LAND COVER CHANGE AND ITS EFFECT ON LANDSCAPE FUNCTION IN THE KOUE BOKKEVELD

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DECLARATION

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* The candidate performed all technical work, but due to sight impairment, the supervisor provided extensive aid in spatial pattern interpretation and scientific communication.

ABSTRACT

Natural vegetation and wetlands in regions of the Western Cape are being replaced by agricultural development. Previous studies on one such region – the Koue Bokkeveld, a high mountainous region at the source of three major drainage basins, demarcated for study purposes to cover nearly 2500 km^2, have failed to provide a comprehensive overview of such change and its landscape outcomes. This research aimed to detect, capture, record and classify the spatial nature, extent and change dynamics of various landscape elements and functions due to change in the land cover of this region. It assembled a comprehensive spatial database by digitising existing maps, aerial photograph mosaics and satellite imagery. Land cover maps were created for three historical and land cover change analyses were performed for the interim periods. Morphological landscape images were derived from a DEM and used to explain and interpret the location of land cover types and trends in change patterns. The effects on three landscape functions were determined, namely modelled run-off production, biodiversity deduced from landscape pattern structure and SANBI ratings, and carbon storage potential based on published figures.

The research found that the regional landscape has undergone substantive land cover change , since the reference state. Increased intensity and productivity of agriculture and its related infrastructure increased its coverage to nearly 45 000 ha or 20 % of the total area. Perennial agriculture (nearly 10 000 ha of orchards and plantations) and annual (intensive vegetable growing and diminishing cereal crops) agriculture, accompanied by improved enabling infrastructure, such as irrigation technology (large storage dams, pipelines, micro delivery modes), transportation, roads, product cooling and packing plants, have extensively replaced natural vegetation. Located in valley bottoms and along toe-slope locations, where they compete for space directly with expanding and constantly intensifying agricultural activities, wetlands, shale fynbos and renosterveld face complete replacement. Land use and land cover changes have profoundly affected landscape functioning. Modelled rainfall run-off has increased (2% overall) in most subregions, opening possibilities for sedimentation and erosion. A high degree of fragmentation of the vulnerable and affected vegetation types threatens biodiversity. Increased carbon storage in perennial agriculture offers a benefit of change, as opposed to the negative outcomes on biodiversity of change in the Koue Bokkeveld.

The research recommends improved institutional provision of the data required for system and regional modelling of processes like run-off in developing communities and for meeting the requirements of more sophisticated and accurate landscape models. Improved availability and appropriateness of GIT software solutions to conduct regional research and the use of more economical open software for GIS applications are to be encouraged. Ongoing and improved management and control are advocated for the expanding and intensified agriculture in a sensitive fynbos setting and for the maintenance of healthy landscape functioning. Concerning the discipline of geography, the exploitation of landscape functioning as a transdisciplinary focus inherent to a new regional geography is encouraged to arrest disciplinary drift. Specifically, future research should intensify the examination of the linkages between land use, land cover, change and ecological landscape functioning.

Keywords

Koue Bokkeveld, regional geography, geographic information technology (GIT), geographic information system (GIS), land use classification, land cover classification, change detection, landscape change, landscape structure, landscape functions, land degradation, wetland loss

OPSOMMING

Natuurlike plantegroei en vleilande in substreke van die Wes-Kaap word voortdurend vervang deur landbou-ontwikkeling. Vorige studies oor een so 'n streek – die Koue Bokkeveld, 'n hoogliggende bergagtige streek op die oorsprong van drie groot dreineerbekkens, wat afgebaken vir studie-doeleindes byna 2500 km^2 dek – bied geen omvattende oorsig van sodanige verandering en die landskapsuitkomste daarvan nie. Hierdie navorsing was daarop gemik om die ruimtelike aard, omvang en veranderingsdinamika van verskillende landskapselemente en -funksies as gevolg van die verandering van grondbedekking van hierdie streek na te spoor, op te teken en te klassifiseer. 'n Omvattende ruimtelike databasis is saamgestel uit versyferde bestaande kaarte, lugfoto-mosaïeke en satellietbeelde. Grondbedekkingskaarte vir drie historiese tydsnitte is geskep en verandering oor die tussentydse periode is ontleed. Morfologiese landskapselemente is uit 'n DEM onttrek en gebruik om die patroon van grondbedekking en tendense in veranderingspatrone te verklaar en te verduidelik. Die nagevolge op drie landskapsfunksies, naamlik reënval-afloop produksie, biodiversiteit soos afgelei van die landskap se patroonstruktuur en SANBI graderings, en koolstof-opgaringspotensiaal gebaseer op gepubliseerde syfers, is bepaal.

Die navorsing het bevind dat die streekslandskap sedert die vroegste verwysingstaat wesenlike grondbedekkingsverandering ondergaan het. Verhoogde intensiteit en produktiwiteit van die landbou en sy verwante infrastruktuur het die dekking daarvan vergroot tot byna 45 000 ha of 20% van die totale oppervlakte. Permanente (nagenoeg 10 000 ha boorde en plantasies) en jaarlikse (intensiewe groente en dalende graangewas verbouing) landbou, saam met verbeterde infrastruktuur, soos besproeiingstegnologie (groot opgaardamme, pypleidings, mikroleweringstoerusting), vervoer, paaie, produkverkoeling en -verpakkingsgeriewe, het natuurlike plantegroei grootskaals vervang. Geleë in valleivloere en aanliggende heuwelhange, waar hulle direk om ruimte meeding met die uitbreidende en voortdurend intensiferende landbou-aktiwiteite, is vleilande, skalie-fynbos en renosterveld onderhewig aan volledige vervanging. Grondgebruik- en bedekkingsverandering raak landskapsfunksionering wesenlik. Gemodelleerde reënvalafloop het toegeneem (2% in totaal) in die meeste substreke en vergroot so die moontlikhede vir sedimentasie en erosie. ‘n Hoë vlak van landskapsfragmentasie in die kwesbare en geaffekteerde plantegroeitipes bedreig biodiversiteit. Verhoogde koolstofopgaring in meerjarige landbougewasse impliseer wel 'n positiewe opbrengs van grondbedekkingsverandering, in teenstelling tot die negatiewe biodiversiteitsuitkomste van verandering in die Koue Bokkeveld.

Die navorsing beveel aan dat institusionele voorsiening van data wat benodig word vir stelsel- en prosesmodellering (bv. reënvalafloop) in ontwikkelende gemeenskappe, en die vereistes van meer gesofistikeerde en akkurate landskapsmodelle, verbeter word. Die beskikbaarheid en geskiktheid van GIT sagteware-oplossings vir streeksnavorsing, en die gebruik van meer ekonomiese oop-programmatuur vir GIS-toepassings, word aangemoedig. Vir praktiese doeleindes word deurlopend-verbeterde bestuur en beheer oor die uitbreiding en intensifering van van landbou in 'n sensitiewe fynbosomgewing en die instandhouding van gesonde landskapsfunksionering bepleit. Met betrekking tot die dissipline van geografie, moedig die navorsing die ontginning van die landskap se funksionering as 'n transdissiplinêre fokus inherent aan 'n nuwe tipe streeksgeografie aan, om dissiplinêre uiteenloping te stuit. Toekomstige navorsing kan spesifiek die ondersoek van die skakels tussen grondgebruik, grondbedekking, verandering en ekologiese landskapsfunksionering verskerp.

Sleutelwoorde

Koue Bokkeveld, streeksgeografie, geografiese inligtingstegnologie (GIT), geografiese inligtingstelsel (GIS), grondgebruikklassifikasie, grondbedekkingklassifikasie, veranderingsopsporing, landskapsverandering, landskapstruktuur, landskapsfunksies, landskapsverval, vleilandverlies

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CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

AGIS Agricultural Geo-referenced Information System

AU Astronomical unit

CARA Conservation of Agricultural Resources Act

CAPE Cape Action for People and the Environment

CCD charge coupled device

CGA Centre for Geographical Analysis

CGS Council for Geo Sciences

CN curve number

CNES Centre National d'Etudes Spatiales

CVA change vector analysis

DA Department of Agriculture

DEAT Department of Environmental Affairs and Tourism

DAFF Department of Agriculture Fisheries and Forestry (formerly known as DA)

DEM digital elevation model

dpi dots per inch

DWA Department of Water Affairs (formerly known as DWAF)

DWAF Department of Water Affairs and Forestry

EPA United States Environmental Protection Agency

ESKOM Electricity Supply Commission (South Africa)

ESUN exo-atmospheric solar irradiance

GCBC Greater Cederberg Biodiversity Corridor

GCPs ground control points

GIS geographic information system

GIT geographic information technology

HIS Hydrological Information System

HRG Haute Résolution Géométrique (High Geometric Resolution)

HSPF Hydrologic Simulation Program-Fortran

IDW inverse distance weighted

LANDSAT Land Satellite

LCM Land Change Modeller (for ecological sustainability)

LGGI Leica Geosystems Geospatial Imaging

LPOS landscape position

LPS Leica Photogrammetry Suite

LULCC land use and land cover change

LWP landscape wetness potential

MIR mid infrared

NDVI normalised difference vegetation index

RHP River Health Programme

RMS root mean square

SAC CSIR Satellite Application Centre

SANBI South African National Biodiversity Institute

SARA *South Africa rain atlas*

SASOL Suid-Afrikaanse Steenkool, Olie en Gas Korporasie) (Afrikaans for *South African Coal Oil and Gas Corporation)*

SAWS South African Weather Service

SCS Soil Conservation Service

SCS-CN Soil Conservation Service curve number

SP slope position

SPI slope position indexes

SPOT Satellite Pour l'Observation de la Terre

SWAT Soil And Water Assessment Tool

TPI topographic position index

UTM Universal Transverse Mercator

WARMS Water Authorisation and Registration Management System

WGS84 World Geodetic System 1984

LEGEND A: NATURAL FYNBOS TYPES IN THE STUDY AREA (SANBI code)

CR	Ceres Shale Renosterveld (FRs4)
CF	Cederberg Sandstone Fynbos (FFs4)
KA	Kouebokkeveld Alluvium Fynbos (FFa1)
KS	Kouebokkeveld Shale Fynbos (FFh1)
MS	Matjiesfontein Shale Renosterveld (FRs6)
NH	North Hex Sandstone Fynbos (FFs7)
NI	Northern Inland Shale Band Vegetation (FFb1)
SH	South Hex Sandstone Fynbos (FFs8)
SQ	Swartruggens Quartzite Fynbos (FFq2)
TW	Tanqua Wash Riviere (AZi7)
TWa	Tanqua Wash Riviere (AZi7) Alluvial Shrublands and Herblands
TWr	Tanqua Wash Riviere (AZi7) Riparian Thickets
TWs	Tanqua Wash Riviere (AZi7) Sheet Washes
WA	Western Altimontane Sandstone Fynbos (FFs30)
WS	Winterhoek Sandstone Fynbos (FFs5)

LEGEND B: LAND COVER CLASSES

AA	Annual agriculture
CD	Clear-water dams
Bu	Built-up area
In	Urban intensification
NV	Natural vegetation
PA	Perennial agriculture
PT	Plantations and trees
Rd	Roads
T	Town
TD	Turbid-water dams
WC	Wetland channels
WF	Wetland flats

LEGEND C: LAND COVER CHANGE CLASSES

A	Abandonment
Al	Agricultural loss
Ar	High agricultural retention
Ce	Extensive conversion
Ci	Intensive conversion
D	Deforestation
Dl	Waterbody loss
Dn	Natural dynamic
Dr	Waterbody retention
E	Built abandonment
Fl	Forestry loss
Fr	Forestry retention
Ia	Agrarian intensification
Ld	Light development
Ng	Natural vegetation loss / habitat gain
Nl	Natural vegetation loss
Nr	Natural vegetation retention
P	Persistence
R	Afforestation
Wbc	Waterbody creation
Wbr	Waterbody retention
Wel	Wetland loss
Wg	Wetland loss: habitat gain
Wl	Wetland loss: high impact
Wr	Wetland retention

LEGEND D: VEGETATION TAXA GROUPS

CH	Carnivorous herbs
G	Graminoids
GH	Geophytic herbs
H	Herbs
HS	Succulent herbs
LS	Low shrubs
PS	Pseudocarnivorous shrubs

SS	Succulent shrubs	**ST**	Small trees
SSr	Semi-parasitic shrubs	**TS**	Tall shrubs

CHAPTER 1 GAUGING THE EFFECT OF LANDSCAPE CHANGE

Landscapes are what people observe about their surroundings: how the observable is structured, populated and altered over time. Human agency is pivotal in altering the appearance and functioning of landscapes. It is therefore imperative that geographical research pays close attention to how particular or critical landscapes function and how the changing footprint of human occupation and utilisation of landscape resources affect their functioning – often to the detriment or enhancement of sustainable human quality of life. This introductory chapter briefly explores the concepts of landscape and land cover before formulating the research problem, aim and objectives. The study area is described and the research methodology and data sources are explained. The chapter concludes with a research design and exposition of the structure of the thesis.

1.1 LANDSCAPE AND LAND COVER

The concepts landscape and landscape function have different meanings depending on the context or disciplinary field in which they are used. This section clarifies these terms. Because change in land cover is the main agent of change to landscapes, it is discussed first, before focusing attention on the problem of land cover change in the Koue Bokkeveld[1].

1.1.1 Landscape and its functions

Landscape is semantically adapted depending on the context of study (e.g. ecology, management) in which it is referred to. Green, Simmons & Woltjer (1996) define landscape as a specific arrangement of topography, land use, settlement and vegetation cover patterns which demarcates some consistency of cultural and natural activities and processes. This concise yet apparently exhaustive definition is adopted for this research.

Landscapes consist of many elements that interact with each other and the interaction of these landscape elements circumscribes landscape function (Mladenoff 2011). Landscape function is the

[1] The Koue Bokkeveld (two words) is a region in the Western Cape province of South Africa and spelled as such throughout the thesis. The designation Kouebokkeveld (one word) appears as qualifier in several SANBI vegetation types and this spelling is adhered to in that context.

services that landscapes provide to humans and they include the provision for biological diversity, recycling of nutrients, sequestering of carbon or producing clean water. Two types of landscape elements determine landscape function, namely functional or structural elements (Farina 2000; 2006) elements. Structural elements include topography, drainage lines or rivers and land cover, all of which are directly observable. Functional elements are calculated elements such as run-off potential, biodiversity and carbon storage or sequestration. For example, "Carbon sequestration refers to the provision of long-term storage of carbon in the terrestrial biosphere (soil and organisms) – or the oceans, so that the build-up of carbon dioxide concentration in the atmosphere will reduce or slow down" (EPAW 2007: 2). Carbon sequestration is measured in carbon credits signifying storage capacity. Carbon is a greenhouse gas with a wide-ranging climate changing effect, so the ability of a landscape to store carbon away from the atmosphere is functionally important (Dawson & Spannagle 2009). Increased carbon storage in the landscape means reduced carbon dioxide that traps radiated heat in the atmosphere.

1.1.2 Land cover change

Land cover is the most visible (hence structural) element in a landscape, implying that change in land cover affects other elements and functions of the landscape, for example run-off and biodiversity patterns. Elements such as topography might determine the type of land cover in a landscape. For instance, agricultural cultivation will be more likely in a valley bottom than on the mountaintop. Temporal change in land cover is an often-studied topic, because change in land cover can have vital economic, social and biodiversity implications for an area.

Land cover change caused by human interference is the main force impacting the world's landscape alterations. Agricultural, mining and settlement development can fundamentally change the functions and structure of landscapes, both positively and negatively (Farina 2000; 2006). Land cover change affects landscape functions – clearing of a forest lowers the carbon storage of a landscape and reforestation increases the carbon storage, as well as providing new habitat. These development dynamics can be recorded by various methods of change detection over time.

Since humans have caused the disappearance of many species from ecosystems, the restoration of the natural habitat (a structural alteration) can increase biodiversity (a function) (Vermeij 1986). However, to preserve the biodiversity of an area, discernible habitat areas must be fragmented as little as possible to allow unimpaired movement of species as would be the case under reference (stable, original, pristine) conditions. The amount of landscape or habitat fragmentation can be determined by performing vegetation pattern analysis.

Change in land cover can also influence hydrology by altering the run-off from and inside an area's physical boundaries (Shi et al. 2007; Troy et al. 2007; Choi & Deal 2008). Such change in run-off (notable increases or decreases) can affect human activities (e.g. agriculture) and natural ecological conditions (e.g. river systems) downstream from the change occurrence. Detection of a real or potential change in run-off should alert users and authorities to the need for further research.

1.1.3 Fynbos under threat: A highlands concern

The concern about the prospects of the unique fynbos vegetation kingdom permeates SANBI's so-called 'vegetation bible' of Mucina & Rutherford (2006). Fynbos in the Western Cape has been and remains under constant and escalating threat from invasion by alien vegetation, agricultural and urban development. The Western Cape has a moderate climate suitable for the cultivation of orchards, vineyards, vegetables and wheat which all provide excellent economic opportunities. Consequently, agriculture, for example, has already replaced more than 90% of all lowland renosterveld in the Western Cape.

This degradation also manifests in the highlands region of the Koue Bokkeveld, where renosterveld and other fynbos, especially wetlands, have been replaced by agriculture. The Koue Bokkeveld covers a mountainous region with interspersed valleys where different types of fynbos occur at different heights and on various geological outcrops, hence not all types of fynbos are similarly at risk. The sensitivity of the Koue Bokkeveld as a region is enhanced by its drainage through three primary catchments in which potential change in run-off regimes can have wide-ranging effects inside and outside the regional borders. Changes in run-off not only affect the agricultural and related industries in the dependent settlement framework, but riverine habitats downstream from the region are also prone to serious ecological damage.

There is a dearth of research on the landscapes and land cover change in the region. Some research on the Koue Bokkeveld has focused on spatial and related variance in crop production in the region but not on change detection as such. Furthermore, the spatial foci have been fragmented at best. Earlier, Conradie (1942) reported on agricultural production modes in the area as a whole and predicted (correctly as it turned out) that perennial agriculture would increase because of the new refrigeration technology then being introduced. Honours-level research (Richards 1999; Heyns 2000; Tesfamariam 2000) has probed smaller subregions of the Koue Bokkeveld to record land cover change. At master's level, Fourie (2005) analysed aspects of landscape aesthetics and Donald (2005) performed a landscape fragmentation analyses – both experimentally and for a small sub-region of the Koue Bokkeveld. Vos (2009) more recently confirmed cropland expansion over the whole region, but did not subdivide natural veld into the various vegetation classes exposed to change, so failing to comment on the impacts on communities variously exposed to change and risk. The explanatory effects and determining roles of geographical factors, such as topographic variation, on land cover change and landscape functions in the Koue Bokkeveld have not been studied at all. The natural vegetation of the area is a rich and well-adapted assembly of fynbos, about which more is explained in Section 1.3.

1.2 RESEARCH PROBLEM, AIM AND OBJECTIVES

The introduction has sketched some critical issues worthy of regional investigation. This section narrows these issues to an operational research problem, formulates the research aim and stipulates a number of research objectives.

1.2.1 Research problem

The expansion of agriculture in the Koue Bokkeveld has replaced and displaced a range of natural systems salient among which are various natural vegetation communities and wetlands. Because the region's mountainous nature, diverse landscapes offer different potential for agricultural development, for example natural vegetation on steep mountainsides is much less exposed to replacement by agriculture than that on plains. The Koue Bokkeveld is a species-rich fynbos region (DEAT 2005) where some species are endemic (Rebelo & Low 1996; Mucina & Rutherford 2006; Rebelo et al. 2006). This species richness, endemism and limited spatial occurrence of stands of some species, signal that catastrophic extinctions of species may occur if land cover changes. The *Erica greyi* of the Koue Bokkeveld was thought to be extinct for almost a century but was rediscovered recently (Meintjes 2008; Pekeur & Stoll 2009). Aside from exterminating some species, cropland development has also deleteriously fragmented natural vegetation communities in the Koue Bokkeveld. The 'edge' effect diminishes species richness in smaller patches of vegetation and places some vegetation communities at greater risk than others.

A related question is how the expansion of agriculture affects the structure and the functioning of landscapes. Elements of landscape structure affected by land cover change are land cover pattern and morphology. Three landscape functions potentially affected by land cover change, namely biodiversity maintenance, carbon storage and run-off production are selected for attention in this study. Furthermore, the catchments in the Koue Bokkeveld are topographically diverse so that the land cover varies and the changes in land cover are variable. These variations call for analysis and understanding so that the threats can be identified and remedial actions launched to safeguard the natural heritage of the area while fostering sustainable development.

The following questions arise from the research problem: What is the historical variation in the nature and extent of land cover types? What trends punctuate land cover changes in the region?

How is the landscape structured morphologically, and what explanatory and development implications does it have for sustainable land use? How does the change in land cover affect various landscape functions? Each of these questions has a rider: how do trends and characteristics differ among the various catchments and subcatchments?

1.2.2 Research aim and objectives

The research aimed to detect, capture, record and classify the spatial nature, extent and change dynamics of various landscape elements and functions due to change in land cover, allowing the determination of its effects on landscape functioning in the Koue Bokkeveld. The research will reach this aim by pursuing seven objectives as distinctive steps to yielding traceable deliverables. They are:

- Assemble a full spatial database for the study region from both primary and secondary sources by digitising/scanning and georectification of source imagery and maps into an electronic landscape mosaic ready for analysis.
- Create land cover maps for three historical time slices, namely pre-development (colonial or 'reference state' approximating the status in 1700) based on SANBI natural vegetation zonation; pre-modern (1949) land cover reconstruction, and current (2009) patterns (the latter from the assembled data). Conduct land cover change analyses for the interim periods.
- Create morphological landscape images for height above sea level, slope, aspect, drainage and hydrology networks, landforms, and slope position for the region using the digital elevation model (DEM).
- Use land cover and landscape morphology to determine, explain and understand the historic trends in the location of land cover types and those in change patterns and landscape function.
- Analyse the hydrological functioning of catchments through flow accumulation, flow direction and calculation of run-off potential.
- Perform landscape pattern analyses (patch size, patch density) for the historical periods and, by comparison with the SANBI vegetation base map, speculate on the effects of land cover change on biodiversity.
- Analyse carbon storage potential in the region for the different historical periods.

For achieving these objectives, the delimitation and the unique character of the study area need to be comprehended and hence a regional overview of the Koue Bokkeveld follows to provide a solid backdrop to the empirical research unfolding thereafter.

