area to be discerned as a separate catenal element. Where they do occur, typically along the banks of high order rivers, they fall between the toeslope and the channel.

Duplex soils (Sterkspruit, Escourt) dominate on toeslopes as well as on midslopes. However, the underlying clay horizon accumulates salts towards the bottom of slopes, causing the clay to deflocculate and form a layer that is not only high in sodium, but is also almost impenetrable by both plant roots and water. Furthermore, water moving down from the steeper midslope will tend to accumulate on the toeslope, forming waterlogged areas on the toeslope in which the coarser topsoil is liable to be eroded.

It is likely that grassy and shrubby toeslopes are found in areas where the sandy/loamy A horizon is deep enough to provide a rooting zone and in areas where alluvium has been deposited. However, areas where the A horizon is either very thin or totally absent are inhospitable to most plants. These are 'sodic sites', which are very open, containing only sparse cover of salt resistant shrubs such as *Euclea divinorum.* The accumulated salts in these areas and the high nutrient content of the soil produce highly palatable grasses that are preferred grazing sites for many herbivores early in the season. By the end of the wet season, these sites are often almost devoid of cover, appearing as bare patches in the SPOT5 imagery.

Water movements in the toeslope catenal elements occur in every direction. Water is received from upslope elements and also from the channel during flood events. Vertical movements also occur, with limited seepage downwards through the clay layer and upward capillary movements through the clay, which add further salts to the sodic layer.

Channels

Channels in the study area typically consist of a coarse sand bed, which contain patches of reeds and grass and occasional wooded islands. River beds are usually dry, containing a continuous channel only briefly following storm events. Coarse grains are stored for long periods in the channel, whilst fines are episodically flushed downstream.

The steep banks bear witness to the erosive power of flash floods. Levees are often seen along higher order rivers, which support tall riparian trees on young, poorly developed soils (e.g. Oakleaf).

Water movement in the channel zone is in many directions, with vertical movements between the surface and the phreatic zone, downstream flows, which are often subsurface and lateral inputs (again mainly subsurface) from the toeslopes. Channel elements provide the main stores for groundwater, which provides the major source of water for the large riparian trees that border high order channels.

Typical hillslope profiles of CASSs within the N'waswitshaka study area

The downslope sequence of woody crests, grassy midslopes, grassy, woody or bare toeslopes (depending on network position) and channel elements forms a classic catena, with strong vegetation/soil associations at each hillslope position (Figure 7.2) .This sequence, typical of the southern granites in KNP, has been well described by Venter (1990), Gertenbach (1983) and Khomo (2008). Water fluxes and the consequent hydrological connectivity between catenal elements will vary in time according to the history of rain events.

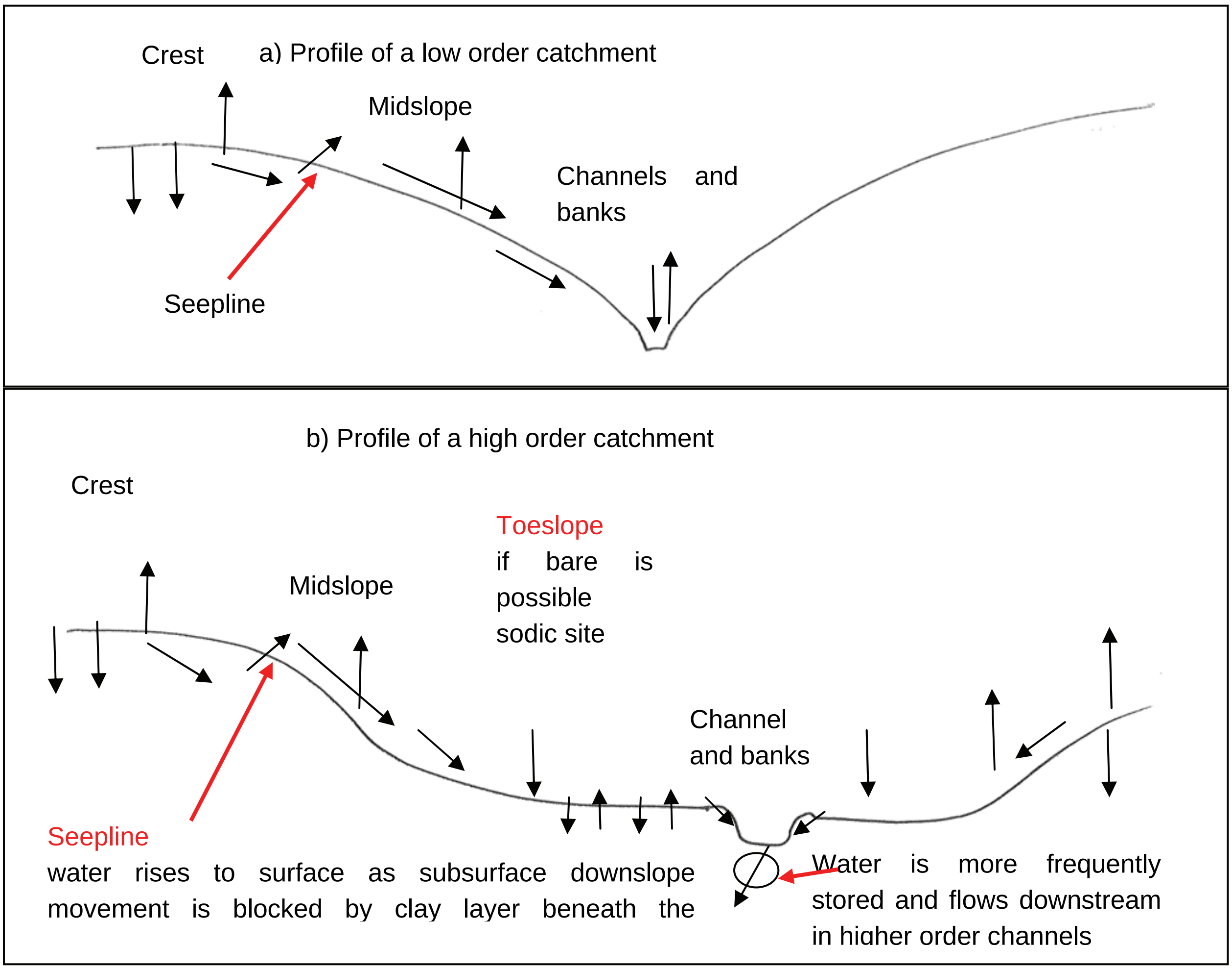


Figure 7.2: Features and hypothesised directions of water fluxes in typical CASSs in the N'waswitshaka basin

In low order CASSs (a) the midslope generally drains directly into the channel, whilst in higher order CASSs (b) a flat toeslope is often seen. This toeslope may be a flood plain and, if bare of vegetation, a sodic site.

Grassy crests and woody midslopes

There are many deviations from the catenal sequence described above. For example, to the east of the study area, relatively woody cover extends from the crests right down to the channel and woody midslopes are common. This pattern may be associated with the presence of dolerite dykes, which weather in situ producing nutrient-rich clay soils (e.g. Mayo, Swartland) that can support more woody vegetation and are often densely covered with *Spirostachys africana*. The pattern may also be associated with higher levels of plant-available groundwater charged by flooding of the nearby Sabie river.

Areas to the west and north of the study area are more open, with less woody cover even on the crests. Here relatively grassy crests are common and toposequences are less distinct.

Koppies

Koppies have much bare rock, with thin lithic soils (e.g. Mispah). Weathered products are moved quickly downslope, usually transported by surface flow. Infiltration and water storage is very irregular, since there is practically no infiltration over the bare rock surfaces, but infiltration may be high in areas where there are rock fractures. Such fractures create preferential flow paths and places where water may be stored locally, forming pockets where vegetation can take root. Over time, the fractures may be enlarged by tree roots, increasing water storage capacity and improving conditions for plant life.

Summary

There is a strong coupling of soils and vegetation within each catenal element, which is both cause and consequence of the topographically controlled distribution of water that characterises each element.

7.3 Lower Sabie basalts

7.3.1. Physiographic zone

The Lower Sabie study area has been classified as falling within the southern basalts physiographic zone, which is characterised by very low stream density (and hence very large catchments and CASSs) and flat relief.

7.3.2. Catchments

The catchments in this physiographic zone are very large, and only five catchments fall completely within the study area. The only variation in catenal elements with network position are subtle changes in channel morphology along the course of the river (Figure 7.3).

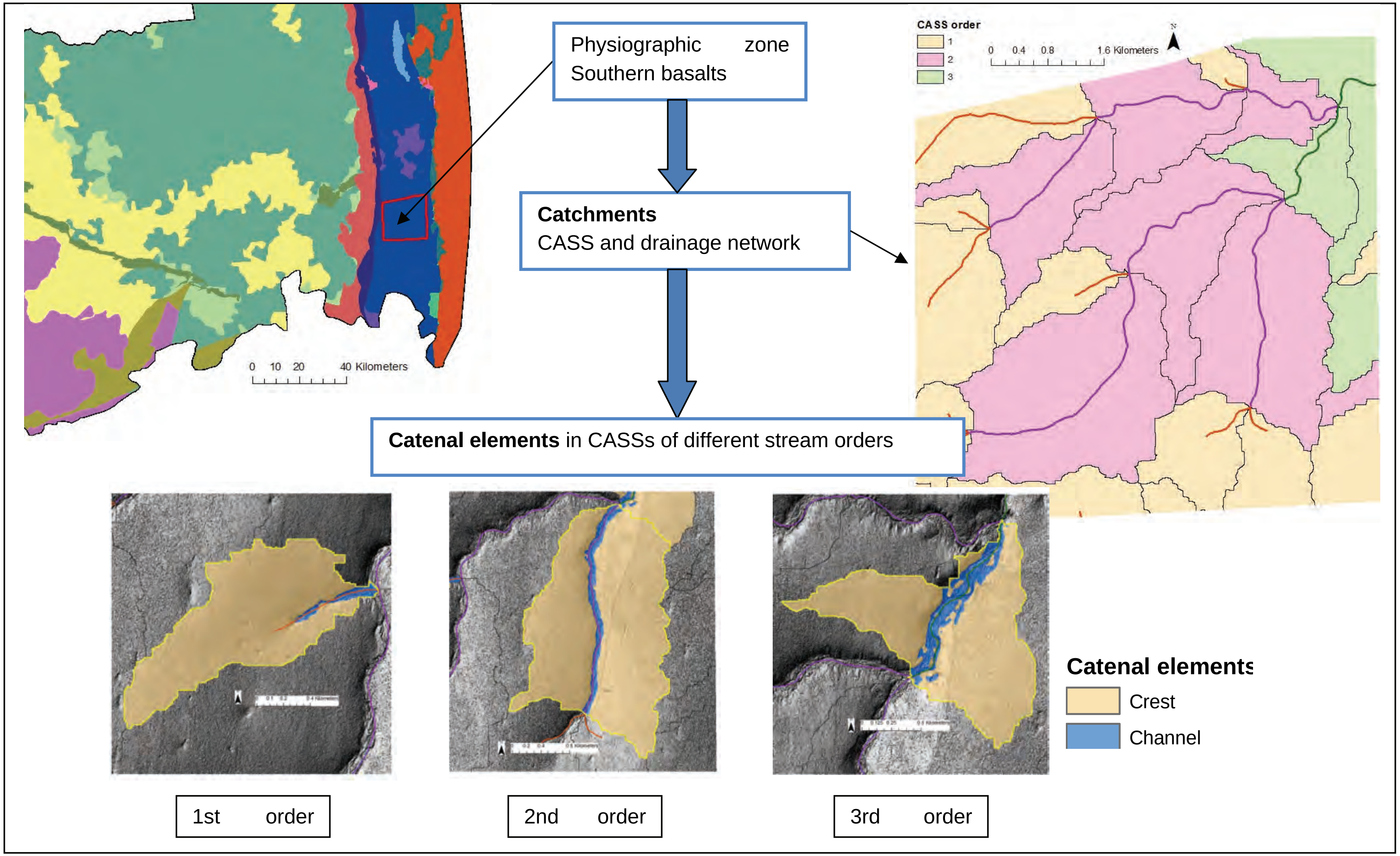


Figure 7.3: Physiographic zone, catchments and catenal elements in the Lower Sabie basalt study area.

*The Lower Sabie site lies within the southern basalt **physiographic zone** and includes the majority of a 3rd order **catchment**. There are only two distinct **catenal elements.** The only variation in catenal elements with network position are subtle changes in channel morphology along the course of the river.*

7.3.3. Catenal elements

Only two catenal elements at were identified within all the catchments in this area: interfluves and channels.

Interfluves

Almost all of the landscape in this area is classified as interfluves. Soils are deep clays formed by chemical weathering of the underlying laval bedrock (Shortlands, Swartland). The flatness of this physiographic zone means that little potential energy is available for lateral movement of water towards the channel, so fine particles remain in situ. Infiltration is slow to medium, with a medium drainage and storage capacity. It is likely that there is little surface (and subsurface) water movement downslope except in areas near channels. Overland flow is rare, since it only occurs when the soils are completely saturated. Under these circumstances water tends to collect in local depressions, forming small ponds, rather than incising gullies and forging new connections to the stream network.

This means that large areas of the interfluve are effectively disconnected from the drainage network, with water movement that is predominantly vertical over most of the landscape, infiltrating the surface clays and/or being lost via evapotranspiration.

These soils are high in nutrients, supporting dense stands of the sweetveld grasses favoured by many herbivores. With few natural barriers to the spread of fire and plenty of fuel available, intense fires spread quickly across the plains. The distribution of woody cover is therefore more likely to be controlled by fire history than by slope position. Indeed the vegetation boundaries to the west and, to a lesser extent, to the east of the study area coincide with roads, which are likely to act as fire breaks. Shrubby patches of *Pterocarpus rotundifolius,* occasional clusters of *Acacia nigrescens* and *Dichrostachys cinerea* and lone *Sclerocarya birrea* occur seemingly randomly across the crests. There is no evidence to link patches of shrubs and trees with distance to the channel or the presence of pans.

Subsurface slumping creates depressions that retain surface water and that are subsequently deepened and expanded by animal use to form pans. If these depressions occur along a linear subsurface geological feature, then a chain of ponds may form and eventually develop into a channel. However, most pans are disconnected from the drainage network, with water is lost through evapotranspiration and/or subsurface seepage rather than by means of a surface stream.

Channels

Channel areas consist of relatively steep banks that enclose a wide flat grass-covered bed, with patches of water or reeded wetland areas or bare areas from which surface water has evaporated. There is rarely continuous flow of water in low order channels, but rather a chain of disconnected ponds.

Soils tend to be dark smectic clays (e.g. Arcadia), with a tendency to swell and crack. Although highly fertile, few woody plants can survive multiple cycles of swelling, shrinking and cracking. When dry, infiltration is rapid, through the cracks, but then slows dramatically once the soil is saturated, since drainage is poor. Water can therefore be stored for long periods in the soils of the channel bed.