1.3 THE STUDY AREA

The study area is located north, north-east and east of Ceres in the Western Cape, South Africa (Figure 1.1, reproduced larger as Figure C1 as an appendix). Five major upland valleys among

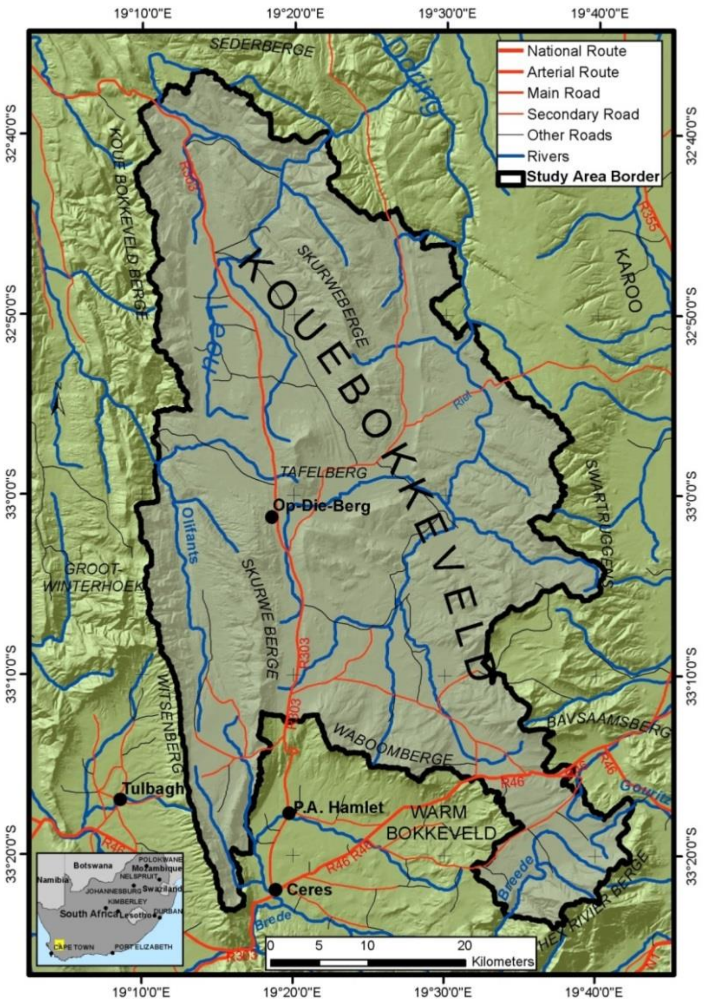


Figure 1.1 The location of the study area

rugged surrounding mountains designate the watershed between three large river systems. The study area covers an area of 247 210 ha. The landscape is complex regarding a number of defining characteristics: geology and topography, climate and hydrology, vegetation typology, development patterns and history. These features are explored in the following sections.

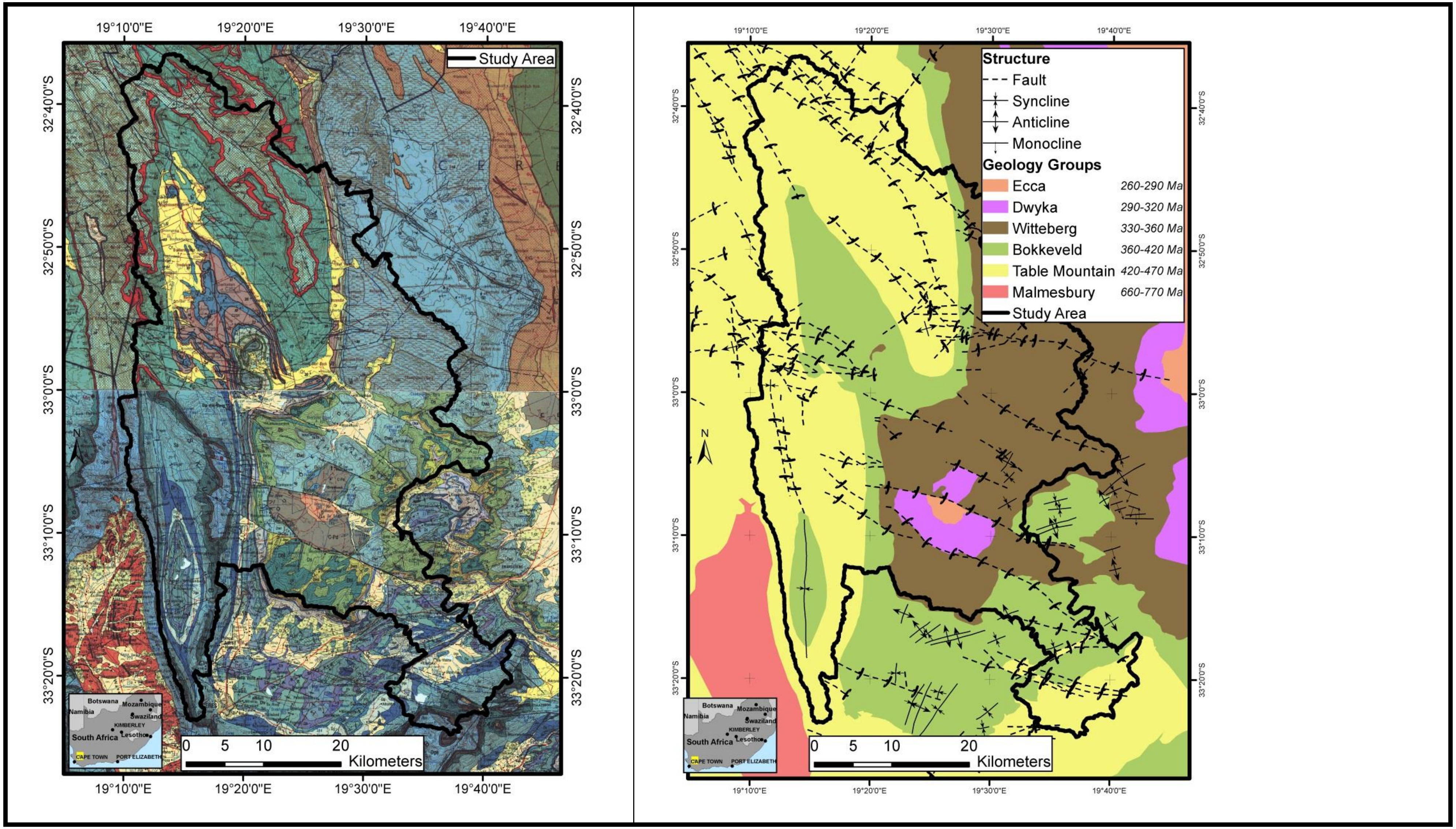
1.3.1 Geology and topography

The Koue Bokkeveld highland topography of fold-mountain ranges and interlinked valleys is explained geologically by Thamm & Johnson (2006) as crustal folding due to rising of the earth's crust after a period of extension which formed the Cape Fold Belt when the crust thickened through compression caused by a nearby subduction zone. The oceanic plate at the southern edge of the

Gondwana supercontinent subducted beneath the continent, lifting and compressing the continental crust and forming the fold belt. The Cape Fold Belt comprises the Cape Super Group sedimentary rocks deposited as sediments on a lake bottom that formed during the extension period. During the folding and compacting processes, the sediments solidified into rocks. After the folding, the rocks at the surface were eroded so accounting for the sand and clay deposits in valleys on the surface. Sandstone (slower) and shale (more readily) undergo different rates of erosion so that, together with folding, erosion created the present-day valleys. Clearly, normal erosion processes are continuously active today cutting valleys, eroding mountains and hills and transporting sediments to the sea (Johnson, Anhaeusser & Thomas 2006).

Figure 1.2a shows the detailed geology of the Koue Bokkeveld and the main geological groups surfacing in the Koue Bokkeveld are delimited as polygons in Figure1.2b. Table Mountain sandstone, Bokkeveld shale and the Witteberg shale and sandstones form the members of the Cape Supergroup dominating the area. An important anomaly is evident in the south-central part of the study area where two members of the Karoo Supergroup (Dwyka tillites and Ecca shales) make unexpected and island-like appearances. It is noteworthy that the coarsely-structured, well-drained, nutrition-poor, white, sandy soils and alluvium along the river courses are derived from Table Mountain formations in the west. Towards the east, the valley bottoms are mainly covered by sandstone-shale sediments from the Witteberg Group, a combination that forms soil of a clay-rich consistency. The Bokkeveld shales and Karoo formations generate reddish, fine-grained, poorly drained, more nutritious soils. These geological distributions are especially important because of their controlling influence on resultant soil types and the vegetation types growing on them under the influence of climate variability.

The Koue Bokkeveld landscape is topographically characterised by a number of mountain ranges (named in Figure 1.1) that are part of the Cape Fold Belt stretching north-south in the west and east-west in the south. The western regional border of the Koue Bokkeveld is formed by the Skurweberg and Koue Bokkeveld ranges in the west, the Witsenberg in the south-west and the Hexriver Mountains in the south-east. The latter range is an oblique exponent of the syntaxes zone between the western and southern fold belts. In the centre and eastern parts the Waboomsberg, Baviaansberg, eastern Skurweberg and the Swartruggens form mountain masses that define the landscape. The mountains are pronounced, reaching 2249 m at Matroosberg in the Hexriver range (highest peak in the western part of the Western Cape province), and well above 1800 m MSL for a number of peaks in the northern and central ranges. The highest point in the area is over 2 200 m in altitude, the lowest point is only about 350 m high and the mean height is 1080 m. Local relief



Sources: CGS (1997); DM (1973)

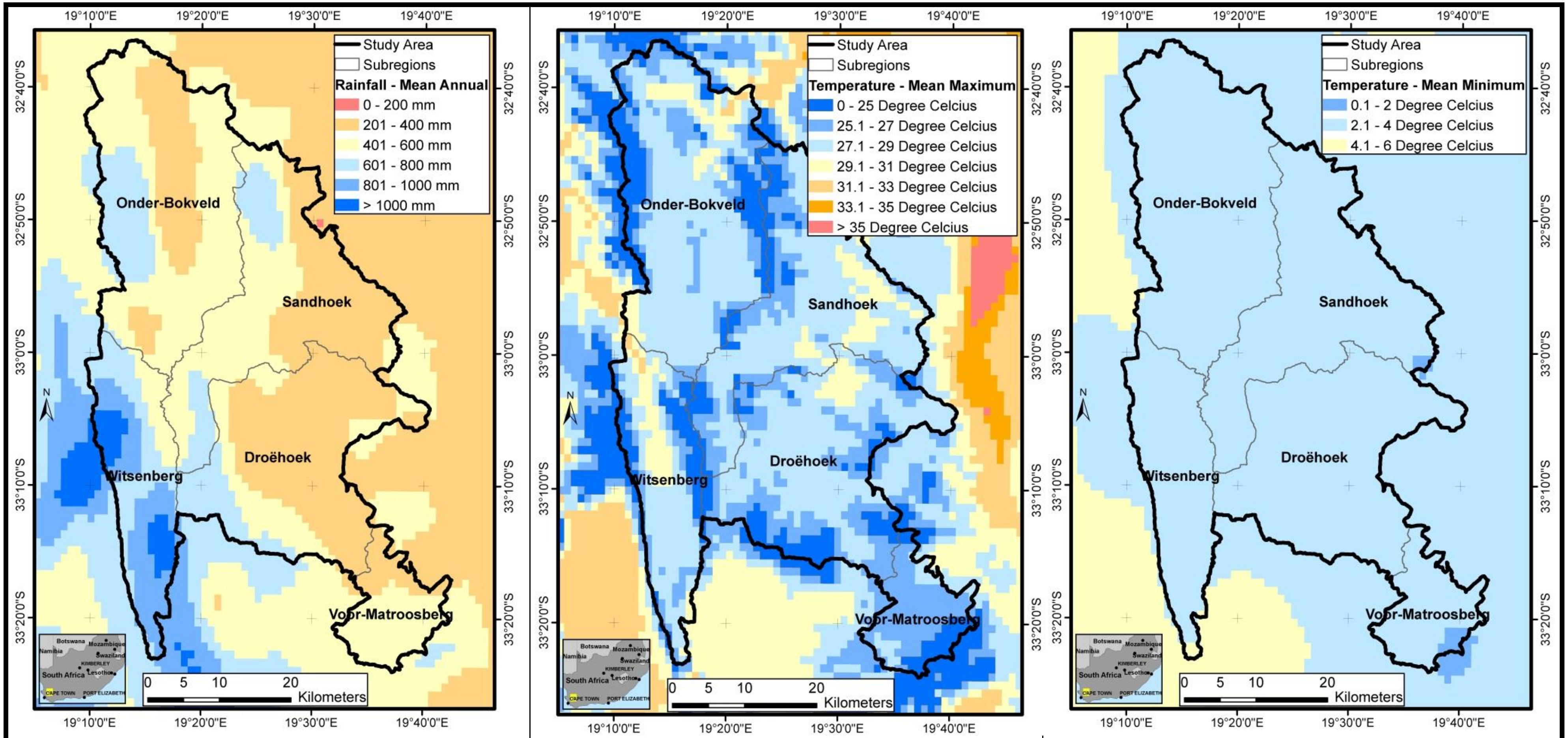
Figure 1.2 Koue Bokkeveld geology: a) Detail; b) Generalised main features (height difference between highest and lowest points locally) averages 700m, so characterising a fairly dramatic landscape morphology.

Road access to the Koue Bokkeveld is via a number of mountain passes of variable importance, surface character and capacity. The most important ones link the Koue with the Warm Bokkeveld (the latter region is formed by the lower-lying Ceres basin to the south), namely the Gydo, Swaarmoed and Theronsberg passes. The Hottentotskloof and Katbakkies passes provide access to the interior Karoo to the east and the Middelberg pass to Citrusdal in the north.

1.3.2 Climate and hydrology

Topography determines climate variability in the Koue Bokkeveld. Rainfall has a distinctive west-east shadow effect – linear to north-south-stretching mountain ranges – of diminishing precipitation: from relatively high in the south-western mountain ranges (>1000 mm/a) to quite low in the east (200-400 mm/a), as Figure 1.3a indicates. This steep range from well-watered western mountainous locations to near-desert, interspersed eastern valleys attests to severe climatological variation. The accompanying variability is exacerbated locally by microclimatic effects due to topographic influences. Temperature variation is similarly accentuated by height above sea-level: Maximum temperatures (Figure 1.3b) are notably lower along high-lying mountain ranges, although still rather balmy compared with the hot, more easterly low-lying valleys and plains. The average maximum for the Koue Bokkeveld is below 30°C in the major agricultural areas, making the farms here high-yielding perennial crop producers. The cooler night-time temperatures in summer favour red-apple production (red colouring towards the end of summer requires relatively cool conditions) not readily obtained elsewhere.

The region's name (literally Cold Bokkeveld), becomes evident from the image in Figure 1.3c that shows the almost constant near-freezing average minimum (winter) temperatures. Snowfall occurs fairly regularly on the mountains in winter and, on average, several times a year in the interspersed valleys too. These low winter temperatures are conducive to perennial agriculture because they afford fruit-bearing trees the proper 'resting' period required to ensure good yields. The Koue Bokkeveld's temperature regimes are punctuated by very low winter averages (regular occurrences of frost and snow) and relatively high summer temperatures. The warm summers and cold winters are conducive of perennial agriculture (mainly deciduous fruits like apples and pears). The region has a climate with distinctly winter rainfall and low temperatures that ensure rainfall efficiency allowing run-off to be generated for storage, followed by long (six months), dry summers when crops have to be irrigated.



a) Mean annual precipitation b) Mean annual maximum temperature c) Mean annual minimum temperature

Source: Derived from AGIS (DA 2007)

Figure 1.3 Climate indicators: Precipitation and temperature

Five pronounced, broad valley-subregions interrupt the mountain chains (see Section 2.2.5) and accommodate the headwaters of three primary river basins – the Olifants/Doring, Breede and Gouritz Rivers (see Figure 1.1). In the west of the study area the headwaters of these rivers are mostly perennial – especially higher up in the mountains, but streams in the central and drier eastern region only flow periodically. It is noteworthy that the region's rainfall is generally relatively efficient owing to its winter character. In winter, considerable amounts of run-off are generated in the mountain ranges and these are captured through ingenious private water-storage schemes with large reservoirs for irrigation during the dry summers. Irrigation dams are a conspicuous surface feature of the regional landscape.

1.3.3 Vegetation patterns

Natural vegetation, defined as "the grouping of plants which has developed in an area without human interference" (Mayhew 2004: 346) constitutes the original land cover of an area. It provides the habitat for all naturally-occurring faunal and insect species. Fynbos (explored in greater detail in the next subsection) is the natural vegetation of the Koue Bokkeveld. It is species rich with a large number of indigenous species, uniquely biodiverse and is threatened virtually everywhere. Because wetlands are similarly species rich, they are also severely threatened and hence treated here as a separate landscape element.

1.3.3.1 Fynbos vegetation

This section draws heavily on Mucina & Rutherford (2006), although several other sources have contributed towards an understanding of the diversity of the Cape Floristic Region (Rebelo & Low 1996; Cowling, Proches & Partridge 2009), mountain fynbos and Renosterveld (McGinley 2008), critical species endangerment (SANBI 2009a) and the rediscovery of seemingly lost species in the area (see Meintjes (2008) and Pekeur & Stoll (2009) about *Erica greyi)*.

The fynbos biome consists of three vegetation types: Renosterveld, fynbos and strandveld, the first two being fully represented in the study area. Fynbos is fire dependent for procreation of the plants, requiring a fire frequency with 5-50-year intervals, but it survives the shortened frequency of 15 to 20 years that often prevents full species richness to develop (Mucina & Rutherford 2006). Studies on local environmental problems such as river health (RHP 2006) and fragmentation of Renosterveld (Kemper, Cowling & Richardson 1999; Walton 2006) provide helpful insights into these issues. More detail on the species distribution patterns and the impacts on them are explored later. Suffice it here to point out fynbos prominence and vulnerability.

Historically, larger animals (>20 kg) like elephant, black rhinoceros, eland and hippopotamus roamed the lower-lying areas of the Koue Bokkeveld. Today, due to extensive agricultural cultivation, only small game and the odd mountain leopard are found in the wild. This aspect of natural life is not pursued in this thesis. Several laws enforce preservation of ecosystems in South Africa: the Conservation of Agricultural Resources (CARA) (DA 1983) and the National Environmental Management: Biodiversity Act (Act 10 of 2004). The CARA (Act 43 of 1983) imposes a limit (20% slope) above which no cultivation is allowed (Mucina & Rutherford 2006; South Africa 2009). The relevance of some of these laws in managing the environment in the Koue Bokkeveld is raised where applicable in this work.

1.3.3.2 Wetlands

Like natural vegetation, wetlands provide landscape functions and they are important contributors to vegetation and faunal species biodiversity. Wetlands are variously called marshes, swamps, bogs, wet meadows, potholes, sloughs, and river-overflow lands and they are defined depending on the purpose of their use (United States Environmental Protection Agency (EPA) & United States Department of the Army 1990; Kent 1994; Oellermann et al. 1994; DWAF 2005). In this research the Ramsar Convention Secretariat (2006: 1; 2007: 1) definition is adopted:

> Wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by shallow water…areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres and may incorporate riparian and coastal zones adjacent to the wetlands.

Cowan (1995) has created a useful classification of South African wetlands by region, but Richards (1999), Heyns (2000), Tesfamariam (2000) and Vos (2009) have gone further by dividing the Koue Bokkeveld wetlands into mappable categories this research has accepted, namely wetland channels, wetland flats, clear-water dams and turbid-water dams.

Many plant and animal species depend on wetlands as vital habitat, making them some of the world's most productive environments that contain high concentrations of species (Ramsar Convention Secretariat 2006; 2007). In combination with the presence of fynbos in the region, the wetlands acquire exceptional importance owing to the overall species richness. Wetlands perform vital ecological functions regarding its biological, physical and chemical components of water, animals, plants and soils (Ramsar Convention Secretariat 2006; Zhoua, Gong & Liu 2009).

Ecological services of wetlands include water storage, ground water recharge, flood negation, storm protection, retention of pollutants, nutrients and sediments and water purification. Local climatic conditions, for example temperature and rainfall, are even stabilised by wetlands (Ramsar Convention Secretariat 2006). Economic benefits include the capacity and quality of water supply, tourism attraction, recreation and wildlife resources, peat and plant material as energy sources and fish harvests. Inevitably there are various threats to wetlands, namely climate change, chemical pollution, invasive plants (Cowan & Van Riet 1998), eutrophication (Rossouw, Harding & Fatoki 2008) and land use and/or land cover changes (Winter 2000). In the Koue Bokkeveld, agriculture has or is directly replacing wetlands and indirectly the wetlands are threatened by organic and inorganic pollution (Cowan & Van Riet 1998; Tesfamariam 2000). Wetlands in the Koue Bokkeveld are converted to agriculture and are channeled to aid drainage for cultivation. These wetlands may be uniquely different from those in the rest in the Western Cape, but they are not Ramsar recognised due to relative smallness. Despite this oversight, wetlands in the Koue Bokkeveld must be surveyed to identify the threats and to determine their effect on landscapes and their functioning.

1.3.4 Historical development pattern

The study area was occupied sparsely by itinerant, frontier European stock farmers from the early 1700s. The traveller Lichtenstein (1812: 128) provides a unique contextual peek at the study area in the early 1800s:

> The soil is fruitful and is richly watered with plentiful springs, while it bears excellent corn and fruit of every sort, even some fruits that will not usually thrive in African climates. Sheep, cattle and horses are abundantly supplied with wholesome food, and the murrain (redwater fever), so destructive in other parts, never intruded itself into this delightful retreat.

The climate and sandy soils of the area are eminently suitable for the cultivation of vegetables like potatoes and deciduous fruit like apples. By the 1940s, fruit orchards had become established and began to replace the dominant wheat fields and stock-farming in the area (Conradie 1942; Van der Merwe 2008, Pers com), along with vegetables such as potatoes, onions, gem squash, beans, tomatoes and cucumbers. The expansion of the more profitable crop cultivation in the area had replaced the less profitable stock-farming and mixed farming for some time (Conradie 1942).

Fruit cultivation (orchards) has expanded vastly in the Koue Bokkeveld and includes deciduous (apples and pears) and stone fruit (peach, plum and cherry) orchards. Annual agriculture has expanded to include more types of vegetables cultivation under centre-pivot and mobile irrigation systems (Van der Merwe 2009a, Pers com). Improved agricultural technology (micro irrigation, fruit refrigeration, packing and drying) and farming methods have boosted production over the past half century.

The only urban settlement of note in the Koue Bokkeveld is the small town of Op-die-Berg in the centre of the study area. It is essentially an agricultural service centre and agrivillage established some 50 years ago and still houses only about 1 500 people. Total population of the Witzenberg local municipality, in which the Koue Bokkeveld largely falls incongruously, reached 115 946 (10.78 per km^2) in 2011 (Witzenberg Municipality 2013) and this rural subregion (including Op-die-Berg) accounted for some 11 000 of the total. The region is rightfully regarded as a valuable agri-production and rural population nucleus.

Having introduced the study area (where), the question of how the research had been done can be overarchingly addressed next.

1.4 RESEARCH METHODOLOGY, METHODS AND DATA

To achieve the objectives of the research, an exacting methodology incorporating the methods of data gathering and data preparation were followed to ensure the validity of the quantitative analyses. A range of remotely sensed observation materials were accessed and used following the application of preparatory procedures. These are described in the next sections to confirm the integrity of the methodology, methods and data used.