Typical profile

Downslope profiles are similar for all stream orders (Figure 7.3). The hydrological characteristic of the soils suggest that there is little lateral movement of water, except in areas immediately adjacent to a channel or pan. In low order catchments, lateral surface movement of water may even be rare in channels. Water fluxes and the consequent hydrological connectivity between catenal elements will vary in time according to the history of rain events.

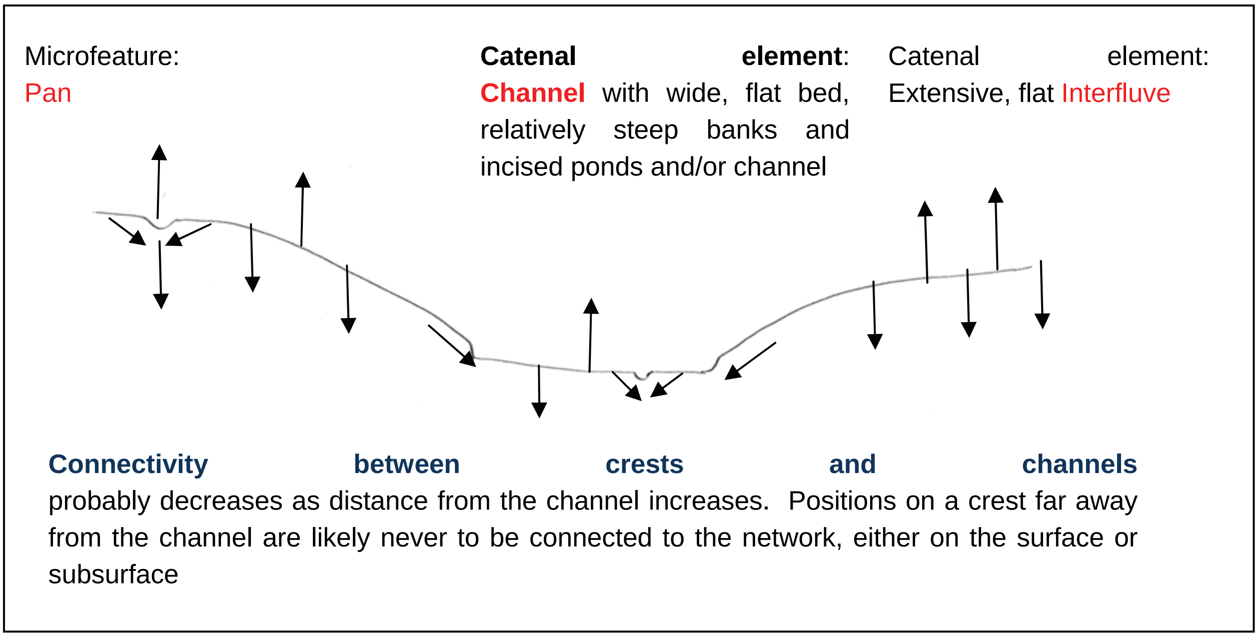


Figure 7.4: Features and hypothesised directions of water fluxes in a typical CASS in the Lower Sabie basalt study area

Summary

This landscape consists almost entirely of large, relatively homogenous interfluves, within which there is no systematic vegetation pattern related to topography. We suggest that these patterns are randomly distributed, and are most likely the result of interactions between fire, herbivory, animal diggings and very local geological differences.

7.4 Summary

This chapter illustrates how knowledge from different disciplines can be synthesised to link landscape patterns at each hierarchical level with the processes that generate and sustain these patterns. Each facet of a landscape element interacts with other facets to produce an ecological entity. For example, the soils and vegetation (facets of catenal elements) interact with hydrological flows (another facet) to produce a catenal element (an ecological entity that can be spatially defined).

The framework suggests that each catenal element has a distinct hydrological response, determined not only by the character of the soil, vegetation and topography, but also by the degree of hydrological connectivity between adjacent elements. By aggregating the hydrological responses for each catenal element, an overall catchment response can be estimated. Furthermore, since CASSs of each stream order within a physiographic zone have similar assemblages of catenal elements, the water budget associated with the entire physiographic zone can be calculated. Using our framework, hydrological models can be stratified, treating landscape elements at each hierarchical levels as 'hydrological response units' (sensu Flugel, 1995). It is hoped that the WRC project led by Simon Lorentz and Pieter le Roux will be able to test this hypothesis in the KNP 'super sites' (see para. 8.5 below).

This chapter contains many other hypotheses that need to be tested in future projects. Over time, a database of knowledge about each class of landscape elements can be built up (see para. 8.4 below), including topics such as the range of variability in form and process that characterises each class of landscape elements and the variability of responses to disturbances, human intervention or environmental change that is associated with each class.

The use of our framework to underpin such scientific investigations and to inform conservation planning and management forms the subject of our next chapter.

CHAPTER 8 IMPLICATIONS FOR MANAGEMENT AND SCIENCE

8.1 Introduction

Spatially explicit landscape classification lies at the very heart of both systematic conservation planning and strategic adaptive management. Both activities aim to conserve the heterogeneity of ecological patterns and processes that generate and sustain the compositional, structural and functional dimensions of biodiversity.

In systematic conservation planning (Margules and Pressey, 2000), spatially explicit landscape classifications are used to produce an inventory of different types of ecosystems, each of which are then assessed in terms of integrity, degree of protection and vulnerability to perceived risks. Conservation targets identify the minimum area of each ecosystem type that needs to be conserved in order for the system to persist over time as well as areas occupied by rare and critically endangered species. Priorities are then set that focus efforts in less well protected or threatened areas that need additional protection if the conservation targets are to be met.

Currently, many different approaches are used to assess spatial biodiversity, reflecting the large variety of ecosystem patterns and processes that can be considered, the multiplicity of datasets available and the fact that the terrestrial, river, estuarine and marine components of biodiversity are assessed separately, by different groups of experts. We suggest that our approach to landscape classification could offer a way of integrating many of these perspectives, at least in water controlled ecosystems such as KNP, where the spatial and temporal distribution of water generates and sustains a multitude of ecological patterns and processes.

The mission of KNP is “to maintain biodiversity in all its natural facets and fluxes, to provide human benefits and build a strong constituency and to preserve as far as possible the wilderness qualities and cultural resources associated with the park.” (Freitag-Ronaldson and Venter, 2008). The park is managed according to the principles of Strategic Adaptive Management (SAM), which involves setting a hierarchy of objectives that describe the acceptable states of the landscape. With respect to objectives aiming to conserve biodiversity, Thresholds of Potential Concern (TPCs) are agreed and monitoring implemented that is designed to signal unacceptable levels of change and the possible need for management intervention.

Since different patterns and processes are evident when the landscape is viewed at different scales (Levin, 1992), patterns of change need to be visualised and monitored at different scales. Furthermore, landscapes in different settings may respond to similar drivers in different ways. Thus a hierarchical framework of different landscape types informs the entire process, from setting objectives and acceptable states, through developing and monitoring TPCs, visualising the likely effects of management intervention and environmental change. The ongoing gathering of data, knowledge and experience relating to each landscape class then informs revisions to the management plan, in an iterative learning process.

The approach to landscape classification developed in this project has great potential application, not only for informing SAM, but also in providing a framework for organising the repository of knowledge that underpins successful strategic adaptive management. The framework provides a consistent frame of reference for gathering and communicating information on ecological structure, function and dynamics that can be used for scenario building, envisioning the different risks, threats, vulnerabilities and responses of landscapes in different settings and at scales appropriate to the organisational levels of the hierarchy. Furthermore, the holistic standpoint of this classification facilitates the coupling of terrestrial and aquatic systems, offering a framework that can be used and contributed to by scientists and managers from a wide range of perspectives.

The classification also finds application in selecting sites where research and monitoring is concentrated. These data-rich sites are chosen to be commonly recurring examples of different landscape types, allowing extrapolation of findings to other landscape elements with similar characteristics. The first of these 'super' sites are shortly to be established in KNP and basic soil, vegetation and hydrological data will be collected at various scales as part of a national WRC-funded project to develop a hydrologically based classification system of South African soils and hillslopes.

This report details ways in which the proposed landscape classification can contribute in each of the above mentioned fields: conservation planning, strategic adaptive management, knowledge management and the selection of 'super sites', focussing on implementation in our study area, KNP. In conclusion, applications in other fields are briefly considered.

8.2 Contribution to conservation planning

The systematic approach to conservation planning developed by Margules and Pressey (2000) is widely used in South Africa. This approach underpins the conservation policies of SANBI (South African National Biodiversity Institute), regional conservation plans and the conservation development framework produced for KNP (Eber *et al.*, 2008). Data sets that serve as surrogates for biodiversity in the planning region are assembled and then quantitative conservation targets are set for species, vegetation types or other features. After calculating the proportion of this target met through existing protected areas, other areas are identified that require protection if the targets are to be met. These conservation priorities are then used to inform development policy, management and decision-making (Driver *et al.*, 2005).

However, a multitude of data sets describing spatial biodiversity are used by different agencies, who combine the data in different ways. Approaches range from those who use many biodiversity variables, with conservation targets set separately for each (e.g. Mpumalanga regional diversity plan (Ferrar and Lötter, 2007)), to those who prefer to synthesise many variables into an 'ecoregion' (e.g. the approach to river health assessment used by DWAF (Kleynhans *et al.*, 2005), or the inshore and offshore 'bioregions' used in the marine component of SANBI's National Spatial Biodiversity Assessment (NSBA) (Lombard *et al.*, 2004)). Whereas some agencies favour an approach in which layers are combined by a panel of experts (e.g. the estuarine component of NSBA), others prefer to systematically overlay datasets (e.g. the riverine component of NSBA), whilst still others combine both GIS overlays with expertly derived layers (e.g. the terrestrial component of NSBA). Furthermore, each agency incorporates a different approach to scaling both biodiversity variables and the overall assessment they produce.

All these agencies assess biodiversity separately for terrestrial and freshwater environments, producing separate conservation targets for each component. These targets are often combined at a later stage of the planning process, aiming to optimise the conservation priority assigned to land units within the planning region. The fragmented approach to the initial assessment of biodiversity not only risks generating a sub-optimal allocation of conservation priorities, but also overlooks the fact that ecosystem components do not function as independent systems. Biological and abiotic features are interdependent, such that several features need to exist together in order that each can persist.

The hierarchical approach to classification of the overall (aquatic and terrestrial) landscape developed in this project offers great potential for integrating the various approaches to biodiversity assessment. The proposed framework offers a perspective that integrates aquatic and terrestrial environments and a transdisciplinary view of ecological systems. Classifications based on this framework integrate hydrology with soil, vegetation and morphology, capturing structural/functional units at various scales. Since these units represent the biophysical template upon which ecosystem processes are played out, they offer a holistic way of spatially assessing the heterogeneity upon which biodiversity ultimately depends (Pickett *et al.*, 2003).

The value of using such a representation of the biophysical template in conservation planning is recognised in KNP, where the zoning plan uses Venter's land classification (1990) as a basis for the assessment of biodiversity (Eber *et al.*, 2008). Venter's classification has many similarities to that proposed in this project. Although not derived with explicit reference to water movement or drainage networks, Venter's classification is based on spatial grouping of soils, vegetation and morphology, thus capturing the most significant aspects of landscape variability from a hydrological perspective. Although geology and climate variables were not explicitly included by Venter, the signals of each are effectively encoded within the soil and vegetation patterns he observed. As with the approach developed in this project, Venter's classification is underpinned by a conceptual framework that recognises a landscape hierarchy ranging from catenal patterns to broad-scale zones based on differences in geology and climate. In many ways, the new approach developed in this project builds upon Venter's work, utilising the fine scale satellite imagery and sophisticated GIS techniques that are now available. It differs from Venter's approach by incorporating a different focus that emphasises the pivotal role of river systems in structuring the biophysical template, facilitating the integration of riverine and terrestrial ecosystem components.

Conservation planning focuses on the long term and on land use in both protected and unprotected areas. We now turn towards more short term conservation planning in protected areas, focussing on potential applications of our approach to landscape classification in our study area, Kruger National Park.

8.3 Contribution to strategic adaptive management in KNP

Kruger National Park is managed according to the principles of Strategic Adaptive Management (SAM) (Biggs and Rogers, 2003). SAM involves the negotiation of a range of desired (or acceptable) states that reconcile the conservation of biodiversity with the requirements of stakeholders. Management objectives are then directed towards maintaining the park within the range of acceptable states. Thresholds of Potential Concern (TPCs) are agreed and monitoring implemented that is designed to signal unacceptable levels of change and the possible need for management intervention. Scenarios can be used to foresight system responses to various perceived threats and TPCs developed to signal the advent of high-risk events that are likely to lead to unacceptable states. Scenarios can also be used to play out the likely effects of various management interventions and the best option selected. However, both our imperfect knowledge of ecological processes and the complexity of ecological systems (with non- linear interactions, contingency and multiple possible outcomes) mean that the outcome of interventions can never be predicted with certainty. Management interventions therefore need to be constantly evaluated to ensure that they are having desirable effects, with both targets and practice open to adaptation through an iterative learning process.

Since landscape patterns and processes appear differently when viewed at different scales (Levin, 1992), patterns of change need to be monitored and visualised/ modelled at different scales. Furthermore, landscapes in different settings may respond to similar drivers in different ways, be exposed to different threats and have different vulnerabilities to these threats. For example, catchments within a flat basaltic landscape in a relatively dry rainfall area will respond to fire in a different manner to catchments in a more dissected granitic landscape in a higher rainfall area. The character of neighbouring patches will also influence the fire response within a particular patch.

A hierarchical landscape classification therefore forms an integral part of SAM. Levels of the hierarchy provide the scales at which landscape patterns and processes are viewed, whilst the classes at each organisational level provide a means of stratifying a sample design for monitoring and modelling ecological processes and system response at each scale. When developing desired states, TPCs and monitoring procedures, each class within the hierarchy should be considered separately, within the limits of logistical and resource constraints.

Some of the most important TPCs in KNP are already informed by the hierarchical landscape classification developed by Venter (1990), which is based on similar principles to the new approach proposed in this project (see above). For example, TPCs that track potentially unacceptable changes in vegetation structure and composition, large herbivore populations and heterogeneity per se are all set within classes and scales based on Venter's (1990) landscape classification, overlaid with areas designated by SANBI as being of particular importance to conservation at a national scale *(Kruger National Park Biodiversity Management Programme, in preparation).*

However, despite calls for integration in the KNP management plan (Freitag-Ronaldson and Venter, 2008), riverine objectives and TPCs are still considered separately from their terrestrial counterparts. Indeed, riverine TPCs focus exclusively on perennial rivers (600 km), monitoring levels of flow and sedimentation, water quality and fish assemblages. Although ephemeral and seasonal streams comprise the vast majority of streams (32 000 km) within the park, they receive little attention, falling through a 'science and management gap' between aquatic and terrestrial systems. We believe that the holistic framework developed in this project will help to bridge this gap.