1.4.1 Research methodology and design

In agreement with Van der Merwe & De Necker (2013) this introduction to the methodology of this research refers to the theoretical paradigm or framework in which the work was conducted. The study was broadly approached from a synoptic perspective, considering spatio-regional land cover scenarios as three time slices and then longitudinally considering and analysing the spatial patterns that had become established between these synoptic views. The research was based on a quantitative paradigm and methods as depicted in Figure 1.4. It comprises five components:

- A spatial data base containing various secondary spatial data sets as well as primary remotely sensed imagery that were sourced, georeferenced, manipulated and mosaicked;
- Classificatory land cover mapping and quantification for three time periods (reference state, 1949 and 2009) performed on the base materials;
- Calculation of spatial landscape morphological parameters (catchments, structure and landforms) from the 20 m-DEM;

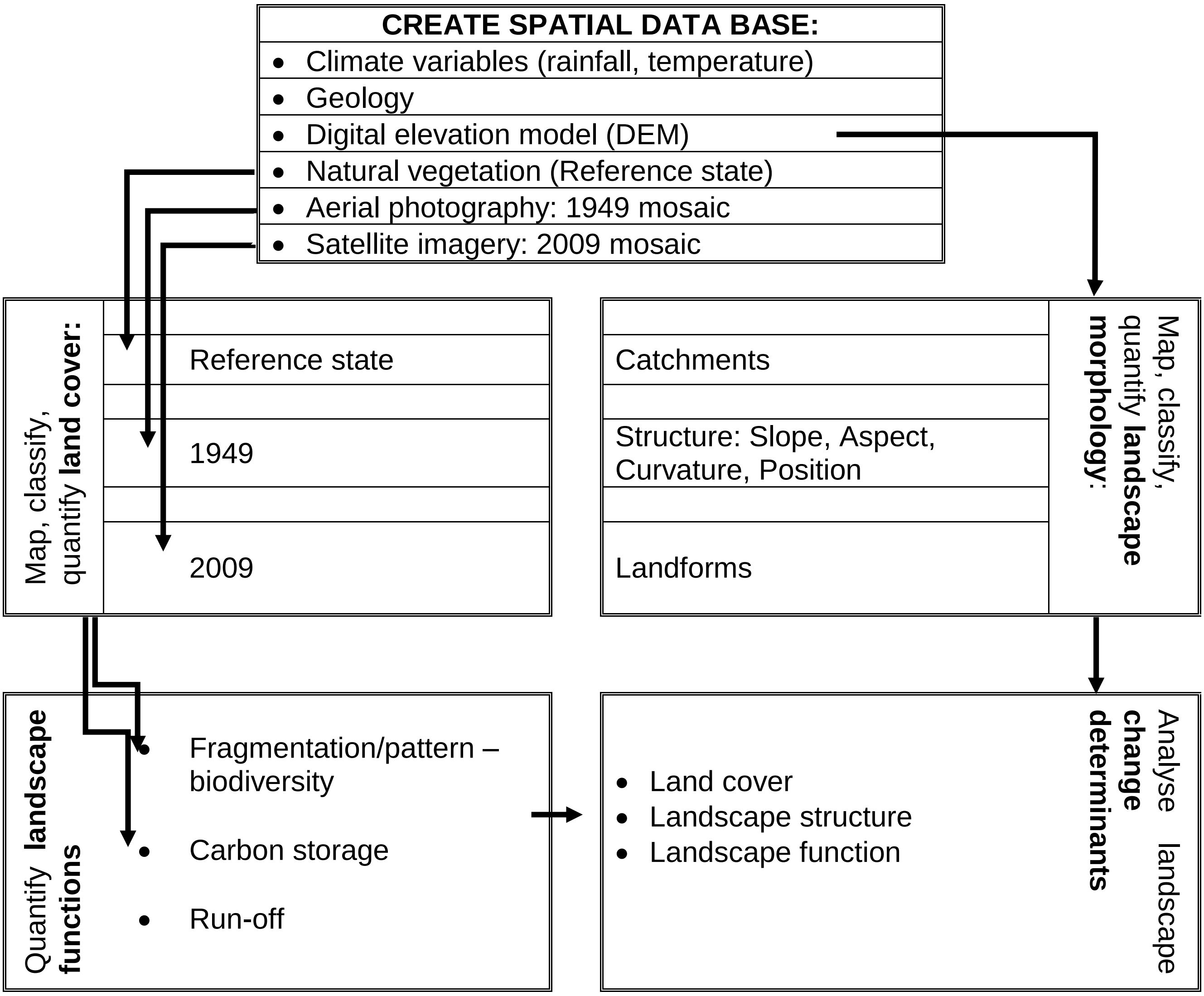


Figure 1.4 Research data and project design

- Derivation of spatial landscape functional parameters (run-off, fragmentation and carbon storage) from the land cover images;
- Change scenarios were backdropped against explanatory topographical and morphological variables to gain insights into the land cover change process and its implications in the region.

The work relied heavily on formal spatial analytical techniques in a geographical information system (GIS) and map analyses of environmental features as recommended (Rebelo, Finlayson & Nagabhatla 2009). Assumptions and theoretical frameworks and approaches related to landscape analysis were developed and the research was structured according to research questions rather than hypotheses.

The next section describes the data sources accessed and data manipulation procedures followed. The overarching approach and types of methods are highlighted, while the detail of each method is preserved for explanation at the relevant thematic section of the text where it is directly relevant.

1.4.2 Data gathering and manipulation

A wide range of landscape-related data and concepts is relevant to this research, so sources are introduced in this chapter and are added to in sections where they apply in more detail. The Internet, through the various university-based search engines and internal, licensed media, was the main medium used to find databases, journal articles and websites. The web-based *South Africa rain atlas* (Zucchini, Nenadić & Kratz 2003) provided climatic data with a spatial component. Downloadable maps were sourced from the AGIS website, and run-off data from the HIS website (DWA 2008). Aerial photographs, satellite images, maps and books were also sourced and so referenced. The following subsections give accounts of the Internet sources, the spatial data sources (general, aerial photography, satellite imagery) used and how the spatial data were manipulated. During this research a large range of media sources was accessed and consequently the discussion focuses on literature and the various spatial data sources separately.

1.4.2.1 Internet sources

Google Scholar offered excellent tools for an initial literature search as it accesses the Internet and databases like J-Store and Science Direct. In Google Scholar, the starting date limits were set at 2000 (and later). The JS Gericke Library at Stellenbosch University and its resources website gave access to J-Store, Science Direct, GEOBase, PROQest and Ebscohost and ranges of electronic journals, after which source mining was done to generate new information. Besides the keywords listed in the Abstract, the following terms and functional combinations were used in searches: wetlands, wetland degradation, landscape, landscape patterning, landscape ecology, mountain landscape, natural vegetation of Western Cape South Africa, Koue Bokkeveld, land use change, Western Cape natural vegetation conservation, Western Cape endangered species, morphology, landscape modelling and agricultural landscape. The salient sources used to substantiate and benchmark results are referenced in the applicable sections of the thesis.

1.4.2.2 Spatial data sources: General

Spatial data contain indicators of spatial location of objects or areas of interest (Mather 2009). A range of spatial data sources, both analogue and digital, were used in this research. Table 1.1 lists the relevant information about the nature of the sources: type, provider, resolution, date and scale. Additional technical information on the aerial photography and satellite imagery not discussed here

Table 1.1 Overview of spatial data sources

THEME/ FORMAT	ID	dpi	Scale	Colour	Resolution (m)	Date	Provider
Aerial photographs	Job 226	360	1:18000	Panchromatic	1.27	Dec 1948 - Mar 1949	Directorate of Surveys and Mapping
	Job 225	600	1:30000	Panchromatic	1.27	Jan 1949	
SPOT scenes	J/K 119/417			Panchromatic	2.5	2008/11/20	SAC
				Multispectral	10		
	J/K 119/416			Panchromatic	2.5	2008/11/20	
				Multispectral	10		
	J/K 120/417			Panchromatic	2.5	2008/12/21	
				Multispectral	10		
SPOT mosaic	3219C			RGB	2.5	2006	
	3219D						
	3319A						
	3319B						
	3219C					2008	
	3219D						
	3319A						
	3319B						
Topographic Maps	3219CA		1:50000	Four-colour (digital version)	N.a.	Latest	Directorate of Surveys and Mapping
	3219CB						
	3219CC						
	3219CD						
	3219DA						
	3219DC						
	3319AA						
	3319AB						
	3319AC						
	3319AD						
	3319BA						
	3319BC						
DEM					20		CGA
Geology			1:250000	Analogue			CGS
Vegetation			1:250000	Digital			SANBI
Temperature				Analogue			SAWS
Rainfall map							AGIS
Rainfall							DWA/HIS/SAWS/ SARA
Run-off (text file)							DWA/HIS

is provided in Appendices A and B respectively. The digital elevation model (DEM) used for this research has a 20 m resolution and was provided by the Centre for Geographical Analysis (CGA), at Stellenbosch University. Soil maps were downloaded from the Agricultural Geo-referenced Information System (AGIS) website or were ordered from the Department of Agriculture, Fisheries and Forestry (DAFF), but because they covered limited areas only they served no useful function. A comprehensive spatial database was compiled, requiring elaborate engagements to ensure data quality, including digital capture of analogue materials, georeferencing, and preprocessing of purchased imagery covering three time slices for the area. Functional analyses required additional information on run-off, carbon storage and pattern analyses – the latter using GIS functionality. The potential run-off was calculated for the region for the different periods to determine the effect of land cover change on run-off regimes in the area. Carbon storage was analysed rather than carbon sequestration. Pattern of the land cover and their effects on biodiversity were analysed using fragmentation indices derived from the land cover patterns.

1.4.2.3 Spatial data sources: Aerial photography

In South Africa, aerial photography normally offers the only means to reconstruct historical land cover prior to the early 1970s (Lyon 2001). The photographic negatives and paper copies degrade over time, but while still usable, are irreplaceably valuable archival documents. The 1949 photographs were faded or damaged towards the edges, so that some of the fiducial marks were invisible, but the rest of the images remained clear. Jobs 225 and 226 have different scales but compensation was made during preprocessing. The aerial photographs – 9x9 inch (23cmx23cm) photographic paper copies – were scanned electronically on an A3 flatbed scanner for computer analysis of the imagery. Differential scanning resolutions standardised the imagery to a high ground resolution of 1.27 m. Images were geo-rectified through the Leica Photogrammetry Suite (LPS) to orientate them to an accurate spatial coordinate system. LPS uses a bundle block adjustment that minimises errors between photographs. Ground control points (GCPs) effected ground referencing (LGGI 2005).

Given that the fiducial marks were absent from some photographs, the ‘frame camera geometry’ option could not be used, but rather the ‘non-metric camera’ option. The frames of the photos were removed using an image editor. The SPOT 2006 mosaic images served to source the horizontal GCPs. The vertical GCPs were obtained from a 40-metre resolution DEM. The root mean square (RMS) error for the rectification presses was a satisfactory 0.45 metres. The photographic imagery was rectified using ERDAS Imagine software.

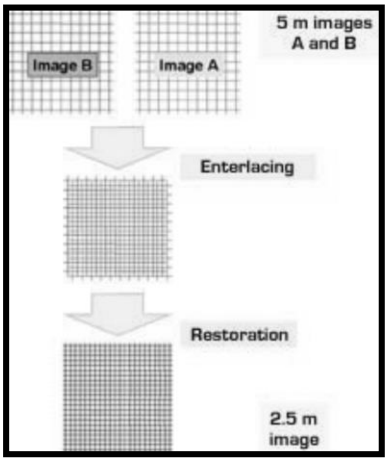
1.4.2.4 Spatial data sources: Satellite imagery

The Satellite Pour l’Observation de la Terre (SPOT) (Mather 2009) was selected owing to its gratis availability from the Satellite Application Centre (SAC) and its high ground resolution. SPOT sensors capture an image of the earth’s surface, requiring the raw data to be customised for each user (Spot Image 2005). Table 1.2 presents the different resolutions and spectral bands of the SPOT5 imagery that was used. The SPOT5 panchromatic sensor has a five-metre spatial resolution, that can be refined to 2.5 metre panchromatic imagery through the SPOT5 supermode® tool. Figure 1.5 shows the supermode image creation process when two 5 m images with a 2.5 m offset are combined to form one supermode image (Mather 2009; SPOT Image 2009). This process applied in this research as well.

Table 1.2 The resolutions and spectral bands of the SPOT images

Sensor	Electromagnetic Spectrum	Pixel Size (m)	Spectral Bands (µm)
SPOT 5	Panchromatic	2.5 or 5	0.48 - 0.71
	B1: green	10	0.50 - 0.59
	B2: red	10	0.61 - 0.68
	B3: near infrared	10	0.78 - 0.89
	B4: mid infrared (MIR)	20	1.58 - 1.75

Source: Spot Image (2005)



Source: SPOT Image (2009)

Figure 1.5 The process flow to create SPOT 2.5 m-images.

The different SPOT5 products are listed in Figure 1.6 with their processing levels and geometrical and locational accuracies given (SPOT Image 2008). This information makes it clear that positional accuracy determines which imagery to use for specific purposes. Level 1A images were chosen for this study to identify the land cover in 2009, because they are most suited for classification using the available software, that is, they are multispectral and panchromatic and can be used for supervised classification, unlike aerial photographs that must be classified by manual digitization of class boundaries.

The sequencing of the preprocessing of the aerial photographs and satellite images is shown in the Figure 1.7 diagram. It demonstrates the similarity in procedures to follow between aerial photography and satellite images. LGGI (2005) describes the different geo- and orthorectification processes in LPS. The reflectance and radiance calculations remove the effect of the earth’s surface and sun on the image. Mather (2009) has described radiance and its effects on satellite imagery, and the formulas given by Teillet, Markham & Irish (2006), Chavez (1996) and Landsat Project Science Office (2009) for calculating radiance and reflectance were used in this research. The necessary calculation for the earth-sun distance was obtained in Mather (2009). Methods documented by Chavez (1996) and Song et al. (2001) were used for the atmospheric correction process and the

		SPOT Scene			SPOTView		
Product	Level	1 A	1 B	2 A	2 B (Precision) with GCPs	3 (Ortho) with DEM from Reference3D	3 (Ortho) with DEM from other source
2,5-m colour	Spot 5	30 m	NA	30 m	depends on the quality of the exogenous data used	10 m	depends on the quality of the exogenous data used
2,5-m B&W	Spot 5	30 m	30 m	30 m		10 m	
5-m colour	Spot 5	30 m	NA	30 m		10 m	
5-m B&W	Spot 5	30 m	30 m	30 m		10 m	
10-m colour	Spot 5	30 m	30 m	30 m		10 m	
	Spot 4	350 m	350 m	350 m		10 m	
	Spot 1 to 3	NA	NA	NA		10 m	
10-m B&W	Spot 1 to 4	350 m	350 m	350 m		10 m	
20-m colour	Spot 1 to 4	350 m	350 m	350 m		10 m	

Source: SPOT Image (2008)

Figure 1.6 The locational accuracy of SPOT imagery

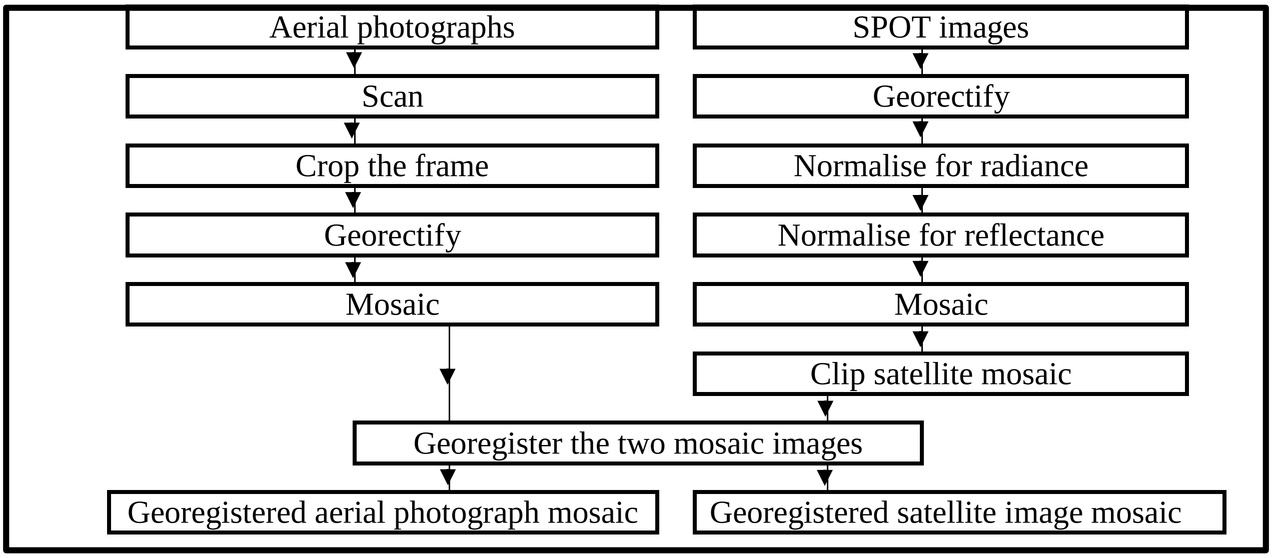


Figure 1.7 Image preprocessing methods in sequential order

improvement of classification accuracy after the application of atmospheric correction. Models for atmospheric correction given by Chavez (1996) and Engelbrecht (2005) were not required in this research since the images for given time slices were not compared.

Preprocessing of the satellite images was performed with the polynomial-based pushbroom option in the SPOT Pushbroom geometric model in LPS. The interior and exterior parameters from the header file were imported as were the GCPs from the SPOT mosaic image and DEM. Radiance and reflectance were calculated using the ERDAS model builder and Equation 1.1 was applied for the radiance calculation using the gain and bias values in the metadata file of each image.

$$L_{\lambda} = G \times DN + B$$ Equation 1.1

where L_{λ} = radiance at λ

G = gain

DN = digital number

B = bias

Source: Teillet et al. (2006)

Equation 1.2 was used to calculate the reflectance and Equation 1.3 the earth-sun distance with the ESUN values shown in Table 1.3

$$\rho_{\lambda} = \frac{\pi \times L_{\lambda} \times d^2}{ESUN_{\lambda} \times COS\theta_s}$$ Equation 1.2

where L_{λ} radiance at λ;

ρ_{λ} reflectance at λ;

$ESUN_{\lambda}$ the exo-atmospheric solar irradiance in Watts/(m^2 μm)

d the earth-sun distance in astronomical units (AU) for the date on which the image was taken, the mean distance if 1AU

θs the solar zenith angle

Source: Landsat Project Science Office (2009); Mather (2009)

$$d = 1 - 0.01674 \times \cos(0.9856 \times (JD - 4))$$ Equation 1.3

where d earth-sun distance in astronomical units for the date on which the image was taken, the mean distance if 1AU

JD 'Julian day' counting the number of days starting from January 1st

Source: Mather (2009)

Table 1.3 The exo-atmospheric solar irradiance (ESUN) values for the SPOT 5 satellite

ESUN		
	SPOT 5	
Spectral Bands	**HRG 1**	**HRG 2**
HMA/HMB	1762	1773
B1	1858	1858
B2	1573	1575
B3	1043	1047
MIR	236	234

Source: SPOT Image (2005; 2009)

SPOT has two sensors, unlike the single one onboard LANDSAT (Mather 2009). Because the HRG 2 sensor was used to capture these SPOT images, its values were used. A mosaic of the reflectance images was constructed with the mosaic tool in ERDAS Imagine. The mosaic image was clipped to the same size as the aerial photograph mosaic using the Clip tool in ArcMap and the two images were georegistered using ArcMap to superpose images perfectly. Because Song et. al. (2001) found that classification is not improved much if atmospheric correction is performed, no atmospheric correction was performed on the data.

1.4.3 Catchment delimitation from the DEM

The study area is drained by three primary river systems: the Olifants/Doring, Breede and Gouritz Rivers but, as Appendices C2 and C3 (1:50 000 map extracts) show, subsidiary subcatchments network the area. Appendix C4 shows the primary- and quaternary-level catchments and their proportional coverage of the study area appears in Table 1.4. Catchment data was clipped from shape files downloaded from AGIS. An E10A/E10B border anomaly of the catchment map was fixed using calculated stream and small catchment layers created with Spatial Analyst in ArcGIS. Whereas the Olifants/Doring River catchment covers about 90% of the area and the Gouritz is rather insignificant in the extreme south-east, run-off is not proportional to catchment size.

Table 1.4 Primary river catchments of the study area

Catchment code	Primary river	Percentage of study area
E	Olifants/Doring	90.5
H	Breede	8.7
J	Gouritz	0.8
Total		100.0

Since the quaternary catchment boundaries extend beyond the study area, some drain insignificant surfaces in the study area. Figure 1.8 shows the broad steps followed to delineate the subcatchments of the study area and Figure 1.9 sketches the intricate process flow for running the Watershed Delineation tool downloaded from ESRI (2010), subsequently used to calculate the various catchment values. A comparison of the combined aerial photographs with Appendixes C 2

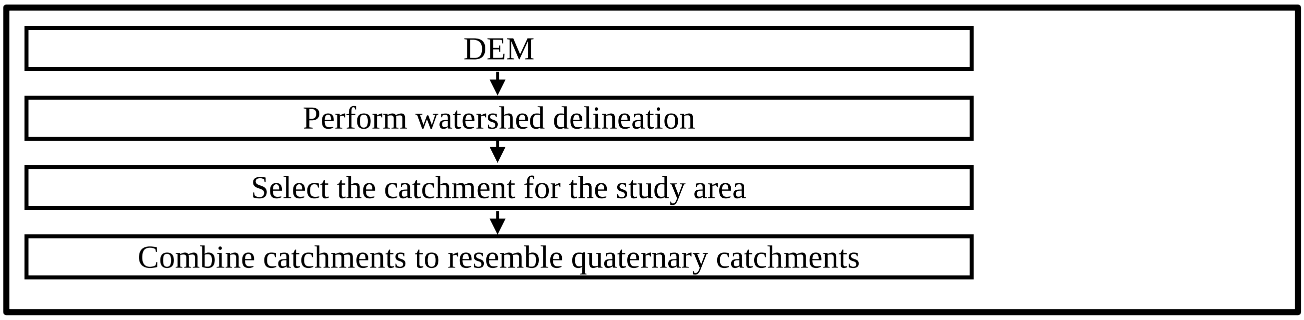
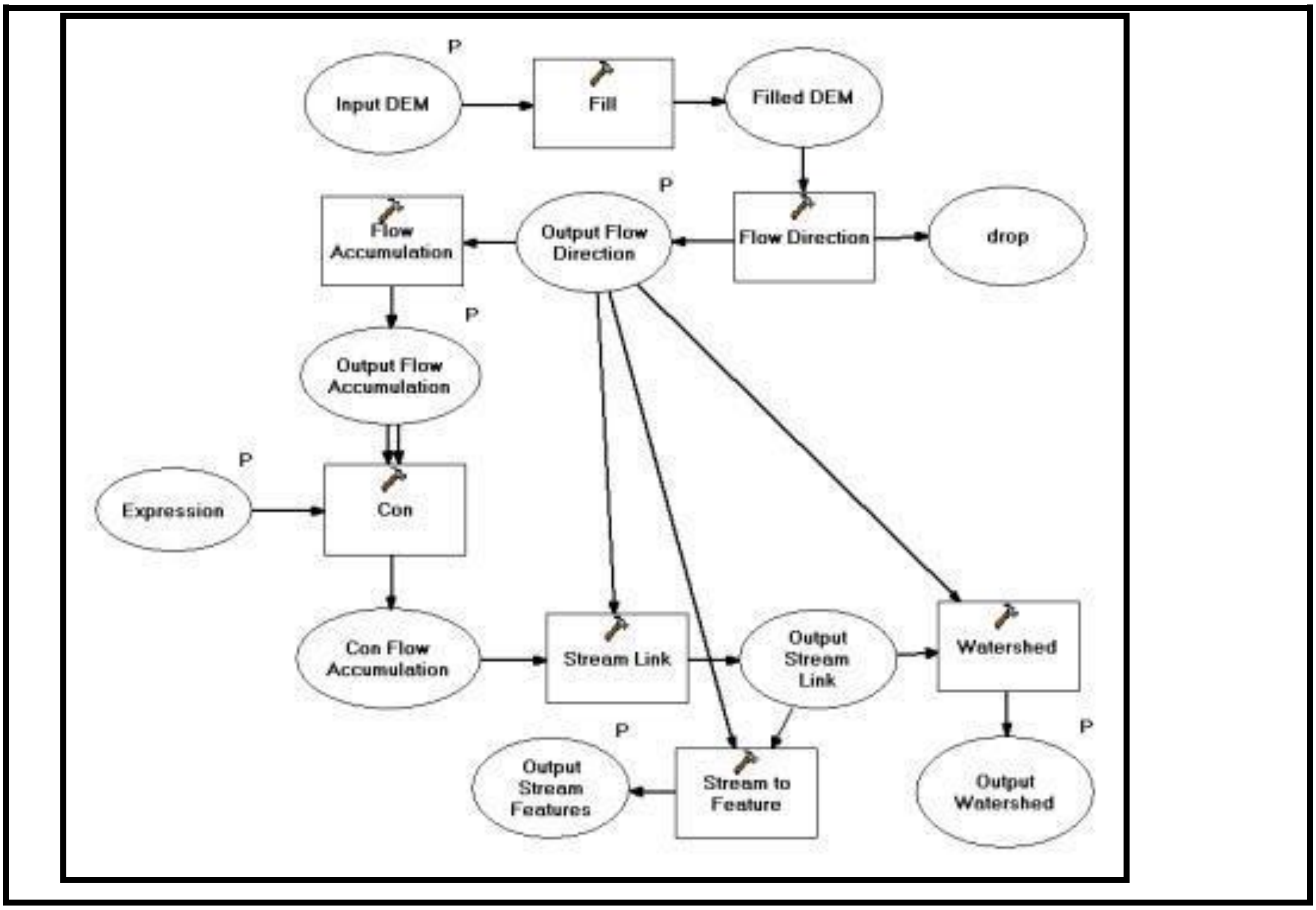


Figure 1.8 The steps to create the catchment map

and C 5 reveals that the stream map contains a mix of non-perennial and perennial streams. Appendices C6 and C7 depict the images before and after merging respectively.

Table 1.5 shows the relative area coverage of the subcatchments. Most of the catchments are similar in size, with the three very small catchments occurring at the borders of the study area.



Source: ESRI (2010)

Figure 1.9 Process flow of the watershed delineation tool

Table 1.5 Quaternary catchment dimensions

Quaternary catchment	**Area**		**Height (Metre)**			
	ha	**%**	**MIN**	**MAX**	**RANGE**	**MEAN**
E10A	22735.4	9.2	353.9	1973.3	1619.4	1032.0
H10C	11122.4	4.5	432.4	1713.2	1280.8	929.3
E21A	19309.4	7.8	951.1	1841.6	890.5	1129.1
E21B	19047.8	7.7	952.5	1941.3	988.8	1179.4
E21C	24194.4	9.8	930.0	1801.4	871.5	1152.8
E21D	23843.1	9.6	911.8	1900.1	988.3	1090.5
E21E	28154.3	11.4	911.0	2021.1	1110.1	1101.7
E21F	8928.7	3.6	620.2	2023.4	1403.2	1125.4
E21G	26087.3	10.6	733.8	1900.3	1166.5	987.3
E21H	36688.8	14.8	506.4	2021.8	1515.5	1053.6
E10B	9514.5	3.9	355.4	1675.4	1320.0	929.0
E10C	819.6	0.3	355.2	1100.6	745.3	806.4
E22C	5063.9	2.1	896.9	1752.4	855.4	1176.2
H20C	8121.5	3.3	857.6	2202.5	1344.9	1275.4
H20D	1529.3	0.6	735.7	2202.3	1466.6	1356.3
J12A	2049.4	0.8	925.4	2104.1	1178.7	1320.8
Total	247209.5	100.0	353.9	2202.5	1848.6	1084.2

As expected the mean elevations of all the catchments are relatively high. Mean elevation values cancel the difference between valley and mountain elevation and the range equates to local relief, of which the lowest is still over 700 metres. The highest local relief occurs in catchment E21H where the highest mountain peak is located.

1.5 THE STRUCTURE OF THE RESEARCH REPORT

The thesis is structured so that each objective is treated in a designated chapter.

Chapter 1 introduced the research problem, aim and objectives, described and demarcated the study area, justified the selection of data sources, explained the preparation of the data and the various analytical procedures. To some extent, Objectives 1 and 5 have been partly reached already, namely to:

- Describe the assembling of a full spatial database for the study region; and
- Explain the mapping of the hydrological catchments to be used operationally.

Chapter 2 focusses on the analysis of land cover and land cover change in the Koue Bokkeveld and results in maps of land cover and land cover change over the three study periods and in the various catchments as envisioned by Objective 2. In Chapter 3 the structure of the landscape and its morphology is dissected and the location of the land cover types is explained. So doing, Objectives 3 and 4 are reached in this chapter, namely to explain land cover patterns in terms of landscape morphology. In Chapter 4, the focus shifts to a focus on landscape functions and the effect of land cover and land cover change on these functions on a catchment basis. Run-off, carbon storage and biodiversity are addressed to realise Objectives 5 to 7. The concluding Chapter 5 closes the report with the standard summaries of the findings, conclusions, recommendations and suggestions for future research.

It is important to finally note that the body of the report does not contain all relevant materials in print at the best scale because maps are either too large or a large number in the text would have been disruptive to textual flow. Consequently, they are listed in Appendix C in A4 format, and are published in shape file format on a data DVD in the back jacket. The structures of the original rasters are retained so that the shape files are convertible to raster should they be required. The maps are also stored on DVD at A2 size in .pdf format for reference in this and future research.

Attention now turns to the three chapters contributing the body of the report, beginning in the next chapter with an analysis of land cover in the Koue Bokkeveld and how it has changed over time.

CHAPTER 2 LAND COVER IN THE KOUE BOKKEVELD AND ITS CHANGE OVER TIME

The chapter commences with an overview of approaches to and methods for identifying, classifying and detecting change in land cover. This is followed by a practical demonstration of these techniques to record land cover for three target dates in the Koue Bokkeveld and its separate catchments, and to analyse the trends in change over time.

2.1 LAND COVER AND LAND COVER CHANGE

This section deals with the theory of land cover analysis, classification and change detection procedures and the analytical detection means available for use in this research. The various concepts and procedures are explained to justify their adoption in the research.

2.1.1 The mechanics of land cover analysis

Land cover and land use are not necessarily the same concepts, although they are sometimes used interchangeably. Ellis (2007: 1) defines land cover as “the physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures.” and land use as “syndromes of human activities such as agriculture, forestry and building construction that alter land surface processes including biogeochemistry, hydrology and biodiversity.” Clearly, land use and land cover are not the same: land cover refers to the physically observable phenomenon and land use to the interpreted human activity related to that observed feature for a particular analytical or descriptive purpose. In this research, observable land cover features were recorded so that the term is used throughout in this sense.

Analysis of the complex landscape objects captured in remotely-sensed imagery of the earth’s surface is facilitated through classification (Demers 2009). Buildings, trees and plants are examples of objects that are members of different feature groupings or classes. A building can be classified as ’town’ or ’built-up’ depending on the classification scheme adopted and the nature of surrounding objects. Similarly, a tree might fit into a ’tree’ class or a ’plantation’ or ’forest’ class, on the same grounds.

Images are classified by grouping similar image pixels into classes by various methods depending on data type and available software (Demers 2009; Mather 2009). A classification of object features in an image helps to record land use and land cover in an area and to analyse change. The nature and extent of classes are determined by the requirements of particular projects (Demers 2009; Mather 2009). Classification implies simplifying and grouping objects into meaningful classes for better comprehension. Change detection with different media requires that imagery be captured in the same format and spatial extent. This principle implies that historical photographs and modern satellite images can be classified and the results compared analytically. This ability enables comparison over longer periods for change detection.

Ellis (2010: 1) defines land cover change as “land use and land-cover change (LULCC) or land change is a general term for human modification of Earth's terrestrial surface.” Berberoglu & Akin (2009: 46) specify that “change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times”. Camps-Valls et al. (2006: 1) concur by stating that “In image spectroscopy, the formal definition of change detection involves the use of multi-temporal data to discriminate areas of the land cover that changed between dates.” Therefore, change detection uses accurate and well-timed images taken at different dates of the same area to determine change due to human interaction with natural phenomena (Berberoglu & Akin 2009).

Various methods for change detection have been developed (Pontius & Chen 2006; Clark Labs 2009). This alerts one that the selection of the correct method for particular data is vital to yielding the best results. Most change detection methods use data from the same source (Bergen et al. 2005), but some compensate for differences among sources (Petit & Lambin 2001). It is preferable to separately classify data from different sources and then perform change detection among the classes, rather than pixel-by-pixel change detection (Bergen et al. 2005). By classifying different images, less complex change detection methods, such as pixel-by-pixel, can be used since spatial superposition is accounted for when the image is classified. Consequently, this research employed pixel-by-pixel change detection, together with change matrixes and gain/loss diagrams to analyse change.

2.1.2 Land cover classification and identification

The land cover classification system set out in Table 2.1 was used for this research. It constitutes an amalgamation of two formulae: The SANBI (Mucina & Rutherford 2006) scheme (twelve classes occurring in the study area) adopted for regional-scale natural vegetation (NV) mapping in South Africa; and the standard nine-class rural and agricultural developments scheme developed for previous land cover studies in the Koue Bokkeveld (Richards 1999; Heyns 2000; Tesfamariam 2000). On these agricultural land use maps all areas classified as single NV class were those undisturbed areas free of any development, subsequently reclassified according to the eleven superposed SANBI vegetation classes. The SANBI vegetation map reflects the determinate relationship between geology and vegetation types (Mucina & Rutherford 2006). These classes are explained below, starting with the agricultural land use subgroup.

Table 2.1 Land cover classification for the Koue Bokkeveld

Code	Land cover class		Code	Land use class
***SANBI Natural vegetation classes* (Mucina & Rutherford 2006)**			***Agricultural land use classes***	
WS	Winterhoek Sandstone Fynbos (FFs 5)		**WC**	Wetland channels
CF	Cederberg Sandstone Fynbos (FFs 4)		**WF**	Wetland flats
SQ	Swartruggens Quartzite Fynbos (FFq 2)		**CD**	Clear-water dams
KS	Kouebokkeveld Shale Fynbos (FFh 1)		**TD**	Turbid-water dams
KA	Kouebokkeveld Alluvium Fynbos (FFa 1)		**PT**	Plantations and trees
CR	Ceres Shale Renosterveld (FRs 4)		**AA**	Annual agriculture
NI	Northern Inland Shale Band Vegetation (FFb 1)		**PA**	Perennial agriculture
MS	Matjiesfontein Shale Renosterveld (FRs 6)		**Bu**	Built-up
NH	North Hex Sandstone Fynbos (FFs 7)		**T**	Town
WA	Western Altimontane Sandstone Fynbos (FFs 30)			
TW	Tanqua Wash Riviere (AZi 7)			
SH	South Hex Sandstone Fynbos (FFs 8)			

Wetland channels (WC) are the observable sinewy, narrow, linear features of rivers, streams and channels containing naturally-flowing water. On the 1949 image, visual observation alone identified these features, aided by the use of 1:50 000 topographical maps. Image appearance of these features on the 1949 photographs were defined as the dark zones next to streams and rivers and include tree-and-shrub linings too. Classification of the 2009 satellite imagery classification was aided by normalised difference vegetation indexing (NDVI) to identify streams, rivers and channels containing water. Equation 2.1 shows the calculation method followed:

$$NDVI = \frac{IR - R}{IR + R} \qquad \text{Equation 2.1}$$

where $NDVI$ Normalised difference vegetation index
IR Infrared band
R Red band

Source: LGGI (2005)

Since landscape shadows can be mistaken for water, 1: 50 000 maps were used as a controlling data source. Visual inspection improved the accuracy of the classification so that fewer streams were identified for the spatial mapping exercise. The reference state map copied the 1949 pattern, but was modified by removing the instream irrigation dams that had appeared by 1949.

Wetland flats (WF) include marshland, standing water, pans and their surrounding vegetation that appears as a darker green shading compared to other vegetation. None of these is a man-made feature (like dams, reservoirs). These wetland areas appear dark on the 1949 monochrome imagery and they could be checked against the 1:50 000 topographic maps. The panchromatic and multispectral images were both used to classify the wetland flats on the 2009 imagery. The panchromatic imagery has similar diagnostic characteristics as the 1949 photography, whereas NDVI identified the greener (more lush) vegetation on the multispectral images. Similar modifications as done for WC on the 1949 map were used to create a wetland flats class for the reference state image.

Two classes of artificial dams or reservoirs for irrigation purposes were distinguished. Clear-water dams (CD) receive their waters in unsilted condition from the sandstone mountain subcatchments and so offer a much richer habitat for fauna like waterbirds and fish. CDs are clearly distinguishable on imagery like that of 1949, because the water surfaces appear black in monochrome imagery. Similar image characteristics apply to the 2009 SPOT panchromatic imagery and on the multispectral imagery. This class yields very low NDVI values. Conversely, turbid-water dams (TD) store water that is rich in fine, suspended sediments derived from Bokkeveld and Karoo shales underlying the valleys and hills adjoining the sandstone mountains. TDs are less liveable habitats for wildlife and water-based vegetation because it takes a full season for the fine silt to settle sufficiently. These waterbodies are clearly distinguishable on monochrome imagery (like that of 1949), because the water surfaces show as light grey to white on the aerial photography as well as the 2009 panchromatic image. Their NDVI values are lower than the surrounding areas on the 2009 multispectral imagery. It is noteworthy that standing water in these irrigation dams is subject to fairly rigid cyclical regimes where dams fill in winter (full by September) and they gradually empty during the summer irrigation season, approaching an empty state by May. These dams are, as a rule, uncertain habitats for wildlife in many cases.

Lone clumps of trees and plantations (PT) were classified together as one class. On the 1949 aerial imagery, the elements are clearly distinguishable by their dark colour, normally surrounded by lighter areas, and by their coarser texture that differs notably from that of water with similar colouration. Accurate identification is aided on the 2009 panchromatic image by the dark colour that is a signal and with the high NDVI value on the multispectral image the 2.5 m-resolution melds smaller spaces between trees in a plantation and rows of trees into fairly solid masses.

Annual agriculture (AA), mainly wheat and oats fields as pointed out by Conradie (1942), shows up as spatially extensive, light grey, even-textured areas in the 1949 photographs, clearly contrasting with the surrounding, invariably darker natural surfaces. The panchromatic imagery of 2009 shows the same characteristics but with added circular features of pivot irrigation (mainly for vegetables) providing additional shape indication (Van der Merwe 2009a, Pers com). The leafy growth of this land use class yields high NDVI values on the multispectral imagery.

Perennial agriculture (PA) – invariably consisting of fruit orchards planted in meticulously regular grid patterns – is easily identified on the 1949 imagery due to its (at that time) regularly spaced dots representing individually identifiable trees planted in a 4m x 4m configuration. Orchards were always smaller in extent than the surrounding wheat fields. By 2009, the signal pattern-texture on the panchromatic imagery is no longer valid, because orchard cultivation had now taken on the form of linear, 4 m-spaced tree rows and individual trees in rows at 1-m spacing (4m x 1m pattern) that defies detection by the satellite sensor's pixel size. In addition, when a linear pattern does show up, it could be confused with vineyards (perennial) or even tomato stands (annual) (Van der Merwe 2009b, Pers com). The NDVI values for the PA class are high on the multispectral image and the class is clinically quite identifiable at both time stages.

Built-up areas (Bu) are easily identifiable by the rectangular shapes of building structures and, in the case of farmsteads invariably framed by stands of high trees and converging road patterns. Surprisingly, on the older 1949 aerial imagery, buildings appear in more detail than on the 2009 satellite imagery owing to the difference in resolution. Of course, by 2009 the features of the built-up class had acquired large industrial-sized extensions (machinery storage, fruit refrigeration plants and packing facilities) and the town (class T) of Op-die-Berg had been established. Light-coloured roofs and rectangular shapes aid the detection of buildings and the NDVI values are low when not contaminated by surrounding trees.

2.1.3 Satellite image classification

Image classification methods can be either pixel-based or object-orientated in nature. In pixel-based classification, spatial concepts are ignored, while in object-orientated classification the spatial position of the pixel is considered (Blaschke & Strobl 2001). In pixel-based classification, the individual pixel values are used to classify the pixels (Blaschke & Strobl 2001; Mather 2009) according to methods such as maximum likelihood and artificial neural networks (Pal & Mather 2003). Classification may be unsupervised or supervised. In computerised unsupervised classification users specify the number of classes to enable calculation of pixel signatures for different classes. A pixel signature comprises the values of the same pixel in different spectral bands. In supervised classifications users define real-world training areas which represent targeted land cover classes where the signatures of the different classes are recorded. Unsupervised classification is usually applied in areas with unfamiliar land cover to help identify any distinctive classes. Contrarily, supervised classification is applied in areas with familiar land cover.

Objects are represented as homogeneous pixels grouped together through the application of computerised algorithms. Different algorithms convert pixels with the same texture and reflectance into different objects (Blaschke & Strobl 2001; Mather 2009). Object-orientated classification is more accurate than pixel-based classification (Blaschke & Strobl 2001). eCognition is a computer program that applies rule-based, object-orientated classification methods with tools that use shape and contextual concepts to classify objects in images according to constructed fuzzy rules (Bauer & Steinnocher 2001).

Because of its enhanced accuracy object-orientated classification was the chosen method for multispectral satellite image (2009) classification in this research. Visual classification was selected to map land cover on the 1949 photographic imagery by heads-up onscreen digitising.

2.1.4 Change detection methods

Selection of a sound detection methodology must consider at least three pointers offered in the literature. These issues, covered in the next three sections, concern the various tried and tested analytical approaches, the users' experiences with land cover modelling and the best software tools on offer for performing the task.

2.1.4.1 Analytical approaches

Change detection is typically performed on remotely-sensed imagery of targeted landscapes – field survey, topographical maps, aerial photography or satellite imagery like Landsat or ASTER, either singly (Lyon 2001) or in combination (Richards 1999; Heyns 2000; Tesfamariam 2000; Bergen et al. 2005; Alphan, Doygun & Unlukaplan 2009; Berberoglu & Akin 2009; Mengistu 2009). Common to all methods is the need for efficient classification schemes.

Four change detection methods have become established in remote sensing applications, namely change vector analysis (CVA), image regression, image rationing and image differencing. In all four cases, a threshold is selected to determine affected areas in imagery (Berberoglu & Akin 2009). CVA, a radiometric technique, detects changes in multispectral input data, whereas image regression reduces sun angles and/or atmospheric conditions to detect change (Coppin & Bauer in Berberoglu & Akin 2009). Image rationing is used to negate topological effects such as illumination and shadowing (Eastman et al. in Berberoglu & Akin 2009)and in agricultural and forested areas especially, image differencing (according to various authors in Berberoglu & Akin 2009) often provides the best solution.

So, which method is best? Firstly, Bergen et al. (2005) point out that most methods use data from similar sensors, while Lu et al. (2004) advise that the method should be selected from multiple tested cases, and Petit & Lambin (2001) insist on the necessity to compensate for differences between data types, like maps and aerial photographs. Bergen et al. (2005) contend that pixel-by-pixel change detection fails to deliver when analysing different data sources. Conversely, Demers (2009) and Longley et al. (2005) all found that vector data overlaying analysis produces slivers that negatively affect change detection results. A comparison of the different methods provides a convincing case for applying a raster-based method on classified data, simply because the data used in this study originate from different sources.

2.1.4.2 Change modelling

An often used and efficient way to measure change between two periods is by compiling a change matrix that quantifies change between individual or grouped classes. Richards (1999), Tesfamariam (2000) and Benini et al. (2010) all demonstrated this technique by using different combinations of classes to isolate various aspects of change and also as a means to reduce the number of change classes to simplify analyses. However, analysis can advance beyond mere detection to change prediction (Pontius & Chen 2006; Clark Labs 2009). Examples are provided by Wainwright & Mulligan (2004) who advocate environmental modelling which simplify the environment so that the important concepts for research are highlighted. After all, a model offers only a representation of and not the total environment in all its complexity.

Computerised modelling is enabled through various software tools for performing different procedures (ESRI 2006; Eastman 2009; IDRISI 2009c). Scripts for performing modelling landscape and hydrology exist or can be compiled (ESRI 2010), while Clark Labs (2009) offers a novel landscape change model developed for IDRISI and ArcGIS that can perform change detection as part of change modelling. The GEOMOD tool (Pontius & Malanson 2005; Pontius & Chen 2006; Echeverria et al. 2008) is another modelling tool created for IDRISI and compares favourably with cellular automata Markov (CA_Markov) modelling. It was later incorporated into the Land Change Modeller (for ecological sustainability) (LCM) in the later IDRISI versions.

2.1.4.3 Change detection software tools

Software tools to perform these analyses efficiently have been reported. For instance, Mengistu (2009) has demonstrated generically how GIS overlaying could create change detection tables, whereas Alphan, Doygun & Unlukaplan (2009) use both cross-tabulation (pivot tables) and pixel-based change detection to show temporal change between classified imagery. More specifically, in the raster environment, the LCM offers a versatile tool in IDRISI to analyse and model various aspects of change. The Change Analysis tab of this tool activates change detection between two land cover images (IDRISI 2009a). In the Change Analysis panel land cover class gains or loses –

net change and contributors to net change are calculated and graphically displayed. The Change Map panel creates a range of change maps (IDRISI 2009b).

On a mainly vector platform, the Combine tool in ArcGIS performs raster change detection by combining two raster land cover images and comparing them pixel by pixel (ESRI 2008a). Zwick, Arafat & Patten (s.a.) used this tool to isolate areas of change conflict. The tool uses the raster values from the attribute tables of the original shape files, and exports them to join the result in relatively uncomplicated procedures. After careful consideration of these literature pointers, the Combine tool in ArcGIS was selected for application, as augmented by pivot tables in Excel for constructing cross-tabulations. Land cover gain or loss statistics and percentage area change were also calculated. The selected methods have similar functionality to the LCM tool in IDRISI.

2.2 METHODOLOGY USED FOR CLASSIFICATION AND CHANGE DETECTION

The following sections cover the sequential steps and methods followed to carry out the classification mapping and change detection procedures on the data for the Koue Bokkeveld.