The new framework will also offer improvements to the Venter classification currently used. These improvements are not only the result of using the latest imagery and techniques, but also come from the underlying conceptual model that offers a holistic perspective through the recognition of the pivotal role of water distribution in driving the whole system, acting as both cause and consequence of observed patterns of soil, vegetation and topography. The mosaic of patches formed by numerous interactions between soil, water and vegetation can be observed at different scales that correspond to different hierarchical levels of a self-organised landscape that is highly structured in space. The arrangement of the mosaic is largely controlled by the structure of the drainage network. This recognition of structural controls inherent in the drainage network not only offers a way of integrating aquatic and terrestrial perspectives, but also provides a rationale for scaling that is based on levels of organisation that are inherent to the landscape, rather than imposed by an observer. Furthermore, the new framework encompasses the relatively modern thinking around concepts of heterogeneity that now inform management strategies within KNP. No longer are landscape classes considered to be homogenous areas, but rather as consisting of a range of diverse, interacting and dynamic components. However, the range of variability in the character and behaviour of these components is constrained at each scale by their position in the landscape hierarchy.

The value of this approach has already been recognised in the development of new TPCs related to heterogeneity per se (Margules *et al.*, 2003). These TPCs are based on the principle that biodiversity is ultimately a consequence of diverse conditions (Pickett *et al.*, 2003). Homogenisation of the system, either spatially or temporally, poses a real threat to the core KNP objective of maintaining biodiversity in all its natural facets and fluxes. Proposals are currently being developed for TPCs that will signal decreasing diversity in many system components, including the structure and composition of woody and herbaceous vegetation and fauna ranging from mega-herbivores to insects. However, a pilot study has proved over-ambitious, being too resource-intensive to measure the diversity of all these elements at three landscape scales. Rationalisation of the sampling strategy is needed, and future monitoring is likely to be stratified using our new catchment-based approach to landscape classification, and concentrated in the 'super sites' discussed below.

A SAM approach to the maintenance of biodiversity demands a strong integration of management and science. Science generates understanding of the system, helping to identify the drivers and controls on system change as well as the possible system responses. Such understanding informs the setting of realistic objectives, the identification of potential threats as well as the anticipation of system responses to management intervention. This approach to conservation management assumes that it is possible to learn about the range of ecosystem responses to natural fluxes, human impacts and management intervention through management experience as well as through scientific investigation. However, such learning can only be applied if knowledge, data and experience are well organised and easily accessible.

8.4 Knowledge management

With the advent of GIS, we have become familiar with the notion of maps linked to databases, opening the possibility of using a landscape classification as a framework within which to structure and manage knowledge about ecological systems. The classification provides a consistent frame of reference for gathering and communicating information and knowledge on the composition, structure and dynamics of the biodiversity contained within each class. Data and understanding can be gathered from a wide variety of sources, spanning scientific, management and ranger experience and observation, reaching across disciplinary divides to provide an integrated and holistic perspective.

Such a data repository will prove invaluable for both conservation management and science, providing a solid foundation for consolidating the knowledge and experience upon which the strategic adaptive management approach is based. In order to be most effective, such a database needs to be open and accessible, evolving over time as new knowledge is gained. In the light of new knowledge and understanding, the processes of both SAM and of landscape classification can be refined over time, in a continuous and iterative manner.

Much of the data to be contained in such a repository will originate from ongoing TCP monitoring and baseline data, as well as from scientific projects conducted inside KNP. In order both to minimise disturbance in the park and to facilitate data integration, it is proposed that 'super sites' be established.

8.5 Super sites

'Super sites' are areas within Kruger National Park (KNP) that are being selected as examples of catchments characteristic of a certain physiographic zone. Research projects will be focussed on these areas, aiming to construct a holistic, transdisciplinary description and understanding of the ecological processes and interactions that operate within each physiographic zone. Each site will contain at least three different stream/catchment orders, so that patterns and processes can be described and measured at different scales. The growing pool of data and knowledge relating to each site will be made easily accessible to KNP staff and collaborative researchers, providing valuable contextual understanding for both management and scientific initiatives.

It is recognised that every site is unique and that the range of variability existing within a landscape system cannot be captured within a single site. In the same way that no family has exactly 2.4 children, no one site exhibits the mean values associated with a landscape system. Super sites are better seen as examples, chosen to maximise learning that can be extrapolated to other similar areas. In order to facilitate such extrapolation, super sites should:

- contain the hillslope vegetation and soil patterns that *commonly recur* throughout a land system
- be areas that are delimited by *catchment boundaries,* recognising the fundamental importance of water distribution to the operation of a wide range of ecological processes

- be third-order catchments, allowing ecological patterns to be observed at a *minimum of three scales* associated with different stream/catchment orders
- contain as few as possible *features such as koppies, dykes, dams and roads* that may substantially disrupt the flow of water across and through the landscape. Such features may be studied separately at a later stage
- be easily *accessible* (i.e. close to roads and research facilities/camps)

Linking studies conducted in super sites to a hierarchical landscape classification provides a mechanism to extrapolate the site-specific data to other landscape elements at multiple scales. However, in so doing, it is important to remember that the super site is but one example of the total range of variability that exists within its class.

The first project focussed on supersites will form part of a WRC project led by Simon Lorentz (University of KwaZulu-Natal) and Jaco Nel (University of the Western Cape) that will select the sites and collect basic hydrological data at three nested levels. The supersites will also form part of second WRC project, led by Pieter le Roux (University of the Free State), which aims to develop a hydrologically based classification system of South African soils and hillslopes, in order to inform hydrological modelling in ungauged basins. Detailed soil maps, profile descriptions and soil analyses will be produced for each site and hydrological measurements taken over a period of at least five years. Hillslope elements will be identified and mapped at each site in terms of relatively homogenous soil and vegetation. Water budgets will be calculated for hillslope elements within sampled first, second and third order catchments. Within each landscape system studied, a conceptual model of water distribution and dynamics will be constructed. These data will provide an excellent basis not only for the evaluation of the landscape classification and the underlying conceptual model, but will also become a key component of the core data set for each site, used by a wide range of future researchers examining the effects of water distribution on different ecosystem processes.

The first KNP super sites have been selected as examples of catchments in northern and southern granites and basalts. These four landscape systems, known as the Skukuza (southern granites), Phalaborwa (northern granites), Satara (southern basalts) and Letaba (northern basalts) land systems are the largest in KNP, together accounting for almost 80% of the total park area (Venter *et al.*, 2003). A focus on these four landscape types not only provides knowledge that is relevant to a large area of the park, but also allows broad comparisons to be made between granitic and basaltic landscapes in relatively high and low rainfall areas.

8.6 Applications in other fields

This report has focussed on applications in the fields of conservation management and planning. However, the new approach also has wide application in environmental sciences, where it allows models, experiments and sampling strategies to be designed in a spatially explicit way within the topographic, soil, vegetation and water distribution contexts that drive the system at multiple scales.

The new classification also opens up the possibility of asking a new range of questions relating to landscape structure, exploring the different patterns that can be observed in different landscape units and exploring hypotheses relating to the underlying processes that generate these patterns. For example, the distribution of various features of the riparian zone, such as tall trees or sodic sites, can be related to the stream order (or network position) of streams in different settings, generating hypotheses relating to likely patterns of water movement. Another example of a fruitful structural investigation could involve exploring the morphology of catenal elements commonly found in different settings (e.g. changes in gradient and curvature), which could generate hypotheses relating to the relative influence of hillslope and fluvial mechanisms on landscape evolution.

8.7 Summary

The new approach to landscape classification developed in this project has many potential applications in conservation planning, management and science. Indeed, a classification developed in line with the proposed approach could form a framework for integrating all these activities. Above all, it offers a holistic view of landscapes that can reach across disciplines and different management perspectives and bridge the unnatural divide between the study and management of terrestrial and river systems.

REFERENCES

Allen, T. & Starr, T. (1982) *Hierarchy,* Chicago, University of Chicago Press.