2.2.1 Reference state land cover mapping

In the absence of any usable spatial data or source on the reference or original state of the landscape prior to the advent of extractive human settlement, a surrogate reconstruction of the landscape had to be devised. The simplest and most accurate way was to assume that the spatial patterns of natural vegetation as reconstructed by SANBI (Mucina & Rutherford 2006) in a natural vegetation map for South Africa would accurately reflect this past state. The SANBI vegetation map was thus used as the base map for natural vegetation from which the study area was clipped (using the ArcMap Clip tool) before the resulting vector image was rasterised to a cell size of 2.5 metres resolution (using the ArcMap Polygon to Raster tool). Figure 2.1 outlines the execution

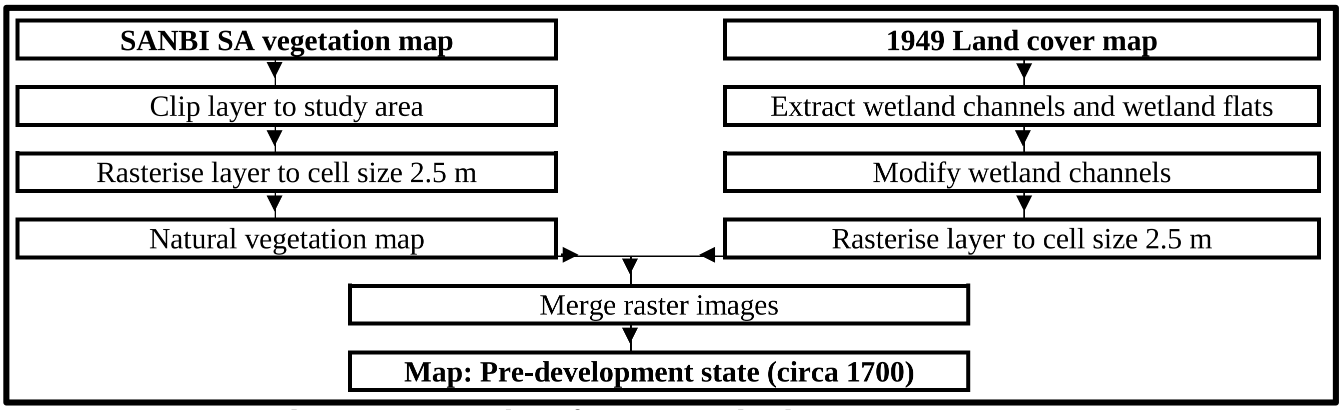


Figure 2.1 Sequential steps to create the reference state land cover map

sequence of these steps to create a usable land cover map that reflects the pristine state of the landscape before European settlement that has left an interruptive footprint potentially altering landscape functions.

2.2.2 The 1949 and 2009 land cover maps

The production process of the 1949 and 2009 land cover maps each followed slightly different sequential steps as depicted in Figure 2.2. As sequenced in the left-hand column, and partly because of its monochrome colour format and because the image quality of aerial photographs deteriorated systematically towards the edges of the photographs, the 1949 aerial imagery could not be auto-classified. Consequently, the 1949 mosaic image served as the basis for digitising the land cover polygons. Digitising was performed using the Edit tool in ArcMap and accuracy was visually assessed by a competent researcher familiar with the region (Van der Merwe 2009b, Pers com). The

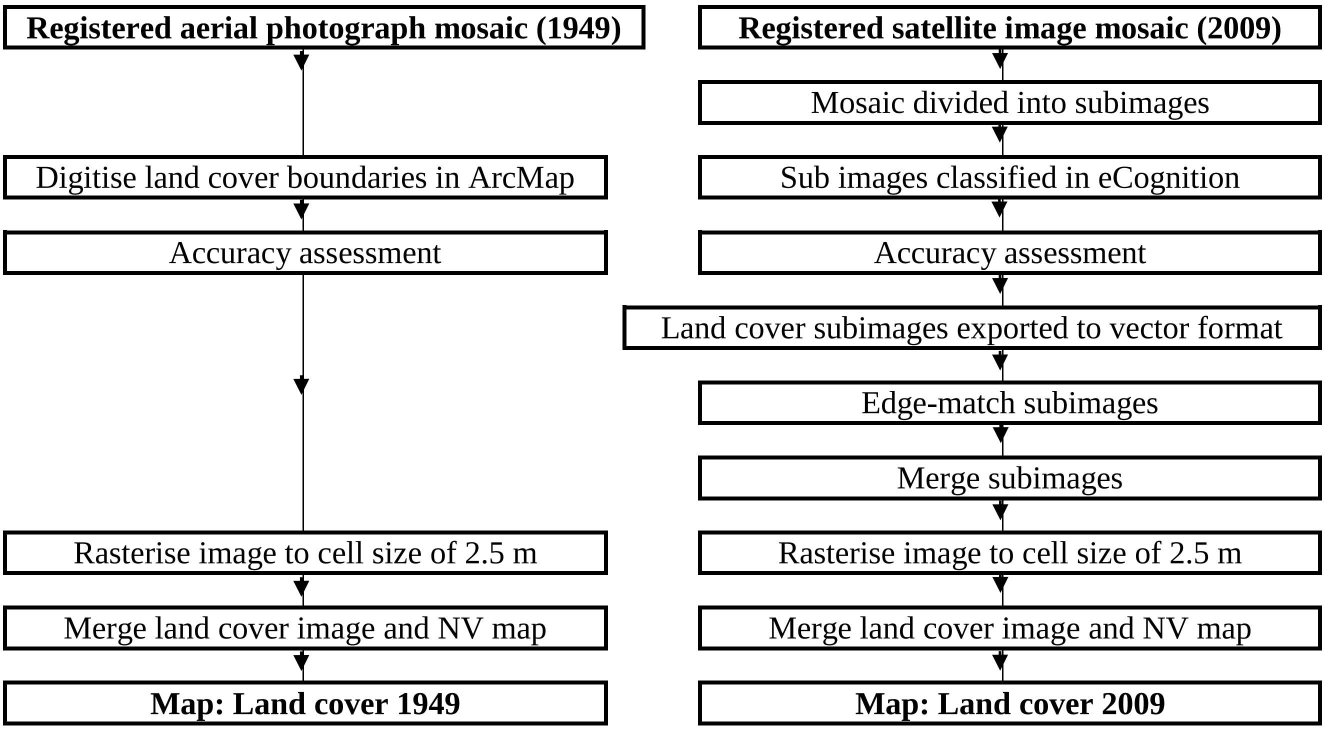


Figure 2.2 Sequential steps to create the 1949 and 2009 land cover maps

database structuring tools of ArcGIS were used to clean the digitised feature data and build the graphic topology. The corrected image was rasterised to 2.5-metre resolution and the Simple Map Algebra tool was used to merge it with the natural vegetation map to enable the classification of the undisturbed natural vegetation areas.

The right-hand column of Figure 2.2 depicts the satellite analysis procedures for compiling the 2009 land cover classification map. The SPOT5 image was clipped into subsections because the image was too large for once-off analysis. Definiens Developer was used to first perform rule-based automatic classification and then to rectify manual visual classification in areas where, upon inspection, classification had failed. It transpired that this combinatory method, rather than just refining the rule-based classification, was most efficient. Accuracy assessment was again performed visually by Van der Merwe (2009b, Pers com) on the various subimages. Standard shape file manipulation and combination, followed by rasterisation to the standard resolution of 2.5 metres, generated the final land cover map for 2009.

2.2.3 Land cover change matrix construction

The complex land cover change matrix model showing potential reciprocal change among all 21 land cover classes (those listed in Table 2.1) for two target years is presented in Figure 2.3.

		2009																				
		WS	CF	SQ	KS	KA	CR	NI	MS	NH	WA	TW	SH	WC	WF	CD	TD	PT	AA	PA	Bu	T
	WS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	CF	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
	SQ	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
	KS	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84
	KA	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
	CR	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
	NI	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147
	MS	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168
1949	NH	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189
	WA	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210
	TW	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231
	SH	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252
	WC	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273
	WF	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294
	CD	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315
	TD	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336
	PT	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357
	AA	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378
	PA	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399
	Bu	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420

Figure 2.3 Complex potential land cover change matrix model

Evidently, there is a complex set of 441 (21x21) change classes, but since only 20 of the land cover types existed in 1949 – the town (T) had not yet become established – the potential number of change classes is only 420 (21x20). Cells along the diagonal represent cases where land cover remained the same (stable usage) between the target years. Because land cover classes are arranged from least intensive use to most intensive (or urban-like) use, classes in the upper-right quadrant above the diagonal intensified and those below the diagonal decreased in use intensity.

To reduce this confusing complexity, a more abstract, simplified change matrix was consolidated, as shown in Figure 2.4. Here, all the natural vegetation classes were grouped in one class (NV) to simplify change mapping and interpretation comprehensively to only 90 classes – clearly still too complex and requiring further refinement.

		2009									
		NV	WC	WF	CD	TD	PT	AA	PA	Bu	T
1949	NV	1	2	3	4	5	6	7	8	9	10
	WC	11	12	13	14	15	16	17	18	19	20
	WF	21	22	23	24	25	26	27	28	29	30
	CD	31	32	33	34	35	36	37	38	39	40
	TD	41	42	43	44	45	46	47	48	49	50
	PT	51	52	53	54	55	56	57	58	59	60
	AA	61	62	63	64	65	66	67	68	69	70
	PA	71	72	73	74	75	76	77	78	79	80
	Bu	81	82	83	84	85	85	87	88	89	90

Code	**Land cover class**	**Code**	**Land cover class**
NV	Natural vegetation	PT	Plantations and trees
WC	Wetland channels	AA	Annual agriculture
WF	Wetland flats	PA	Perennial agriculture
CD	Clear-water dams	Bu	Built-up
TD	Turbid-water dams	T	Town

Figure 2.4 Simplified change matrix

A conceptual approach is needed to consolidate complex classes – i.e. a schema that has explanatory meaning. Richards (1999) and Tesfamariam (2000) grouped the individual change classes according to the implied intensity of land use conversion shown as an increase from top left (no or low-intensity natural vegetation) to bottom right (high intensity conversion to built-up structure and townscape or detrimental landscape change). Intensification implies permanent loss, as in hardened surfaces like roads and buildings replacing natural vegetation. Land cover change from a higher intensity class to a less intensive class (intensity reversal) is unlikely under normal circumstances and therefore implies landscape improvement. Figure 2.5 shows twelve consolidated

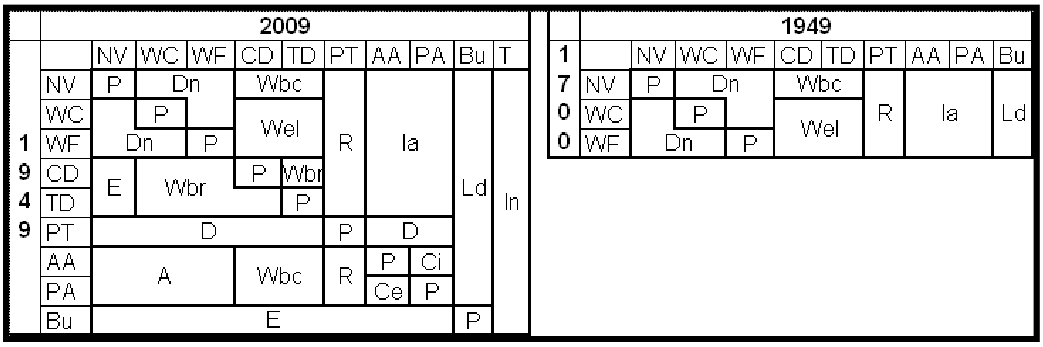
<table>
<tr><td></td><td></td><td colspan="10">2009</td></tr>
<tr><td></td><td></td><td>NV</td><td>WC</td><td>WF</td><td>CD</td><td>TD</td><td>PT</td><td>AA</td><td>PA</td><td>Bu</td><td>T</td></tr>
<tr><td rowspan="9">1949</td><td>NV</td><td colspan="3">Nr</td><td colspan="3">Ng</td><td colspan="4">Nl</td></tr>
<tr><td>WC</td><td colspan="3" rowspan="2">Wr</td><td colspan="2" rowspan="2">Wg</td><td colspan="5" rowspan="2">Wl</td></tr>
<tr><td>WF</td></tr>
<tr><td>CD</td><td colspan="6" rowspan="2">Dr</td><td colspan="4" rowspan="2">Dl</td></tr>
<tr><td>TD</td></tr>
<tr><td>PT</td><td colspan="6">Fr</td><td colspan="4">Fl</td></tr>
<tr><td>AA</td><td colspan="6" rowspan="3">Al</td><td colspan="4" rowspan="3">Ar</td></tr>
<tr><td>PA</td></tr>
<tr><td>Bu</td></tr>
</table>

<table>
<tr><td></td><td></td><td colspan="9">1949</td></tr>
<tr><td rowspan="4">1700</td><td></td><td>NV</td><td>WC</td><td>WF</td><td>CD</td><td>TD</td><td>PT</td><td>AA</td><td>PA</td><td>Bu</td></tr>
<tr><td>NV</td><td colspan="3">Nr</td><td colspan="3">Ng</td><td colspan="3">Nl</td></tr>
<tr><td>WC</td><td colspan="3" rowspan="2">Wr</td><td colspan="2" rowspan="2">Wg</td><td colspan="4" rowspan="2">Wl</td></tr>
<tr><td>WF</td></tr>
</table>

Code	**Land Cover Change Class**	**Code**	**Land Cover Change Class**
Nr	Natural vegetation retention	Dr	Waterbody retention, habitat gain
Ng	Natural vegetation loss/ habitat gain	Dl	Waterbody and habitat loss
Nl	Natural vegetation loss	Fr	Forestry/habitat retention
Wr	Wetland retention	Fl	Forestry/habitat loss
Wg	Wetland loss, habitat gain	Al	Agricultural loss/habitat gain
Wl	Wetland loss, high impact	Ar	Agricultural retention and intensification

Source: Adapted from Richards (1999); Tesfamariam (2000) and Vos (2009).

Figure 2.5 Land cover change matrix: Intensification land cover classes based on the intensification concept. For 1949-2009 the seven classes on the left indicate positive changes and the five on the right negative changes. An alternative, slightly more complex, 14-class consolidation scheme based on the Benini et al. (2010) model was also devised as structured in Figure 2.6. This matrix groups the classes into more subtle types of change,



Code	Land cover change class	Code	Land cover change class
P	Persistence (no change in land use)	Wel	Wetland loss (flooded)
Dn	Natural dynamic (natural changes occurred)	D	Deforestation (plantation replaced)
Wbc	Waterbody creation	Ia	Agrarian intensification (agriculture substitute previous land use)
Wbr	Waterbody retention	Ce	Extensive conversion (agriculture)
A	Agricultural abandonment	Ci	Intensive conversion (agriculture)
R	Afforestation (converted into plantation)	Ld	Light development (farmstead development)
E	Built abandonment	In	Urban intensification (converted to urban)

Source: Adapted from Benini et al. (2010).

Figure 2.6 Land cover change matrix: Productivity dynamics

allowing certain productivity dynamics to be highlighted. For instance, persistence of all base categories along the diagonal is isolated as a class, while abandonment and intensification classes are detailed. The usefulness of this schema for areas undergoing drastic and persistent urbanisation is that the changes will be more apparent than in a predominantly agricultural environment. Nevertheless, both matrix schemes were applied due to their relative utilities. Both classification schemes' results were mapped and graphs and tables created from output results to record the changes in the study area. These changes are discussed based on the graph and table for the area involved by the changes and the maps for the spatial distribution pattern of the changes.

2.2.4 Software selection for change detection

Two software toolboxes were considered for the change detection application, namely the land change modeller (LCM) in IDRISI and ArcMap. LCM is an efficient change detection program, but because it offers a host of other functions with no use for this research, and because it required importation and conversion of data to IDRISI format, there is an unwanted risk of data loss or corruption. Given that the land cover data was already in ArcMap format the more straightforward

Combine tool in the ArcMap toolbox is the platform selected for change detection analysis. The tool combines raster files for the different periods and the attribute table is exported to a database file for analysis in Excel where pivot tables are created as change matrices. These change matrices and charts quantify and display land cover change in the area.

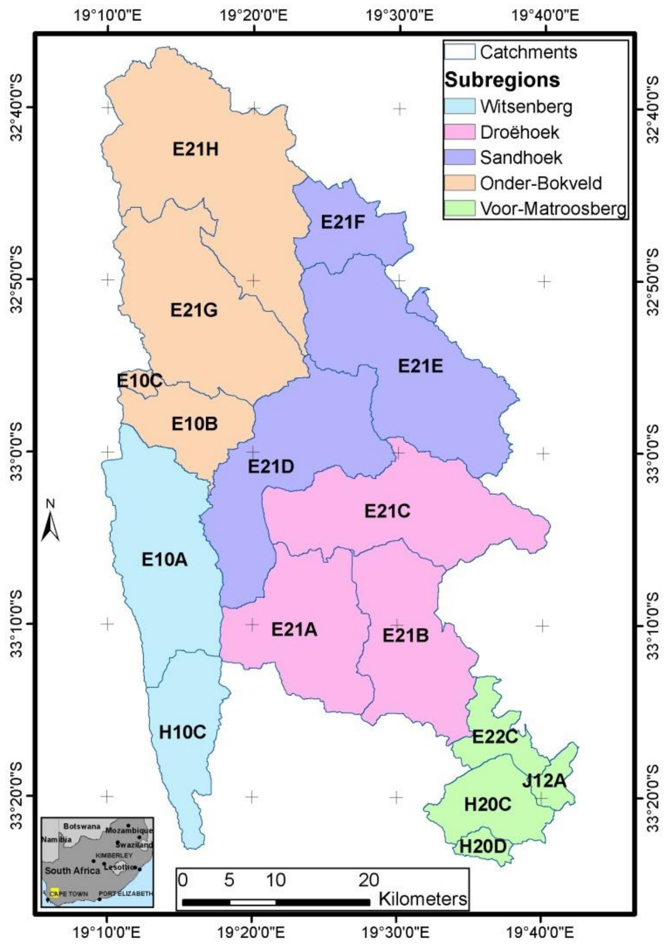
2.2.5 Subregional spatial framework

To enable meaningful understanding of the statistical calculations, especially the trends in land cover and land use over time, it was prudent to engineer a regional amalgamation based on the natural catchments. Consequently, the 16 quaternary catchments (see Table 1.5) were clustered in five subregions (Table 2.2) that possess local regional meaning and appeal and mapped as shown in Figure 2.7. The integrity of natural catchment boundaries was retained and the subregions are

Table 2.2 Subregional spatial amalgamation

Subregion	**Quaternary catchment**	**Area**		**Area**	
		ha	**%**	**ha**	**%**
Witsenberg	E10A	22 735.4	9.2	**33 857.8**	**13.7**
	H10C	11 122.4	4.5		
Droëhoek	E21A	19 309.4	7.8	**62 551.6**	**25.3**
	E21B	19 047.8	7.7		
	E21C	24 194.4	9.8		
Sandhoek	E21D	23 843.1	9.6	**60 926.1**	**24.6**
	E21E	28 154.3	11.4		
	E21F	8 928.7	3.6		
Onder- Bokveld	E21G	26 087.3	10.6	**73 110.1**	**29.6**
	E21H	36 688.8	14.8		
	E10B	9 514.5	3.9		
	E10C	819.6	0.3		
Voor- Matroosberg	E22C	5 063.9	2.1	**16 764.0**	**6.8**
	H20C	8 121.5	3.3		
	H20D	1 529.3	0.6		
	J12A	2 049.4	0.8		
Total		247 209.5	100.0	247 209.5	100.0

functionally coherent (land usage, transportation route links, local organisations), natural (topographically delimited, climatologically similar) and couched in local reference frames. The demarcation is spatially coherent yet provides functional units to which meaning can be attached regarding trends in change. These five subregions are consistently used to muster the empirical statistical analytical output discussed in the sections that follow. The only other spatial units employed for analytical purposes are quaternary catchments when they make sense or as dictated by the available data. Table 2.2 show that roughly one-quarter of the study region's area is encompassed by each of the three larger subregions. The two smaller subregions making up the other quarter lie on the south-western and south-eastern margins of the study area respectively



[See Appendix C8 for enlarged map]

Figure 2.7 Subregional demarcation of the study area

where they are the only ones that contribute run-off to the Breede River primary drainage area.

Having declared the methodology, the discourse now progresses to the discussion of the empirical results of the land cover analysis of the Koue Bokkeveld.

2.3 LAND COVER IN THE KOUE BOKKEVELD

The different types of land cover and land use in an area manifest the levels of development and possible impacts of development on the surrounding landscapes. Due to the negative impacts that development can have on the natural vegetation of an area, it is vital to understand where and by how much land cover has been or is being altered. Wetlands and fynbos are both indispensable habitats and their replacement or disappearance are causes for serious concern. Regrettably , in the Koue Bokkeveld, agriculture is apparently rapidly replacing fynbos and wetlands. The rate of replacement also seems to differ between the subregions. This section explores the empirical evidence of the nature and characteristics of land cover at three time slices, at regional and subregional levels.

2.3.1 Quantitative land cover trends

The results of the empirical survey marshalled in Table 2.3 bring land cover development in the Koue Bokkeveld over the measurable historical time period into focus and, in some sense,

Table 2.3 Land cover in three time periods

Cover type*	Reference state		1949		2009	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Natural vegetation cover						
WS	63 816	25.82	63 220	25.56	60 263	24.38
CF	48 466	19.61	47 998	19.42	46 118	18.66
SQ	44 207	17.88	43 948	17.78	43 849	17.74
KS	29 574	11.96	20 946	8.47	14 693	5.94
KA	14 290	5.78	11 442	4.63	6 179	2.50
CR	13 025	5.27	9 827	3.97	8 455	3.42
NI	8 465	3.43	8 422	3.41	8 309	3.36
MS	8 019	3.24	6 476	2.62	5 598	2.26
NH	7 125	2.88	7 074	2.86	6 782	2.74
WA	1 106	0.45	1 106	0.45	1 106	0.45
TW	99	0.04	99	0.04	99	0.04
SH	3	0.00	3	0.00	3	0.00
Land use						
WC	3 022	1.22	3 044	1.23	2 348	0.95
WF	5 992	2.42	5 356	2.17	1 931	0.78
CD	0	0.0	314	0.13	3 892	1.57
TD	0	0.0	308	0.12	1 178	0.48
PT	0	0.0	683	0.28	1 051	0.43
AA	0	0.0	14 801	5.99	26 226	10.61
PA	0	0.0	1 904	0.77	7 860	3.18
Bu	0	0.0	238	0.10	1 235	0.50
T	0	0.0	0	0.0	34	0.01
Total	247 210	100.0	247 210	100.0	247 210	100.0

* See Table 2.1 for explanation of codes

represents the essence of this research. Recall that the reference state is an assumed state based on the natural vegetation cover presumed to have existed circa 1700 when land use would have consisted at most of the light touch of San hunter-gatherers and Khoi livestock farmers – both groups being distinctly nomadic and fairly low in numbers. Since the beginning of the 18th century, the gradual European occupation of the region began, first by itinerant livestock farmers (probably with limited impacts) and later by grain, fruit and vegetable farmers operating at an intensive commercial scales. While the early stock-farming regimes may have generated the ‘unnatural’ setting of veld fires to stimulate new plant growth for stockfeed, the impacts were probably quite low. The commercial phase, which had commenced in earnest by 1949, however, ushered in a landscape-defining land use regime.