Asner, G. P. K., D.E., Kennedy-Bowdoin, T., Jones, M. O., Martin, R. E., Boardman, J. & Field, C. B. (2007) *Carnegie Airborne Observatory: in-flight fusion of hyperspectral imaging and waveform light detection and ranging (wLiDAR) for three-dimensional studies of ecosystems*. Journal of Applied Remote Sensing, 1.

Baatz, M. & Schape, A. (2000) *Multi-resolution segmentation. An optimization approach for high-quality multi-scale image segmentation*. In Strobl, J., Blaschke, T. & Griesebner, G. (Eds.) Angewandte Geographische Informationsverarbeitung XII. Heidelberg, Wichmann Verlag.

Beven, K. J. & Kirkby, M. J. (1979) *A physically based variable contributing area model of basin hydrology. 24, 43-69.* Hydrological Sciences Bulletin, 24, 43-69.

Biggs, H. C. & Rogers, K. H. (2003) *An adaptive system to link science, monitoring and management in practice*. In Du Toit, J. T., Rogers, K. H. & Biggs, H. C. (Eds.) The Kruger Experience. Washington, D.C., Island Press.

Bond, W. J. (2005) *Large parts of the world are brown or black: A different view on the 'Green World' hypothesis*. Journal of Vegetation Science, 16, 261-266.

Bridge, S. R. J. & Johnson, E. A. (2000) *Geomorphic principles of terrain organization and vegetation gradients*. Journal of Vegetation Science, 11, 57-70.

Brierley, G. J. & Fryirs, K. A. (2005) *Geomorphology and river management : applications of the river styles framework,* Malden, MA, Blackwell Pub.

Bucini, G., Hanan, N. P., Boone, R. B., Saatchi, S., Smit, I. P. J. & Lefsky, M. A. (2010) *Woody fractional cover in Kruger National Park, South Africa: remote-sensing-based maps and ecological insights*. In Hill, M. J. & Hanan, N. P. (Eds.) Ecosystem Function in Global Savannas: Measurement and Modeling at Landscape to Global Scales. CRC Press /Taylor and Francis.

Bull, L. J. & Kirkby, M. J. (Eds.) (2002) *Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels,* London, U.K., J. Wiley.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jager, J. & Mitchell, R. B. (2003) *Knowledge systems for sustainable development*. Proceedings of the National Academy of Sciences of the United States of America, 100 8086-8091.

Caylor, K. K., D'odorico, P. & Rodriguez-Iturbe, I. (2006) *On the ecohydrology of structurally heterogeneous semiarid landscapes*. Water Resources Research, 42.

Chamran, F., Gessler, P. E. & Chadwick, O. A. (2002) *Spatially explicit treatment of soil-water dynamics along a semiarid catena*. Soil Science Society of America Journal, 66, 1571-1583.

Christian, C. S. & Stewart, G. A. (1953) *General report on the survey of the Katherine-Darwin Region, 1946*, CSIRO, Melbourne, Australia

Commission for Environmental Cooperation (1997) *Ecological Regions of North America: Towards a Common Perspective*, Montreal, Quebec

Conacher, A. J. & Dalrymple, J. B. (1977) *The nine unit landsurface model: an approach to pedogeomorphic research*. Geoderma, 18, 1-154.

Davis, W. M. (1899) *The geographical cycle*. Geographical Journal, 14, 481-504.

Deng, Y. X. (2007) *New trends in digital terrain analysis: landform definition, representation, and classification*. Progress in Physical Geography, 31, 405-419.

Dikau, R. (1989) *The application of a digital relief model to landform analysis*. In Raper, J. F. (Ed.) Three dimensional applications in Geographical Information Systems. London, Taylor & Francis.

Dobos, E., Daroussin, J. & Montanarella, L. (2005) *An SRTM-based procedure to delineate SOTER Terrain Units on 1:1 and 1:5 million scales,* Luxembourg, Office for Official Publications of the European Communities.

Driver, A., Maze, K., Rouget, M., Lombard., A. T., Nel, J., Turpie, J. K., Cowling, R. M., P., D., Goodman, P., Harris, J., Jonas, Z., Reyers, B., Sink, K. & Strauss, T. (2005) *National Spatial Biodiversity Assessment 2004: Priorities for biodiversity conservation in South Africa*, South African National Biodiversity Institute, Pretoria

Eber, S., Mac Fadyen, S. & Venter, F. (2008) *Kruger National Park Zoning Plan*, Internal Report, SanParks,

ESRI (1999-2008) *ArcGIS Version 9.3*. In. Redlands, CA., Environmental Systems Research Institute.

ESRI (2004) *ArcHydro GIS for Water Resources* In. Redlands, CA., Environmental Systems Research Institute.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, G., Werner, M., Oskin, M., Burbank, D. & Alsdorf, D. (2007) *The Shuttle Radar Topography Mission*. Review of Geophysics, 45.

Ferrar, A. A. & Lötter, M. C. (2007) *Mpumalanga Biodiversity Conservation Plan Handbook*, Mpumalanga Tourism & Parks Agency, Nelspruit

Fitzsimmons, A. K. (1996) *Sound policy or smoke and mirrors: Does ecosystem management make sense?* Water Resources Bulletin, 32, 217-227.

Florinsky, I. V., Eilers, R. G., Manning, G. R. & Fuller, L. G. (2002) *Prediction of soil properties by digital terrain modelling*. Environmental Modelling & Software, 17, 295-311.

Flugel, W. A. (1995) *Delineating Hydrological Response Units by Geographical Information-System Analyses for Regional Hydrological Modeling Using Prms/Mms in the Drainage-Basin of the River Brol, Germany*. Hydrological Processes, 9, 423-436.

Fotheringham, A. S. (1989) *Scale-independent spatial analysis*. In Goodchild, M. & Gopal, S. (Eds.) The Accuracy of Spatial Data Bases. London, Taylor & Francis.

Franklin, J. (1995) *Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients*. Progress in Physical Geography, 19, 474-499.

Freitag-Ronaldson, S. & Venter, F. J. (2008) *Kruger National Park Management Plan*, SANParks, Pretoria

Gertenbach, W. P. D. (1983) *Landscapes of the Kruger National Park*. Koedoe, 26, 9-121.

Gessler, P. E., Chadwick, O. A., Chamran, F., Althouse, L. & Holmes, K. (2000) *Modeling soil-landscape and ecosystem properties using terrain attributes*. Soil Science Society of America Journal, 64, 2046-2056.

Grayson, R. & Bloschl, G. (Eds.) (2000) *Spatial patterns in Catchment Hydrology,* Cambridge, U.K., Cambridge University Press.

Guntner, A., Seibert, J. & Uhlenbrook, S. (2004) *Modeling spatial patterns of saturated areas: An evaluation of different terrain indices*. Water Resources Research, 40.

Hack, J. T. (1957) *Studies of longitudinal stream profiles in Virginia and Maryland*,

Herbst, M., Diekkruger, B. & Vereecken, H. (2006) *Geostatistical co-regionalization of soil hydraulic properties in a micro-scale catchment using terrain attributes*. Geoderma, 132, 206-211.

Horton, R. E. (1945) *Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology*. Bulletin of the Geological Society of America, 56.

Howard, A. D. (1967) *Drainage analysis in geologic interpretation: a summation*. In Coates, D. R. & Vitek, J. D. (Eds.) Thresholds in Geomorphology. Lonon, U.K., George Allen and Unwin.

ISRIC (2010) *Soil and Terrain Database (SOTER) Programme*. In.

Iwahashi, J. & Pike, R. J. (2007) *Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature*. Geomorphology, 86, 409.

Jax, K. (2006) *Ecological units: Definitions and application*. Quarterly Review of Biology, 81, 237-258.

Jelinksi, D. E. & Wu, J. (1996) *The modifiable areal unit problem and implications for landscape ecology*. Landscape Ecology, 11, 129-140.

Jenness, J. (2006) *Topographic Position Index extension for ArcView 3.x, rewritten for ArcGIS 9.x by Tom Dilts, availiable at http://arcscripts.esri.com/details.asp?dbid=15996*.

Jenny, H. (1941) *Factors of Soil Formation,* New York, McGraw Hill.

Khomo, L. (2008) *Weathering and soil properties on old granitic catenas along climo-topographic gradients in Kruger National Park*. In. Johannesburg, University of the Witwatersrand.

Kienzle, S. (2004) *The effect of DEM raster resolution on first order, second order and compound terrain derivatives*. Transactions in GIS, 8, 83-111.

Kleynhans, C. J., Thirion, C. & Moolman, J. (2005) *A Level I River Ecoregion classification system for South Africa, Lesotho and Swaziland*, N/0000/00/REQ0104, Resource Quality Services, Department of Water Affairs and Forestry, Pretoria

Kuhn, T. (1962) *The Structure of Scientific Revolutions,* Chicago, University of Chicago Press.

Leopold, L. B., Wolman, M. G. & Miller, J. P. (1964) *Fluvial processes in geomorphology,* San Francisco, W.H. Freeman and Co.

Levin, S. A. (1992) *The problem of pattern and scale in ecology*. Ecology, 73, 1943-1967.

Lin, H. S., Kogelmann, W., Walker, C. & Bruns, M. A. (2006) *Soil moisture patterns in a forested catchment: A hydropedological perspective*. Geoderma, 131, 345-368.

Lombard, A. T., Strauss, T., Harris, J., Sink, K., Attood, C. & Hutchings, L. (2004) *South African National Spatial Biodiversity Assessment 2004: Technical Report. Volume 4: Marine Component*, ENV-S-I-2004-063, South African National Biodiversity Institute, Pretoria

Luo, W. & Stepinski, T. (2008) *Identification of geologic contrasts from landscape dissection pattern: An application to the Cascade Range, Oregon, USA*. Geomorphology, 99, 90-98.

MacMillan, R. A., Jones, R. K. & McNabb, D. H. (2004) *Defining a hierarchy of spatial entities for environmental analysis and modeling using digital elevation models (DEMs)*. Computers, Environment and Urban Systems, 28, 175-200.

MacMillan, R. A., Pettapiece, W. W., Nolan, S. C. & Goddard, T. W. (2000) *A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic*. Fuzzy Sets and Systems, 113, 81-109.

MacMillan, R. A. & Shary, P. A. (2009) *Landforms and landform elements in geomorphometry*. In Zhou, Q., Lees, B. G. & Tang, G. (Eds.) Advances in Digital Terrain Analysis. Heidelberg, Springer.

Macvicar, G. N., Scotney, D. M., Skinner, T. E., Niehaus, H. S. & Loubser, J. H. (1974) *A classification of land (climate, terrain form, soil) primarily for rainfed agriculture*. South Africa Journal of Agriculture Extension, 3, 8-24.

Marceau, D. (1999) *The scale issue in social and natural sciences*. Canadian Journal of Remote Sensing, 25, 347-356.

Margules, C. R., Grant, C. C., E., P., A., D., S., M., Biggs, H. C. & H., S. (2003) *A suggested biodiversity survey and monitoring program for Kruger National Park*, Scientific Report 01/03, Conservation Services, Skukuza, Kruger National Park

Margules, C. R. & Pressey, R. L. (2000) *Systematic conservation planning*. Nature, 405, 243-253.

McBratney, A. B., Santos, M. L. M. & Minasny, B. (2003) *On digital soil mapping*. Geoderma, 117, 3-52.

McMahon, G., Wiken, E. B. & Gauthier, D. A. (2004) *Toward a Scientifically Rigorous Basis for Developing Mapped Ecological Regions*. In Environmental Management.

Milne, G. (1935) *Some suggested units for classification and mapping, particularly for East African soils*. Soil Research, 4, 183-198.

Montgomery, D. R. (1999) *Process domains and the river continuum*. Journal of the American Water Resources Association, 35, 397-410.

Moore, I. D., Gessler, P. E., Nielsen, G. A. & Peterson, G. A. (1993) *Soil Attribute Prediction Using Terrain Analysis*. Soil Science Society of America Journal, 57, 443-452.

Mucina, L. & Rutherford, M. C. (Eds.) (2006) *The Vegetation of South Africa, Lesotho and Swaziland,* Pretoria, South African National Biodiversity Institute.

O'Connell, D. A., Ryan, P. J., Mckenzie, N. J. & Ringrose-Voase, A. J. (2000) *Quantitative site and soil descriptors to improve the utility of forest soil surveys*. Forest Ecology and Management, 138, 107-122.

O'Keefe, J. & Rogers, K. H. (2003) *Heterogeneity and Management of the Lowveld Rivers*. In Du Toit, J. T., Rogers, K. & Biggs, H. C. (Eds.) The Kruger Experience. Ecology and Management of Savanna Heterogeneity. Washington DC, Island Press.

O'Neill, R. V. (2001) *Is it time to bury the ecosystem concept? (With full military honors of course!)*. Ecology, 82, 3275-3284.

Openshaw, S. & Taylor, P. J. (1979) *A Million or so Correlation Coefficients: Three Experiments on the Modifiable Areal Unit Problem*. In Wrigley, N. (Ed.) Statistical Methods in The Spatial Sciences. London, Poin.

Openshaw, S. & Taylor, P. J. (1981) *The Modifiable Areal Unit Problem*. In Wrigley, N. & Bennett, R. J. (Eds.) Quantitative Geography: a British View. London, Routledge & Kegan Paul.

Park, S. J., Mcsweeney, K. & Lowery, B. (2001) *Identification of the spatial distribution of soils using a process-based terrain characterization*. Geoderma, 103, 249-272.

Park, S. J. & Van De Giesen, N. (2004) *Soil-landscape delineation to define spatial sampling domains for hillslope hydrology*. Journal of Hydrology, 295, 28-46.

Partridge, T. C., Dollar, E. S. J., Moolman, J. & Dollar, L. H. (2010) *The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists*. Transactions of the Royal Society of South Africa, 65, 1-47.

Petts, G. E. & Amoros, C. (Eds.) (1996) *Fluvial hydrosystems,* London, Chapman & Hall.

Peuker, T. K. & Douglas, D. H. (1975) *Detection of surface-specific points by local parallel processing of discrete terrain elevation data*. Computer Graphics Image Processing, 4, 375-387.

Pickett, S. T. A. & Cadenasso, M. L. (2002) *The ecosystem as a multidimensional concept: Meaning, model, and metaphor*. Ecosystems, 5, 1-10.

Pickett, S. T. A., Cadenasso, M. L. & Benning, T. L. (2003) *Biotic and abiotic variability as key determinants of savanna heterogeneity at multiple spatiotemporal scales*. In Du Toit, J. T., Rogers, K. H. & Biggs, H. C. (Eds.) The Kruger Experience. Washington, D.C., Island Press.