At the time of the *reference stage* about one quarter of the nearly quarter-million-hectare study area was covered by Winterhoek Sandstone Fynbos. Two-thirds of the area was covered by various types of sandstone (mountain) fynbos and the rest by vegetation growing on valley shales of which the Koue Bokkeveld shale and alluvium fynbos together still covered 13%. The Ceres and Matjiesfontein shale renosterveld, although together covering a mere 6.5% on lowland shales, would become vulnerable to early ploughing activities. A similar situation obtains in the coastal renosterveld of the Swartland and Rûens which had already become critically endangered habitat in the twentieth century (Mucina & Rutherford 2006). Note the fairly prominent presence (more than 3% or some 9 000 ha) of wetland-related features, albeit that they were somewhat artificially introduced on the image as explained earlier. This emphasises the importance of these highlands as provenance of pristine and copious amounts of freshwater run-off into the three important river systems draining the area. If one loses sight of this being a region-scale analysis, the figures seem to indicate a certain amount of resilience to change over subsequent time periods. What must be considered, however, are the absolute amounts of land covered by specific natural species (especially higher up in the landscape) and the impacts on the smaller and lower-lying vegetation communities where concern should be greater.

This observation becomes evident when examining the *1949 land cover* figures. By 1949 human use of land had started to make an indelible imprint. Annual agriculture (wheat and oats), perennial agriculture (apple and pear orchards), pine plantations and other alien trees, clear-water and turbid-water irrigation storage dams and built-up homesteads had appeared abundantly in the Koue Bokkeveld. Annual agriculture (6% of the area) was the dominant human land use type, but perennial agriculture already covered almost 1%. The main difference between these two land cover types is the intensity of change implied. Although annual agriculture croplands approximate natural grassland to some extent they may be abandoned and left to revert to natural vegetation, this scenario is highly unlikely for perennial agriculture. Orchard species are completely alien to this environment, their establishment is very capital intensive, hence quite unlikely to be allowed to revert to natural habitat. Moreover, these agricultural developments were bound to have occupied easily accessible, gently sloping low-lying areas of shale fynbos and renosterveld. In 1949 the wetlands were yet to suffer much reversal and they still occupied most of their original areas. Dam structures had made an appearance but the scope of the earthworks was still minimal with just over

600 ha being occupied by clear-water and turbid-water dams. Table 2.3 confirms that other land cover classes and especially the natural vegetation classes (mountain fynbos), remained virtually stable.

The extent to which human-made development had come to dominate much of *the Koue Bokkeveld landscape by 2009* is evident from the expansion of annual agriculture (+10%) and the quadrupled coverage of perennial agriculture and plantations (nearly 9000 ha). Dams now covered almost 2% of the area and especially clear-water dams had become a prominent feature. It is evident that clear-water dams, feeding off sandstone mountain run-off had increased most and this points to the possibility of irrigation having undergone fundamental technological changes by the advent of the new millennium. Forestry plantations (a cash crop occupying more inhospitable land) had become well established and wetlands had gone into a disturbing decline. Clearly, these changes had detrimentally affected the natural vegetation as attested by the decline of virtually every vegetation class bar the highest mountain sandstone fynbos. These changes are scrutinised in the later sections dealing with change analysis.

2.3.2 Overarching spatial land cover trends

Greater understanding of these snapshot-in-time figures comes from examination of the spatial land cover patterns in Figures 2.8, 2.9 and 2.10. The natural vegetation occurrence reflects clear locational patterns of fairly persistent fynbos along the central and peripheral mountainous sandstone spines; well-differentiated vegetation types occupying the low-lying wetlands along river courses; and the lower-lying hilly and slightly inclined flatland areas adjoining the wetlands and mountains where renosterveld dominates. Except where displaced by human development, these features persist as a pattern in the three time slices.

Man-made developments in the Koue Bokkeveld (of course absent in Figure 2.8) become abundantly clear from Figure 2.9. Sinuous distributions along valleys appear by 1949 where agriculture at the time required flat land for development and this was only found on valley-bottom sites or on gentle inclines. By 1949 annual agriculture had consolidated footholds along these sections of the topography where it represented a fairly continuous and extensive development pattern. More importantly, perennial agricultural practices had started to consume space along valley bottoms, apparently close to flowing water sources (streams, rivers). The pattern was still one of patchiness, perhaps a sign of many landowners who simultaneously entered the industry to farm on relatively small landholdings. Irrigation dams were still small and situated to block smaller stream courses upstream from the fledgling perennial agricultural stands. This configuration at the

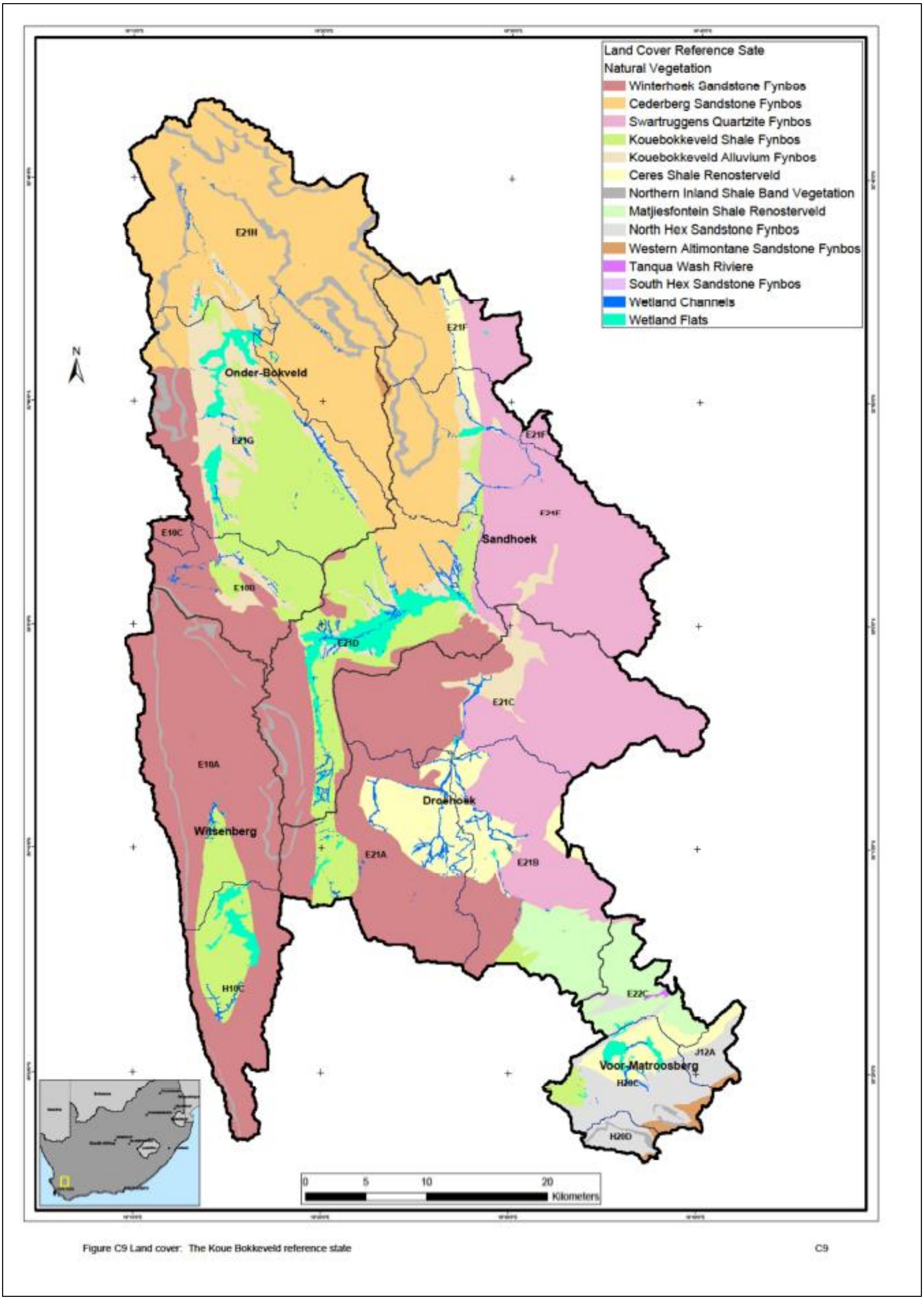


Figure 2.8 Koue Bokkeveld land cover: Reference state

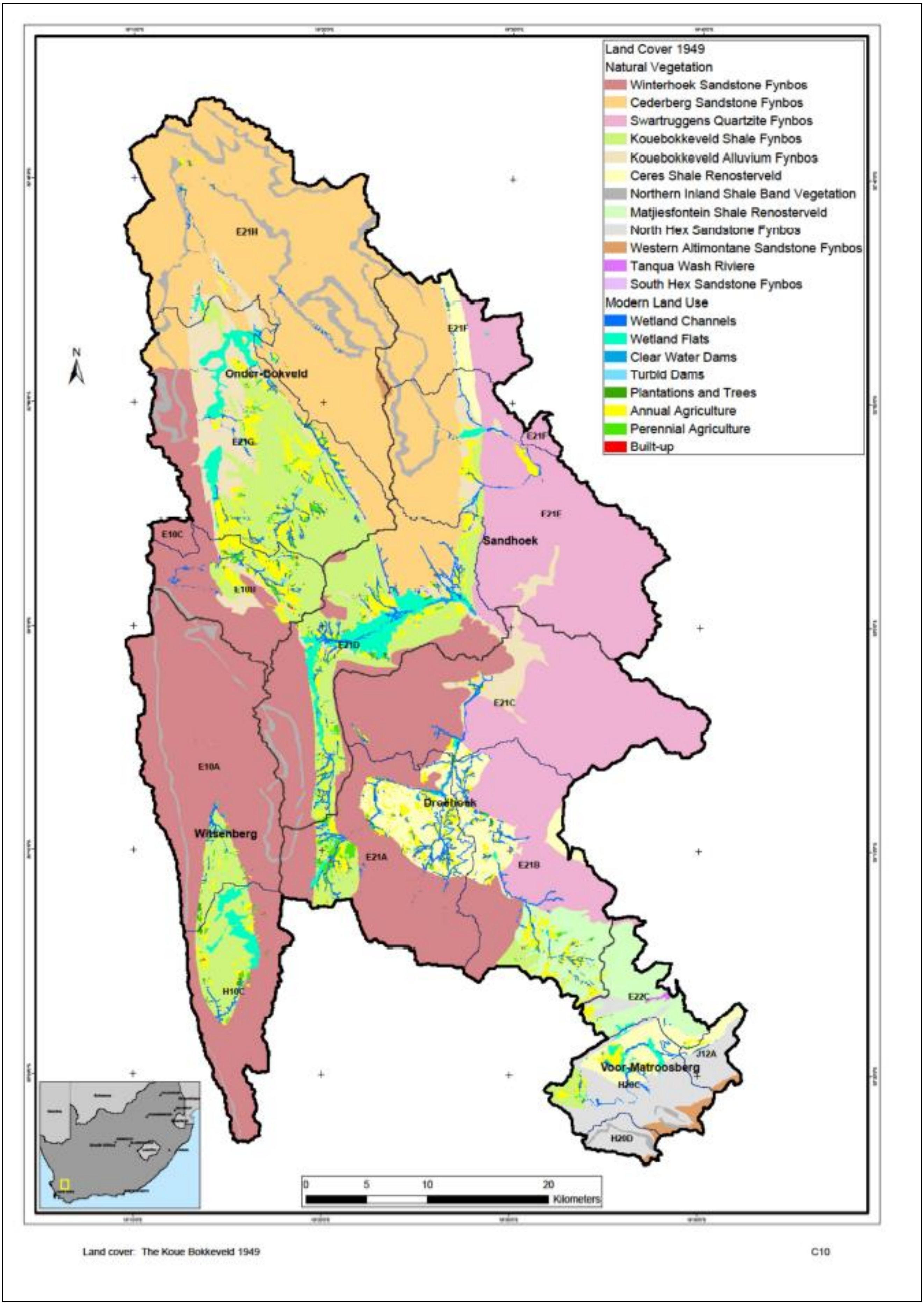


Figure 2.9 Koue Bokkeveld land cover: 1949

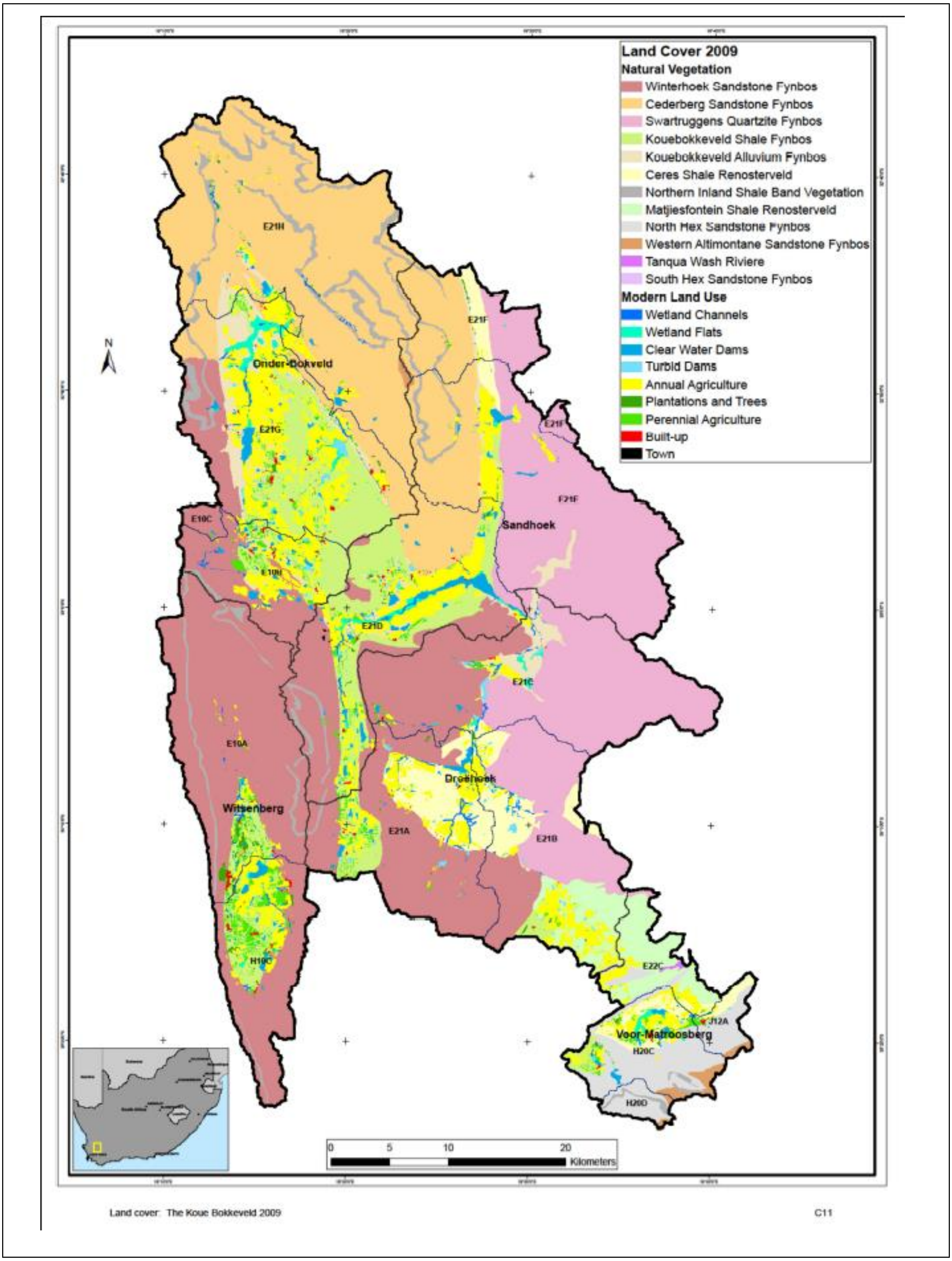


Figure 2.10 Koue Bokkeveld land cover: 2009

time was dictated by the then reigning irrigation technique, that is gravitational water flow down furrows to flood irrigate crops – a wasteful and labour intensive practice.

The land cover and land use patterns broadly remained identical through recent times – bar one important development. A comparison of Figures 2.9 and 2.10 clearly shows the preponderance of a nascent monoculture agricultural landscape. The former lower-lying fields along the river valleys have begun to replace the extensive wetlands as a result of the technological ability afforded by heavy earth-moving machinery to channelise rivers and streams, build drainage ditches and level fields for extensive vegetable cultivation on the heavier salty soils. Concurrently, proliferation of perennial orchards had abandoned the lower-lying lands subject to threats like frost and moved onto the foothills with their fine, shale-based fertile soils. This development had also been facilitated by new technology, that is heavy ground-breaking machinery to till dense and stony, mostly better drained soils higher up along the frost-free topographical profiles. Also, the use of ever heavier earth-moving machinery, improved engineering design and explosives had enabled the construction of large, secure dam walls along the river valleys, where wetlands had previously dominated, and even in mountain ravines. Water was transferred from these dams by gravitational flow or by electric pumps (electricity became available in the region in the early 1960s) via pipes to irrigation outlets where needed. In the case of large, flat vegetable fields (potatoes, onions) centre-pivot or semi-permanent mobile sprinkler systems now operate. Orchards are irrigated by micro-sprayer and drip systems that work on virtually any gradient and they are highly economical regarding water consumption. Such developments are gaining momentum and are driven by a concomitant development in landownership, namely landholdings in the Koue Bokkeveld have become greatly consolidated in the hands of a limited number of large-scale agribusinesses with access to the required capital that fuels ever more expansion and deployment of new technology.

2.3.3 Subregional land cover trends

Land cover in the Koue Bokkeveld is affected by its diverse geology, soils, topography and hydrography, and by the concomitant meso- and microclimatological differentiations deriving from the influence of the rain shadow and temperature inversion so that land cover varies subregionally and has similarly been subjected to diverse trends over time. An analysis of the regional differentiation in each time slice can be tedious without yielding many remarkable insights. Consequently, the land cover patterns per subregion are only analysed for the final year (2009) (see Table 2.4).

Regarding the various types of *natural vegetation*, subregions clearly ‘specialise’, with some

Table 2.4 Land cover by subregions in 2009

Region	**Onder-Bokveld**		**Droëhoek**		**Sandhoek**		**Witsenberg**		**Voor-Matroosberg**		**Total**	
Cover type*	*ha*	*%*	*ha*	*%*	*ha*	*%*	*ha*	*%*	*ha*	*%*	**ha**	**%**
WS	7 582	10.4	21 114	33.8	6 666	10.9	24 903	73.6	---	---	**60 265**	**24.38**
CF	33 492	45.8	---	---	12 625	20.7	---	---	---	---	**46 117**	**18.65**
SQ	---	---	21 567	34.5	22 149	36.4	---	---	133	0.8	**43 849**	**17.74**
KS	6 677	9.1	1 117	1.8	5 401	8.9	1 192	3.5	307	1.8	**14 694**	**5.94**
KA	3 201	4.4	1 462	2.3	1 516	2.5	---	---	---	---	**6 179**	**2.50**
CR	---	---	5 905	9.4	1 310	2.2	---	---	1 240	7.4	**8 455**	**3.42**
NI	4 725	6.5	92	0.2	1 633	2.7	1 465	4.3	394	2.4	**8 309**	**3.36**
MS	---	---	2 106	3.4	---	---	---	---	3 492	20.8	**5 598**	**2.26**
NH	---	---	37	0.1	---	---	---	---	6 746	40.2	**6 783**	**2.74**
WA	142	0.2	---	---	86	0.1	22	0.1	857	5.1	**1 107**	**0.45**
TW	---	---	---	---	---	---	---	---	99	0.6	**99**	**0.04**
SH	---	---	---	---	---	---	---	---	3	0.0	**3**	**0.00**
WC	793	1.1	794	1.3	385	0.6	292	0.9	85	0.5	**2 349**	**0.95**
WF	806	1.1	276	0.4	481	0.8	195	0.6	174	1.0	**1 932**	**0.78**
CD	1 213	1.7	545	0.9	1 320	2.2	525	1.6	288	1.7	**3 891**	**1.57**
TD	373	0.5	617	1.0	133	0.2	14	0.0	41	0.2	**1 178**	**0.48**
PT	264	0.4	156	0.3	155	0.3	423	1.3	53	0.3	**1 051**	**0.43**
AA	10 897	14.9	5 404	8.6	5 589	9.2	2 230	6.6	2 105	12.6	**26 225**	**10.61**
PA	2 481	3.4	1 149	1.8	1 227	2.0	2 330	6.9	672	4.0	**7 859**	**3.18**
Bu	463	0.6	210	0.3	218	0.4	267	0.8	75	0.5	**1 233**	**0.50**
T	---	---	---	---	34	0.1	---	---	---	---	**34**	**0.01**
Total	**73 109**	**100.0**	**62 551**	**100.0**	**60 928**	**100.0**	**33 858**	**100.0**	**16 764**	**100.0**	**247 210**	
%		**29.6**		**25.3**		**24.6**		**13.7**		**6.8**		**100.0**

* See Table 2.1 for explanation of codes

(admittedly smaller) communities occurring in one subregion only. Voor-Matroosberg in the south-east offers a case in point regarding Altimontane, South and North Hex Sandstone Fynbos, and Tanqua Wash Riviere. The centrally located Droëhoek and Sandhoek accommodate the widest range of fynbos and renosterveld (most biodiverse), while the western Witsenberg and Onder-Bokveld have a more modest vegetation diversity. Furthermore, each vegetation type has a dominant subregional location: Winterhoek Sandstone Fynbos in Witsenberg, Cederberg Sandstone Fynbos in Onder-Bokveld, Swartruggens Quartzite Fynbos in Sandhoek and Droëhoek, Kouebokkeveld Shale Fynbos in Onder-Bokveld and Sandhoek, Kouebokkeveld Alluvium Fynbos in Onder-Bokveld, and Ceres Shale Renosterveld in Droëhoek. These patterns remained fairly stable throughout history. The heavily-impacted wetlands of the study area retained a precarious footholds in some subregions (Onder-Bokveld, Droëhoek, Sandhoek) but they do occur in all the subregions.

The natural characteristics of the landscape dictated the proclivity for certain types of land use to locate in specific areas, especially in the lower-lying valley bottoms and along hillsides. Agricultural development was heaviest in the Onder-Bokveld (40% of agricultural area on 30% of the land), lightest in Sandhoek and Droëhoek, while the smaller Voor-Matroosberg and Witsenberg agriculture developed in proportion to their total area. It is evident that perennial agriculture and forestry plantations leave dominant footprints in the Witsenberg (30% of all PA on 14% of the land in this narrow mountain-bounded valley), although the two classes appear in all subregions. To service perennial agriculture's demand for irrigation (note that about 8 000 ha of orchards are serviced by some 5 000 ha of dams). Dams are a notable feature in each subregion. However, the relatively freer availability of irrigation waters in some subregions (Onder-Bokveld, Witsenberg) results in similar or smaller hectarage under dams than orchards, whereas the drier Sandhoek and Droëhoek subregions have proportionally larger dam surfaces due to the damming of broad, shallower river valleys. These results and conclusions concur with those of Richards (1999) in Witsenberg, Heyns (2000) in Sandhoek, Tesfamariam (2000) in Voor-Matroosberg, Fourie (2005) in Droëhoek and Vos (2009) in a selection of areas in the Koue Bokkeveld.

2.4 LAND COVER CHANGE IN THE KOUE BOKKEVELD

The static evidence presented in Section 2.3 of land cover status at each time period makes apparent some dramatic changes in land cover over time. This section concentrates in greater detail on the extent and nature of those changes in terms of, firstly, overall historical change and then moving to change during a time dubbed the industrial phase (post-1950) when technology enabled and dictated large-scale and intensified change. The quantitative empirical evidence for the two periods is provided in Tables 2.5 and 2.6 respectively. Note that the mapped results of change over time are not discussed with direct reference to patterns discernible in Appendices C10-C14 for the sake of textual prudence and because sufficient coverage of spatial change trends has been provided in the discussion of the static time slice patterns. To give effect to the two matrix schemes developed in Section 2.2.3 to model land cover change, they are used here to assess the prevalence and suitability of those frameworks to understand land cover and land use dynamics in the Koue Bokkeveld.

2.4.1 Historical land cover change: Reference state to 2009

The salient changes notable in Table 2.5 over this period was the conversion of reference state natural vegetation to human use for various purposes, mostly agriculture. The large-scale conversion of wetlands (flats and channels) is the most alarming, although some (especially the conversion to other natural groupings) may be due to delimitation inaccuracies. While the losses of wetlands to dam building and flooding might be negated by an argument that they represent a change in wetland definition only, and hence habitat gain or retention, the significant losses to annual and perennial agriculture (some 50% of all wetlands flats) must raise serious concerns about the integrity of the natural landscape. However, other serious losses of natural habitat were also recorded, particularly to low-lying fynbos on valley shales, starting with Alluvium Fynbos (KA) and Shale Fynbos (KS) and both types of inland Renosterveld (CR and MS). Inland renosterveld is a natural community of which its coastal equivalent is one of the most vulnerable types in the Fynbos biome (Mucina & Rutherford 2006).

High-lying Sandstone Fynbos (WA, SH) and arid (TW) communities were left intact, but some other mountainous sandstone communities were beginning to be impacted, although maintaining well above 90% of their original extents. The question remains whether these changes were effected gradually over the entire historical period or are they a more recent and, perhaps, accelerating phenomenon?

2.4.2 Recent land cover change: 1949-2009

The change percentages reported in Table 2.6 for the most recent 60-year period make it clear that the most drastic changes have occurred since 1949. ‘Most drastic’ means change from pristine natural conditions to permanent human-impacted land use. Low-lying fynbos on valley shales or Alluvium Fynbos (KA) and Shale Fynbos (KS) (both retaining about half their original extent) and both types of inland Renosterveld (CR and MS) (losing 20% to 30%) were variously decimated. Among all the categories, the largest recorded losses were to annual agriculture – first through ploughing new fields to grow cereals, and latterly to grow vegetables extensively. The heavy inroads made by annual agriculture into wetlands can be especially attributed to the latter development type. Perennial agriculture replaced Shale Fynbos (KS and wetlands almost more surgically), demonstrating the more demanding nature of these land use types. Tracts previously converted (annual agriculture and plantations) provided ready targets for conversion to the rapidly expanding perennial agriculture. Conradie (1942) had long ago predicted this trend. A salient manifestation of rapidly expanding intrusive agricultural activities is the expansion of area under irrigation reservoirs (CD, TD), the former now occupying ten times its 1949 extent. The conclusion is that an increased demand for irrigation water by permanent (orchards) and annual (vegetables) agriculture has been addressed through the building of many and large new dams that often consumed existing (smaller) dams, riverine channels and wetlands, but also some higher-lying fynbos, mostly the sandstone fynbos types. Expansions in built-up (Bu) and urban (T) area were also recorded. On the basis of the quantitative evaluation of land conversion in the

Table 2.5 Historical land cover change: Reference state to 2009

Row %		2009*																					Total: Reference State (ha)
		WS	CF	SQ	KS	KA	CR	NI	MS	NH	WA	TW	SH	WC	WF	CD	TD	PT	AA	PA	Bu	T	
Reference State*	WS	94.2	-	-	-	-	-	-	-	-	-	-	-	0.5	0.2	0.6	0.3	0.4	2.5	1.1	0.2	0.0500	63 816
	CF	-	94.9	-	-	-	-	-	-	-	-	-	-	0.4	0.1	0.6	0.0	0.2	2.6	1.0	0.2	0.0000	48 466
	SQ	-	-	99.0	-	-	-	-	-	-	-	-	-	0.1	0.0	0.2	0.1	0.0	0.5	0.1	0.0	0.0000	44 207
	KS	-	-	-	48.3	-	-	-	-	-	-	-	-	0.5	0.9	3.2	1.3	1.7	27.1	15.0	2.0	0.0001	29 574
	KA	-	-	-	-	39.4	-	-	-	-	-	-	-	1.1	2.8	4.1	1.1	0.4	43.8	6.0	1.4	0.0004	14 290
	CR	-	-	-	-	-	63.1	-	-	-	-	-	-	1.0	0.8	2.8	1.1	0.6	25.8	4.0	0.7	0.0000	13 025
	NI	-	-	-	-	-	-	98.1	-	-	-	-	-	0.2	0.0	0.5	0.0	0.0	0.6	0.5	0.1	0.0000	8 465
	S	-	-	-	-	-	-	-	69.2	-	-	-	-	0.7	0.0	0.1	1.3	0.1	26.8	1.5	0.3	0.0000	8 019
	NH	-	-	-	-	-	-	-	-	93.5	-	-	-	0.2	0.2	1.0	0.0	0.2	3.1	1.6	0.2	0.0000	7 125
	WA	-	-	-	-	-	-	-	-	-	100.0	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0000	1 106
	TW	-	-	-	-	-	-	-	-	-	-	100.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0000	99
	SH	-	-	-	-	-	-	-	-	-	-	-	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0000	3
	WC	3.7	4.2	2.4	6.6	3.5	3.6	0.2	1.2	2.0	-	-	-	35.2	4.6	8.8	2.9	0.8	16.8	3.0	0.5	0.0230	3 022
	WF	1.0	0.3	0.1	3.5	7.3	2.1	-	0.2	0.9	-	-	-	2.6	14.5	14.7	1.3	0.4	43.5	7.3	0.4	0.0150	5 992
Total 2009 (ha)		60 265	46 117	43 849	14 694	6 179	8 455	8 309	5 598	6 783	1 107	99	3	2 349	1 932	3 891	1 178	1 051	2 6225	7 859	1 233	34	247 209

* See Table 2.1 for legend to the land cover and land use category codes.

Table 2.6 Historical land cover change: 1949-2009

Row %		2009*																					Total: 1949 (ha)
		WS	CF	SQ	KS	KA	CR	NI	MS	NH	WA	TW	SH	WC	WF	CD	TD	PT	AA	PA	Bu	T	
1949*	WS	94.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.15	0.54	0.22	0.38	2.19	0.98	0.20	0.05	63 220
	CF	0.00	95.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.05	0.54	0.03	0.15	2.33	0.82	0.19	0.00	47 998
	SQ	0.00	0.00	99.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.04	0.17	0.07	0.01	0.16	0.02	0.02	0.00	43 948
	KS	0.00	0.00	0.00	59.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.91	2.15	0.81	1.96	19.98	12.02	1.75	0.00	20 946
	KA	0.00	0.00	0.00	0.00	45.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.30	3.31	3.65	0.94	0.25	39.92	3.45	1.18	0.00	11 442
	CR	0.00	0.00	0.00	0.00	0.00	70.49	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.83	1.80	0.72	0.59	20.38	3.69	0.64	0.00	9 827
	NI	0.00	0.00	0.00	0.00	0.00	0.00	98.37	0.00	0.00	0.00	0.00	0.00	0.18	0.04	0.43	0.00	0.05	0.47	0.41	0.05	0.00	8 422
	MS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	81.80	0.00	0.00	0.00	0.00	0.52	0.02	0.03	0.59	0.07	16.35	0.40	0.22	0.00	6 476
	NH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	94.04	0.00	0.00	0.00	0.17	0.21	1.05	0.00	0.11	2.76	1.48	0.17	0.00	7 074
	WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1 106
	TW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99
	SH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	344
	WC	3.88	4.15	2.42	6.61	3.48	4.31	0.22	1.36	2.00	0.00	0.00	0.00	35.72	4.64	6.83	2.63	0.76	17.32	3.08	0.57	0.02	3 044
	WF	1.04	0.30	0.12	3.37	7.88	1.49	0.00	0.23	1.04	0.00	0.00	0.00	2.89	15.62	14.01	1.42	0.35	43.30	6.53	0.40	0.02	5 356
	CD	0.98	0.48	0.00	1.66	0.46	3.35	0.00	0.09	0.00	0.00	0.00	0.00	0.22	0.73	79.26	8.55	0.48	2.76	0.67	0.41	0.00	314
	TD	1.49	0.24	0.00	5.47	1.66	3.90	0.00	1.96	0.14	0.00	0.00	0.00	0.75	0.50	41.52	34.04	0.92	4.57	1.15	1.64	0.00	308
	PT	2.00	1.87	0.23	8.85	1.82	2.16	0.00	0.88	0.15	0.00	0.00	0.00	1.27	1.07	3.91	0.72	11.67	29.95	22.65	10.82	0.00	683
	AA	0.85	0.92	0.58	10.39	2.27	8.35	0.10	1.42	0.08	0.00	0.00	0.00	0.53	0.84	4.33	2.05	0.38	51.43	14.58	0.89	0.00	14 801
	PA	0.94	0.22	0.05	6.81	1.54	1.99	0.08	1.06	0.02	0.00	0.00	0.00	0.53	0.33	2.85	0.63	1.37	46.72	33.09	1.79	0.00	1 904
	Bu	2.53	3.64	1.15	9.29	2.20	2.35	0.68	1.81	0.04	0.00	0.00	0.00	0.84	0.81	1.28	0.82	3.61	11.52	3.99	53.25	0.00	238
	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Total 2009 (ha)		60 265	46 117	43 849	14 694	6 179	8 455	8 309	5 598	6 783	1 107	99	3	2 349	1 932	3 891	1 178	1 051	26 225	7 859	1 233	34	247 209

* See Table 2.1 for legend to the land cover and land use category codes.

Koue Bokkeveld, it appears that land in the region is becoming increasingly used intensively and that this trend is indeed accelerating.

2.4.3 Land cover change: Intensification

Application of the criteria test for change through intensification (Table 2.7), as explained and advocated in Section 2.2.3 (Figure 2.5), confirms the above conclusion. Habitat losses and gains were recorded. A loss of 10% in natural vegetation (Nr), less than 50% of wetlands retained (Wr) and 9% of land converted to agriculture (Nl) all point to the detrimental impacts of intensified development. There is consolation in observing the fairly large amount (>10 000 ha) of land cover retentions (Dr, Fr) and losses (Ng, Wg, Al) that in some ways can be regarded as gains in wildlife habitat. The water surfaces of irrigation dams can function as refuges for waterfowl and other aquatic life forms and forestry plantations as habitat for birdlife in otherwise rather treeless landscapes offer cases in point. Unmistakable landscape and habitat losses related to water are wetlands (Wl), water bodies (Dl) and plantations (Fl), which totalled to a disturbing loss of 3 657 ha. The strongest evidence that the landscape is undergoing an intensification process regarding human habitation is given by nearly 12 000 ha of agricultural retention and intensification (category Ar signifying inter alia a replacement of annual by perennial agriculture). The question remains whether these changes are caused by inherent productivity impulses of modern development and modes in agriculture or by some other, more fickle motives?

2.4.4 Land cover change: Productivity dynamics

The criteria test for change through productivity dynamics (Tables 2.8 and 2.9), as explained and advocated in Section 2.2.3 (Figure 2.6), further endorses the conclusion about the intensification. The first feature in the table that draws the attention is that just less than 17% of the landscape underwent change (some 83% had persisted). This might be reassuring where landscape conversion is the concern, but the change was principally agricultural in nature and it occurred in the lower-lying areas of the landscape, hence particular niche habitats had been more severely impacted, normally wetlands, renosterveld and related shale-rich geological areas.

Some of the change constituted natural dynamics (change between natural categories, viz. Dn), waterbody creation (Wbc, Wbr) to improve water management or afforestation (R) to yield alternative resources for harvest. Agricultural abandonment (A) and built abandonment (E), wetland flooding for dam construction and plantation harvesting (D) yielded nearly 6 000 ha for new productive land usage. Furthermore, and perhaps most disquieting, is that more than 26 000 ha had been given over to various forms of agricultural land use and infrastructure-related construction associated with an agriculturally intensifying use of the environment. Annual agriculture

Table 2.7 Historical land cover change: Intensification 1949 to 2009

<table>
<tr><td colspan="3" rowspan="3">Row %</td><td colspan="21">2009</td><td></td></tr>
<tr><td>WS</td><td>CF</td><td>SQ</td><td>KS</td><td>KA</td><td>CR</td><td>NI</td><td>MS</td><td>NH</td><td>WA</td><td>TW</td><td>SH</td><td>WC</td><td>WF</td><td>CD</td><td>TD</td><td>PT</td><td>AA</td><td>PA</td><td>Bu</td><td>T</td><td rowspan="2">Total: 1949 (ha)</td></tr>
<tr><td colspan="12">NV</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="20">1949</td><td>WS</td><td rowspan="12">NV</td><td colspan="14" rowspan="12">Nr (197390 ha)/89.5%</td><td colspan="3" rowspan="12">Ng (3235 ha)/1.5%</td><td colspan="4" rowspan="12">Nl (19937 ha)/9.0%</td><td rowspan="12">220561</td></tr>
<tr><td>CF</td></tr>
<tr><td>SQ</td></tr>
<tr><td>KS</td></tr>
<tr><td>KA</td></tr>
<tr><td>CR</td></tr>
<tr><td>NI</td></tr>
<tr><td>MS</td></tr>
<tr><td>NH</td></tr>
<tr><td>WA</td></tr>
<tr><td>TW</td></tr>
<tr><td>SH</td></tr>
<tr><td>WC</td><td rowspan="2">W</td><td colspan="14" rowspan="2">Wr (3914 ha)/46.6%</td><td colspan="2" rowspan="2">Wg (1114 ha)/13.3%</td><td colspan="5" rowspan="2">Wl (3372 ha)/40.1%</td><td rowspan="2">8400</td></tr>
<tr><td>WF</td></tr>
<tr><td>CD</td><td rowspan="2">D</td><td colspan="17" rowspan="2">Dr (587 ha)/94.4%</td><td colspan="4" rowspan="2">Dl (35 ha)/5.6%</td><td rowspan="2">622</td></tr>
<tr><td>TD</td></tr>
<tr><td>PT</td><td></td><td colspan="17">Fr (250 ha)/36.6%</td><td colspan="4">Fl (433 ha)/63.4%</td><td>683</td></tr>
<tr><td>AA</td><td rowspan="3">A</td><td colspan="17" rowspan="3">Al (5323 ha)/31.4%</td><td colspan="4" rowspan="3">Ar (11620 ha)/68.6%</td><td rowspan="3">16943</td></tr>
<tr><td>PA</td></tr>
<tr><td>Bu</td></tr>
<tr><td colspan="3">Total 2009 (ha)</td><td>60265</td><td>46117</td><td>43849</td><td>14694</td><td>6179</td><td>8455</td><td>8309</td><td>5598</td><td>6783</td><td>1107</td><td>99</td><td>3</td><td>2349</td><td>1932</td><td>3891</td><td>1178</td><td>1051</td><td>26225</td><td>7859</td><td>1233</td><td>34</td><td>247209</td></tr>
</table>

* See Table 2.1 and Figure 2.5 for legend to change category codes

Table 2.8 Historical land cover change: Productivity dynamic 1949 to 2009

Row %			2009																				Total: 1949 (ha)
			WS	CF	SQ	KS	KA	CR	NI	MS	NH	WA	TW	SH	WC	WF	CD	TD	PT	AA	PA	Bu	T	
			NV																					
	WS	NV	**P 88.7%**												**Dn**		**Wbc 1.4%**		**R 0.4%**	**Ia 9.8%**		**Ld 0.45%**	**In 0.01%**	63220
	CF																							47998
	SQ																							43948
	KS																							20946
	KA																							11442
	CR																							9827
	NI																							8422
	MS																							6476
1949	NH																							7074
	WA																							1106
	TW																							99
	SH																							3
	WC		**Dn 1.7%**												**P 35.7**		**Wel 13.3%**							3044
	WF															**P 15.6**								5356
	CD		**E 20.8 (179/860%)**												**Wbr 26.0%**		**P 79.3**	Wbr						314
	TD																	**P 34.0**						308
	PT		**D 77.5%**																**P 11.7%**	**D**				683
	AA		**A 24.9%**														**Wbc**		**R**	**P 51.4**	**Ci 14.6%**			14801
	PA																			**Ce 46.7%**	**P 33.1**			1904
	Bu		**E**																			**P 53.3**		238
Total 2009 (ha)			60265	46117	43849	14694	6179	8455	8309	5598	6783	1107	99	3	2349	1932	3891	1178	1051	26225	7859	1233	34	247210

Table 2.9 Summary historical land cover change: Productivity dynamic 1949 to 2009

Code	Land cover change class	*ha*	*Totl*	*%*
P1	Persistence: NV (no change in land use)	195577	220561	88.7
P2	Persistence: WC (no change in land use)	1087	3044	35.7
P3	Persistence: WF (no change in land use)	837	5356	15.6
P4	Persistence: CD (no change in land use)	249	314	79.3
P5	Persistence: TD (no change in land use)	105	308	34.0
P6	Persistence: PT (no change in land use)	80	683	11.7
P7	Persistence: AA (no change in land use)	7613	14801	51.4
P8	Persistence: PA (no change in land use)	630	1904	33.1
P9	Persistence: Bu (no change in land use)	127	238	53.3
PTotl	**Persistence (no change in any land use)**	**206305**	**247209**	**83.5**

Code	Land cover change class	*ha*	*Totl*	*%*
Dn	Natural dynamic (natural changes occurred)	3802	228961	1.7
Wbc	Waterbody creation	3411	237266	1.4
Wbr	Waterbody retention	162	622	26
A	Agricultural abandonment	4157	16705	24.9
R	Afforestation (converted into plantation)	963	246288	0.4
E	Built abandonment	179	860	20.8
Wel	Wetland loss (flooded)	1114	8400	13.3
D	Deforestation (plantation replaced)	530	683	77.5
Ia	Agrarian intensification (agriculture substitute previous land use)	22400	229583	9.8
Ce	Extensive conversion (agriculture)	890	1904	46.7
Ci	Intensive conversion (agriculture)	2158	14801	14.6
Ld	Light development (farmstead development)	1108	246971	0.5
In	Urban intensification (converted to urban)	34	247210	0.01

* See Figure 2.6 for legend to change category codes

almost doubled in extent, thanks to innovations in the machinery used to efficiently cultivate and harvest crops. The decisive argument for declaring productivity-driven landscape conversion through a land use intensification process is the more than 3 000 ha of land converted to more profitable, high-intensity agriculture (fruit rather than cereal production) and the sophisticated means available for its proper and modern (value-adding) accommodation in the built-up infrastructure.

To answer the former question whether changes are caused by inherent productivity impulses of modern development and modes in agriculture or by some other, more fickle motives, the answer is that the Koue Bokkeveld is a region subject to an intensifying human usage regime characterised by agricultural intensification driven by an evolving and sophisticated economic productivity mechanism. The next question therefore arises whether this change has a detrimental effect on the natural functioning of the landscape that might eventually disadvantage human habitation and economic utilisation of that landscape? In the next chapter the influence of the structure of the landscape on land cover change is gauged.

CHAPTER 3 LANDSCAPE STRUCTURE IN THE KOUE BOKKEVELD

Having considered the types of land cover and the temporal and spatial extent of land cover changes in the Koue Bokkeveld, it is opportune to evaluate landscape structure as one of the main factors associated with land use and land cover change (Hengl & MacMillan 2009). The theoretical elements of landscape structure are explored first, after which the methods employed to quantify these elements in this study are treated. The chapter concludes by reporting the empirical results of applying these methods to the Koue Bokkeveld to obtain an understanding of the region's landscape structure and its variations.

3.1 LANDSCAPE STRUCTURE ELEMENTS

Morphology is the form of landscapes in terms of its measurable structural elements like slope, aspect, curvature and form (Pike, Evans & Hengl 2009). These four and distance to surface water, which is especially pertinent to agriculture, are considered in this study. A digital elevation model (DEM), as a raster layer where each cell represents the height above sea-level as a value at the centre of that cell, is used to model structure, hydrology and other functions in landscapes by using models developed for the purpose (Hengl & MacMillan 2009). These models are expanded on in this section.

3.1.1 Landscape structure: Slope

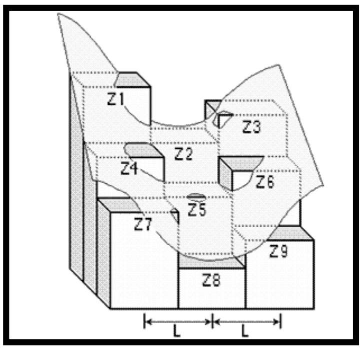
Slope is the rate of maximum change in elevation of the surface in the steepest descending direction (Gallant & Wilson 2000). Slope can be expressed in degrees or percentages (ESRI 2008c) and most slope algorithms use a 3x3 DEM cell matrix input to calculate slope (Wu, Li & Huang 2008) usually in a GIS. Slope determines most calculations relating to the effect of gravity on objects, like rate of erosion, rate of water flow and movement of organisms on and beneath the surface (Gallant & Wilson 2000). Steep slope can be a hindrance to many natural (e.g. animal movement) and human processes in the landscape (Gotelli 2001; Donald 2005). Awasthi et al. (2002) compared the occurrence of agriculture types with slope and found typical associations. The DA (1983) declared the maximum percentage slope above which cultivation in the Western Cape is disallowed at 20% because erosion potential is too high on steeper slopes. Consequently, in this research, slope was simply divided into two classes (<20% and >20%) and qualified as cultivation allowed and cultivation disallowed respectively.

3.1.2 Landscape structure: Aspect

Aspect is the value used to indicate the direction in which the steepest slope of a cell area in a DEM is directed (Gallant & Wilson 2000; ESRI 2008d; Wondie et al. 2012). Flow direction can be used as an approximate alternative for aspect. Aspect is used in simple solar radiance calculations (Gallant & Wilson 2000; Wondie et al. 2012) and the aspect tool in ArcGIS is useful for its calculation (ESRI 2008e). In agriculture, some crops prefer specific aspects, such as southern or northern, due to their sensitivity to specified amounts of solar illumination (Wondie et al. 2012). These preferences are of course hemispherically opposite. In an area of very low slope, aspect is less important than in steeply sloping areas (Gallant & Wilson 2000).

3.1.3 Landscape structure: Curvature

Curvature measures the rate of curve of an imaginary line or surface through points in a slope and is measured in radiance per metre (Gallant & Wilson 2000). Figure 3.1 shows a curved surface passing through a point on a surface.



Source: ESRI (2008f: 1)

Figure 3.1 The curvature through a point on a surface

Curvature is an indicator of accumulation at or dispersion from any given point on a landscape's surface (Donald 2005). Three types of curvature are typically calculated: profile, planform and total curvature. The Curvature tool in ArcGIS calculates these for an area (ESRI 2008f). Profile curvature is parallel to the direction of the maximum slope. A negative value indicates that the surface is upwardly convex at that cell; a positive profile value indicates that the surface is upwardly concave at that cell, and a value of zero indicates that the surface is linear. Profile curvature affects the acceleration or deceleration of flow across a surface. Planform curvature is perpendicular to the direction of the maximum slope, positive values indicating sideward convexity; negative values plan concavity at a cell; and zero indicates the surface is linear. Profile curvature relates to the convergence and divergence of flow across a surface. Planform and profile curvature are both used as indicators in landform classification methods, as in that of MacMillan et al. (2000). Total curvature was used in this research because it relates to the effect cultivation might have on sloping landscapes.