Pickett, S. T. A., Cadenasso, M. L. & Grove, J. M. (2005) *Biocomplexity in coupled natural-human systems: A multidimensional framework*. Ecosystems, 8, 225-232.
Pike, R. J. (2002) *A Bibliography of Terrain Modeling (Geomorphometry), the Quantitative Representation of Topography*, US Geological Survey, Menlo Park, California
Pike, R. J., Acevedo, W. & Card, D. H. (1989) *Topographic grain automated from digital elevation models*. In Auto-Carto 9. Baltimore MD, ASPRS/ACSM, Falls Church, VA.
Poff, N. L. (1997) *Landscape filters and species traits: Towards mechanistic understanding and prediction in stream ecology*. Journal of the North American Benthological Society, 16, 391-409.
Poole, G. C. (2002) *Fluvial landscape ecology: addressing uniqueness within the river discontinuum*. Freshwater Biology, 47, 641-660.
Porporato, A., D'odorico, P., Laio, F. & Rodriguez-Iturbe, I. (2003) *Hydrologic controls on soil carbon and nitrogen cycles. I. Modeling scheme*. Advances in Water Resources, 26, 45-58.
Qin, C. Z., Zhu, A. X., Shi, X., Li, B. L., Pei, T. & Zhou, C. H. (2009) *Quantification of spatial gradation of slope positions*. Geomorphology, 110, 152-161.
Reuter, H. I., Nelson, A., Strobl, P., Mehl, W. & Jarvis, A. (2009) *A first assessment of Aster GDEM tiles for absolute accuracy, relative accuracy and terrain parameters*. In Geoscience and Remote Sensing Symposium,2009 IEEE International,IGARSS 2009.
Ridolfi, L., D'odorico, P., Porporato, A. & Rodriguez-Iturbe, I. (2003) *Stochastic soil moisture dynamics along a hillslope*. Journal of Hydrology, 272, 264-275.
Rinaldo, A., Rodriguez-Iturbe, I. & Rigon, R. (1998) *Channel networks*. Annual Review of Earth and Planetary Sciences, 26, 289-327.
Rodriguez-Iturbe, I. (2000) *Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics*. Water Resources Research, 36, 3-9.
Rodríguez-Iturbe, I. & Porporato, A. (2004) *Ecohydrology of water-controlled ecosystems: soil moisture and plant dynamics,* Cambridge, Cambridge University Press.
Rodriguez-Iturbe, I. & Rinaldo, A. (1997) *Fractal river basins: Chance and self-organisation,* Cambridge, U.K., Cambridge University Press.
Ruhe, R. V. (1956) *Geomorphic Surfaces and the nature of soils*. Soil Science, 82, 441-455.
Rutherford, M. C. & Westfall, R. H. (1986) *Biomes of Southern Africa – an Objective Categorisation*. Memoirs of the Botanical Survey of South Africa, 1-98.
Sankaran, M., Hanan, N. P., Scholes, R. J., Ratnam, J., Augustine, D. J., Cade, B. S., Gignoux, J., Higgins, S. I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K. K., Coughenour, M. B., Diouf, A., Ekaya, W., Feral, C. J., February, E. C., Frost, P. G. H., Hiernaux, P., Hrabar, H., Metzger, K. L., Prins, H. H. T., Ringrose, S., Sea, W., Tews, J., Worden, J. & Zambatis, N. (2005) *Determinants of woody cover in African savannas*. Nature, 438, 846-849.
Sanparks-Gis (2010) *South African National Parks' Geospatial Database*. In., Kruger National Park, Skukuza, GIS-RS Lab.
Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. & Walker, B. (2001) *Catastrophic shifts in ecosystems*. Nature, 413, 591-596.
Schmidt, J. & Hewitt, A. (2004) *Fuzzy land element classification from DTMs based on geometry and terrain position*. Geoderma, 121, 243.
Scholes, R. J. & Walker, B. H. (1993) *An African savanna: synthesis of the Nylsvley study,* Cambridge, Cambridge University Press.
Scull, P., Franklin, J., Chadwick, O. A. & Mcarthur, D. (2003) *Predictive soil mapping: a review*. Progress in Physical Geography, 27, 171-197.
Shultz, R. E. (1997) *South African Atlas of Agrohydrology and Climatology,* Pretoria, Water Research Commission.
Sivakumar, B. (2008) *The more things change, the more they stay the same: the state of hydrologic modelling*. Hydrological Processes, 22, 4333-4337.
Solomon, A. M. & Shugart, H. H. (Eds.) (1993) *Vegetation Dynamics and Global Change,* New York, Chapman and Hall.
Solomon, M., Zambitis, N., Biggs, H. C. & Mare, N. (1999) *Comparison of classifications commonly used as templates for management, scientific and GIS work in the Kruger National Park*. Koedoe, 42, 131-142.
Strahler, A. N. (1957) *Quantitative analysis of watershed geomorphology*. American Geophysical Union Transactions, 38, 913-920.
Tarboton, D. G., Bras, R. L. & Rodrigues-Iturbe, I. (1991) *On the extraction of channel networks from digital elevation data*. Water Resources Research, 5, 81-100.

Tchoukanski, I. (2010) *ET GeoWizards 10.0*. In.

Thwaites, R. N. (2006) *Conceptual and Digital Soil-Landscape Mapping using Regolith-Catenary Units* In P. Lagacherie, A. B. M. A. M. V. (Ed.) Digital Soil Mapping – An Introductory Perspective*.* Volume 31 ed. Oxford, Elsevier.

Townsend, C. R. (1989) *The patch dynamics concept of stream community ecology*. Journal of the North American Benthological Society*,* 8**,** 36-50.

Trimble (1995-2009) *eCognition Developer 8*. In. Westminster, CO., Trimble Navigation Ltd.

Turner, M. G., Other Author: Gardner, R. H. & O'Neill, R. V. (2001) *Landscape ecology in theory and practice : pattern and process,* New York, Springer.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. (1980) *River Continuum Concept*. Canadian Journal of Fisheries and Aquatic Sciences*,* 37**,** 130-137.

Venter, F. J. (1990) *A classification for land management planning in the Kruger National Park*. In. Pretoria, University of South Africa.

Venter, F. J., Scholes, R. J. & Eckhardt, H. C. (2003) *The abiotic template and its associated vegetation pattern*. In Du Toit, J. T., Rogers, K. H. & Biggs, H. C. (Eds.) The Kruger Experience*.* Washington, D.C., Island Press.

Wiens, J. A. (1976) *Population Responses to Patchy Environments*. Annual Review of Ecology and Systematics*,* 7**,** 81-120.

Wiens, J. A. (1989) *Spatial Scaling in Ecology*. Functional Ecology*,* 3**,** 385-397.

Wiens, J. A., Crist, T. O., With, K. A. & Milne, B. T. (1995) *Fractal Patterns of Insect Movement in Microlandscape Mosaics*. Ecology*,* 76**,** 663-666.

Woodcock, C. E. & Gopal, S. (2000) *Fuzzy set theory and thematic maps: accuracy assessment and area estimation*. International Journal of Geographical Information Science*,* 14**,** 153 -172.

Wu, J. G. & David, J. L. (2002) *A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications*. Ecological Modelling*,* 153**,** 7-26.

Wu, J. G. & Loucks, O. L. (1995) *From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology*. Quarterly Review of Biology*,* 70**,** 439-466.

Zambatis, N. (2003) *Determinants of Grass Production and Composition in the Kruger National Park*. In School of Applied Environmental Sciences, Faculty of Science & Agriculture. University Of Natal.

Zhang, W. & Montgomery, D. R. (1994) *Digital elevation model grid size, landscape representation, and hydrologic simulations*. Water Resources Research*,* 30**,** 1019-1028.

Ziadat, F. M. (2005) *Analyzing digital terrain attributes to predict soil attributes for a relatively large area*. Soil Science Society of America Journal*,* 69**,** 1590-1599.

Zonneveld, I. S. (1989) *The land unit – A fundamental concept in landscape ecology, and its applications*. Landscape Ecology*,* 3**,** 67-86.