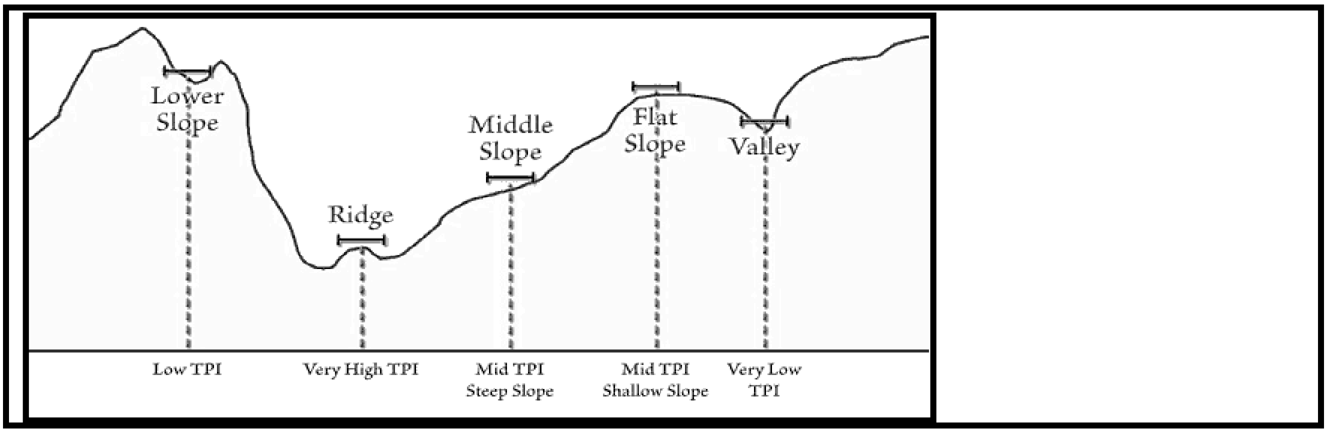
3.1.4 Landscape structure: Topographic position index

The topographic position index (TPI) shows the relative height of a cell compared to cells in its neighbourhood (Iampietro & Kvitek s.a; Weiss 2001; Jenness 2006). A positive TPI value indicates that a cell is higher than its neighbourhood cells; a negative TPI shows that a cell is lower than the neighbourhood cells. TPI classes range from positive to negative values: positive TPI tends toward ridge tops and hilltops, while valleys and canyons tend toward negative values. Values near zero indicate flat areas if slope is shallow and mid-slope position if slope is significant Jenness (2006). TPI values differ when applied at different neighbourhood scales so that neighbourhood scale affects the TPI classification of a landscape (Iampietro & Kvitek s.a; Weiss 2001; Jenness 2006).

TPI is used in both slope position and landform classification and it is considered appropriate for use in agricultural landscapes as demonstrated by Tagil & Jenness (2008). The Topographic tool for ArcGIS created by Dilts (2010) and based on the tool developed by Jenness (2006), was selected for use here. In the following subsections the classification of slope position and landform type are examined separately to elucidate their use in this research.

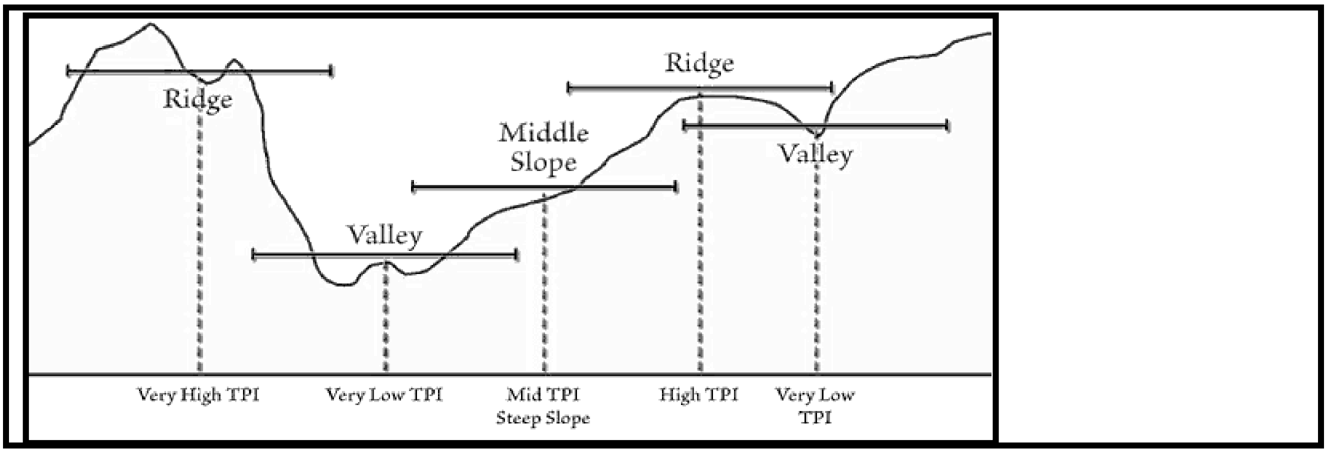
3.1.4.1 Slope position classification

The effect of landscape scale on TPI classification is significant – as Figures 3.2 and 3.3 graphically illustrate. It is therefore imperative to experiment with various landscape scales for a study area to determine the appropriate neighbourhood model for analysis of a given location.



Source: Jenness (2006: 7)

Figure 3.2 Small-neighbourhood slope position classification



Source: Jenness (2006: 7)

Figure 3.3 Large-neighbourhood slope position classification

The slope position classification model created by Dilts (2010) is based on the original by Jenness (2006) that uses TPI for classification. The classes used in the slope position classification model are the six shown in Table 3.1 to distinguish topographic position from valley bottom to ridge lines.

Table 3.1 The slope position classes used in the research

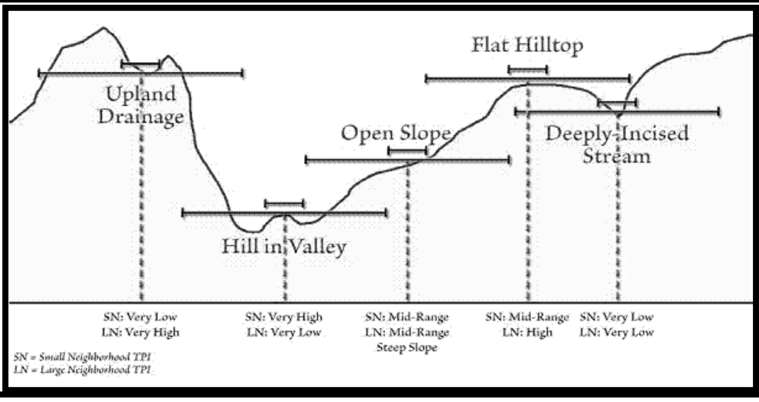
Code	**Description**	**Code**	**Description**
1	Valley	4	Mid-slope
2	Toe-slope	5	Upper-slope
3	Flat	6	Ridge

The slope position classification suggested by Weiss (2001) and Iampietro & Kvitek (s.a) was used to classify the slope position in the Koue Bokkeveld landscape. Classification runs were performed in various topographical neighbourhoods to determine the final neighbourhood size and type for this project. They are explained later.

3.1.4.2 Landform type classification

MacMillan & Shary (2009: 228) define a landform as: "... a physical feature of the Earth's surface having a characteristic, recognisable shape and produced by natural causes...", to which Martnuzzi et al. (2007: 161) add that they "...result from interactions among underlying rock layers, tectonic forces, climate, and human activities." These definitions are adopted here, because they guide the choice of a classification method as the type of landform classification depends on the use to which it is put. The generally accepted landform classification method uses two TPI neighbourhoods of different scales to classify landforms in a landscape, as demonstrated in Figure 3.4 for two complex TPI neighbourhoods (Iampietro & Kvitek s.a; Weiss 2001; Jenness 2006).

The landform classification model created by Dilts (2010), based on that of Jenness (2006), uses TPI for classification. The classes used in the landform classification model for this research are shown in Table 3.2 and they reflect the complex and more informative nature of the adopted



Jenness (2006: 9)

Figure 3.4 Landform classification with large- and small-neighbourhood topographic position index

Table 3.2 Landform type classes used in the research

Code	Type description	Code	Type description
1	Canyons, deeply incised streams	6	Open slopes
2	Mid-slope drainages, shallow valleys	7	Upper slopes, mesas
3	Upland drainages, headwaters	8	Local ridges, hills in valleys
4	U-shaped valleys	9	Mid-slope ridges, small hills in plains
5	Plains	10	Mountain tops, high ridges

system. The system lends itself to explanation and even prediction of real land cover and land use patterns in a landscape.

3.1.5 Proximity of agriculture to water sources

The topography of a watershed influences the surface water flow in an area, thus affecting the response of the watershed hydrology to rainfall run-off in the area. Catchment delimitations and distance from water sources of any location are elements of landscape structure that help explain development patterns resulting from altered technology that releases agricultural practice from the confines (e.g. slope, gravity) of the natural landscape as a resource. In winter-rainfall regions an increase in dam storage is associated with agricultural expansion – the case obtaining in the Koue Bokkeveld as reported earlier. DEMs are widely used to derive attributes for hydrological modelling (Wu, Li & Huang 2008) and potential run-off. Both were executed in this research.

In this study wetland channels (WC, linear features) and all dams (TD, CD, area features) were considered as water sources, whereas wetland flats (WF, area features) were not since they are either being replaced by agriculture or do not freely yield surface waters as a resource. Three maps each were created for 1949 and 2009, namely a map displaying the distance to wetland channels; a map showing distances to clear-water and turbid-water dams; and a map showing distance to wetland channels and dams. All distances were measured in metres in GIS. Annual agriculture (AA), perennial agriculture (PA) and plantations (PT) were combined with these three water-related layers for each target year to determine the change in distances to water sources over time. A change in distance indicates a change in agricultural practice driven by technological development in dam construction and irrigation methods. It also serves to identify natural vegetation communities that are at risk of replacement.

3.2 METHODS OF STRUCTURE AND LAND COVER ANALYSIS

The properties of landscape morphology described in the previous section were all analysed by GIS layer combination of the landscape variables and the land cover maps of the three periods to determine the spatial relationships between land cover type and its morphological position in the landscape. In this subsection, general concepts and tools for landscape analysis are introduced and the methods for determining associations between land cover and slope, aspect and curvature, topographic position, slope position, landform type and proximity to water sources are explained.

3.2.1 General concepts and tools for landscape analysis

The literature was probed for empirical landscape analyses that considered the landscape elements discussed above and used models for landscape morphological analysis. Recommendations made in the literature about the various methods and software platforms informed the analyses done in this study. The salient results of this exercise are reported in this subsection.

Landscape elements for analyses concern recognition of primary topographic attributes (Gallant & Wilson 2000) and morphological aspects of landform (Pike, Evans & Hengl 2009). Van Asselen & Seijmonsbergen (2006) used the geology of an area to combine geomorphology and slope to classify landforms, while Fourie (2005) combined aspects of morphology and landform to analyse landscape aesthetics and Awasthi et al. (2002) explained land use types and slope through layer combination.

Landscape is best portrayed through *hillshading* and quantified through various *modelling methods* (Tagil & Jenness, 2008). A hillshade image shows the morphology of the area in three-dimensional perspective by calculating the illumination effect on an area (ESRI 2008b) from a DEM to extract topographical attributes (Burrough & McDonnell 1998; Wu, Li & Huang 2008; Reuter et al. 2009). Sound theory underlies DEM extraction methodologies (MacMillan & Shary 2009). Geometric analysis for landscape segmentation to aid morphological landscape classification has become an exceptionally functional analytical instruments (Minár & Evans 2008).

Most analytical techniques perform *landscape or landform classification* for specific purposes (Klingseisen 2004; MacMillan & Shary 2009). A range of landform classification schemes exist (Tagil & Jenness 2008; MacMillan & Shary 2009). The Jenness (2006) landform classification is based on the TPI to classify the slope position of a pixel by comparing it with a resizable matrix. In the classification tool, two slope position indexes (SPI) combine matrixes of different sizes to form the TPI (Iampietro & Kvitek s.a; Weiss 2001; Jenness 2006). Saadat et al. (2008) have used a classification scheme developed by Dessaunettes et al. (1971) to classify landforms and Donald (2005), building on MacMillan et al. (2000), used a somewhat obscure 15-class topographic classification scheme of landforms but ignored position in the landscape. The landscape position (LPOS) index measures the difference in elevation of two points in a radius on a DEM (Fels 1994) as demonstrated in Porto Rico by Martnuzzi et al. (2007). In all cases observation scale is paramount in determining the position of landform features (Tarolli & Fontana 2009).

In the world of computerised landscape analysis the *available software platforms and packages* determine procedural pathways. GIS application in landscape analysis has become common (Reuter et al. 2009) and various platforms for extracting morphological parameters from DEMs are on offer – especially from ESRI (Reuter & Nelson 2009). ESRI's ArcView 3.3 has been upgraded for ArcMap 9.2 and 9.3 (Dilts 2010; Jenness 2006) to classify a DEM into topographic position and landform classes. The Slope tool in ArcGIS (ESRI 2006; 2008b) is based on the average maximum technique of Jenson & Domingue (1988), and the Toposhape tool in IDRISI use the landform classification developed by Pellegrini (1995). This latter method uses a 3x3 matrix to classify the position of a pixel. The TPI classification method is more accurate because it uses two matrixes to determine the position of a pixel (in GeoMedia (Klingseisen, Metternicht & Paulus (2008) following the topographic classification developed by Speight (1990)).

Considering the morphology of the study area and the level of detail, the topographic tool developed by Jenness (2006) was employed for the landform classification in this study.

3.2.2 Slope and land cover analysis

The procedures followed to perform the slope-land cover analysis are sequenced in Figure 3.5. Using the 20-m DEM as data source, slope was calculated using the Slope tool in ArcGIS with its 3x3 matrix pass (ESRI 2008b), performing the average maximum technique developed by Jenson & Domingue (1988). The resulting slope layer was first divided in two classes, viz. below 20% (cultivation allowed) and above 20% (cultivation disallowed) according to the DA (1983) regulation. Slope in the cultivable area was classified further to five classes: <2% (flat land); 2-5%

(undulating, nearly flat); 5-9% (lower hill slopes); 9-14% (medial hill slopes); and 14-20% (steep hill slopes).

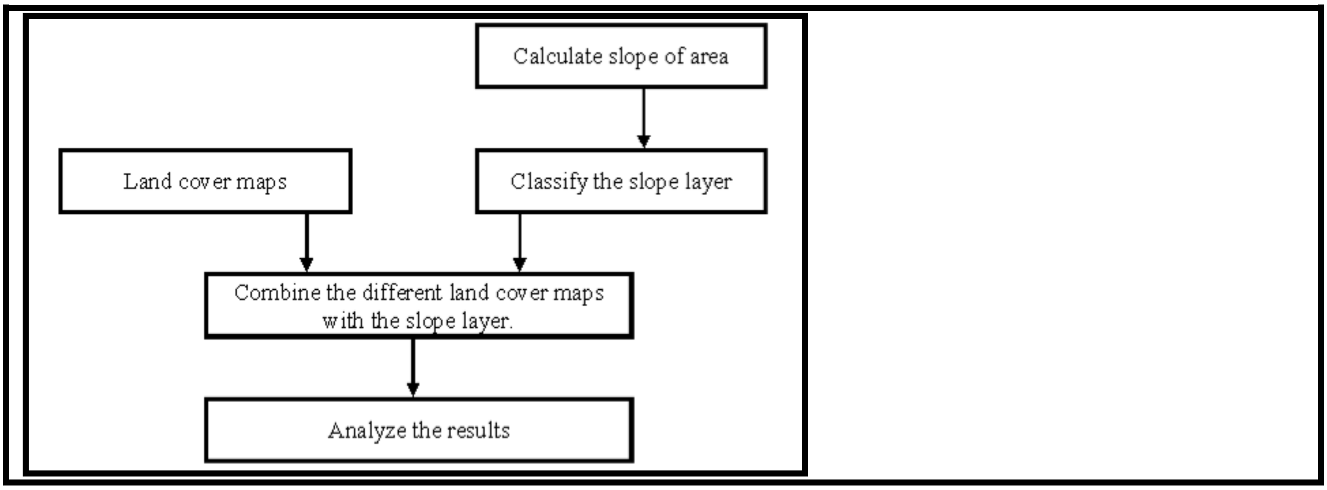


Figure 3.5 The procedures for slope-land cover analysis

Slopes steeper than 20% (non-cultivable steep slopes) formed the sixth slope class. To standardise cell size across slope and land cover to 2.5-m cell resolution, the Resample tool in ArcGIS was employed. The Combine tool in ArcGIS was used to combine the classified slope layer with each of the land cover layers (derived from Chapter 2) and finally the resulting database file was exported and the analyses performed in Excel.

3.2.3 Aspect and land cover analysis

The procedures followed to perform the aspect-land cover analysis are sequenced in Figure 3.6. Using the 20 m DEM as data source, aspect was calculated using the aspect tool in ArcGIS. The

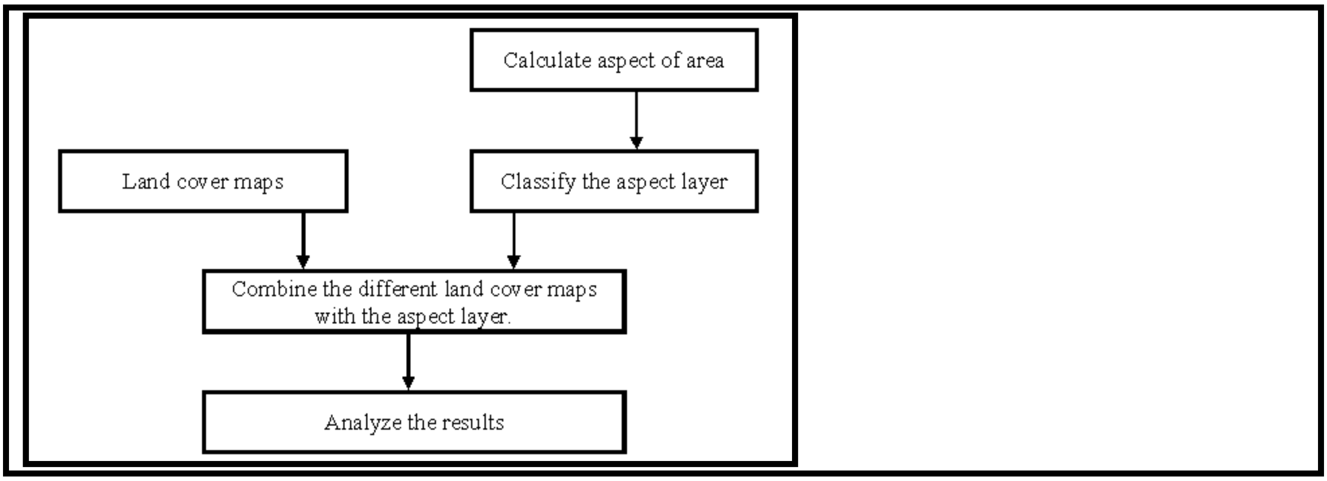


Figure 3.6 The procedures for aspect-land cover analysis

resulting aspect layer was divided in the eight main primary and secondary directional classes shown in Table 3.3 using the Reclassify tool in ArcGIS. To standardise cell size across slope and land cover to 2.5-m cell resolution, the Resample tool in ArcGIS was employed. The Combine tool

Table 3.3 Aspect classification used in the land cover analyses

Code	Class Name	Code	Class Name
1	North (337.5°-22.5°)	5	South (157.5°-202.5°)
2	North-east (22.5°-67.5°)	6	South-west (202.5°-247.5°)
3	East (67.5°-112.5°)	7	West (247.5°-292.5°)
4	South-east (112.5°-157.5°)	8	North-west (292.5°-337.5°)

in ArcGIS was used to combine the classified slope layer with each of the land cover layers (derived from Chapter 2) and the resulting database file was exported and the analyses performed in Excel.

3.2.4 Curvature and land cover analysis

The procedures followed to perform the curvature-land cover analysis are sequenced in Figure 3.7. Again using the 20-m DEM as data source, curvature was calculated using the Curvature tool in

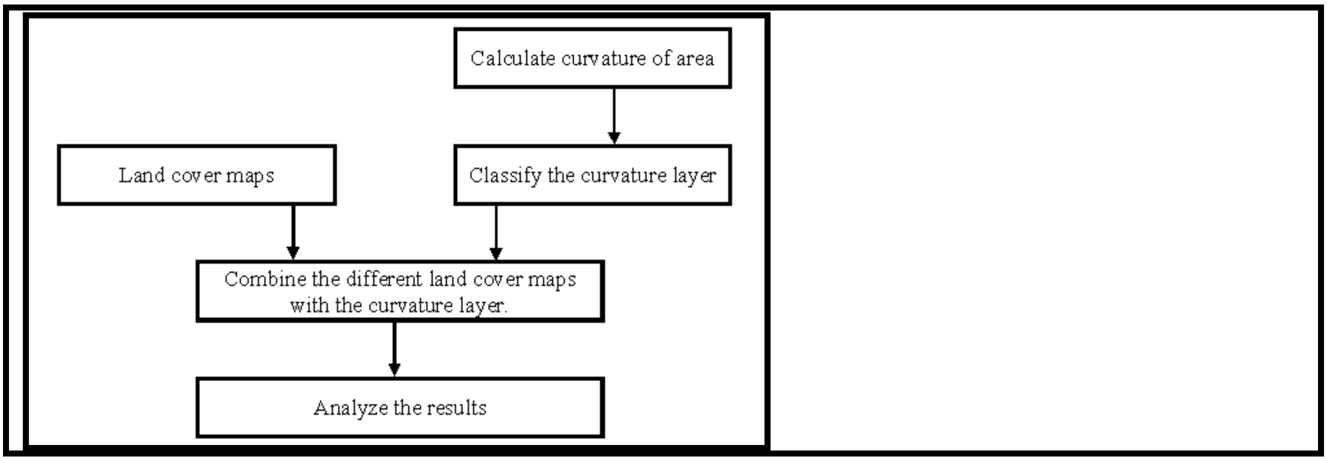


Figure 3.7 The procedures for curvature-land cover analysis

ArcGIS. The resulting curvature layer was classified into three classes, i.e. a convex, concave and neutral. To standardise cell size across curvature and land cover to 2.5-m cell resolution, the Resample tool in ArcGIS was employed. The Combine tool in ArcGIS was used to combine the classified curvature layer with each of the land cover layers (derived from Chapter 2) and finally the resulting database file was exported and the analyses performed in Excel.

3.2.5 Topographic position analysis

Two different types of topographical classification methods were combined with the land cover maps to determine the position of the land cover types, i.e. slope position (SP) and landform. Landform classes are more complex than slope position, although the calculations are similar and comparable products result.

3.2.5.1 Slope position and land cover analysis

The procedural sequences to perform the SP-land cover analysis is shown in Figure 3.8. Slope position was determined from the 20 m DEM as input and the combine tool in ArcGIS was used to combine the resampled SP layers with each of the land cover layers. The resulting table was

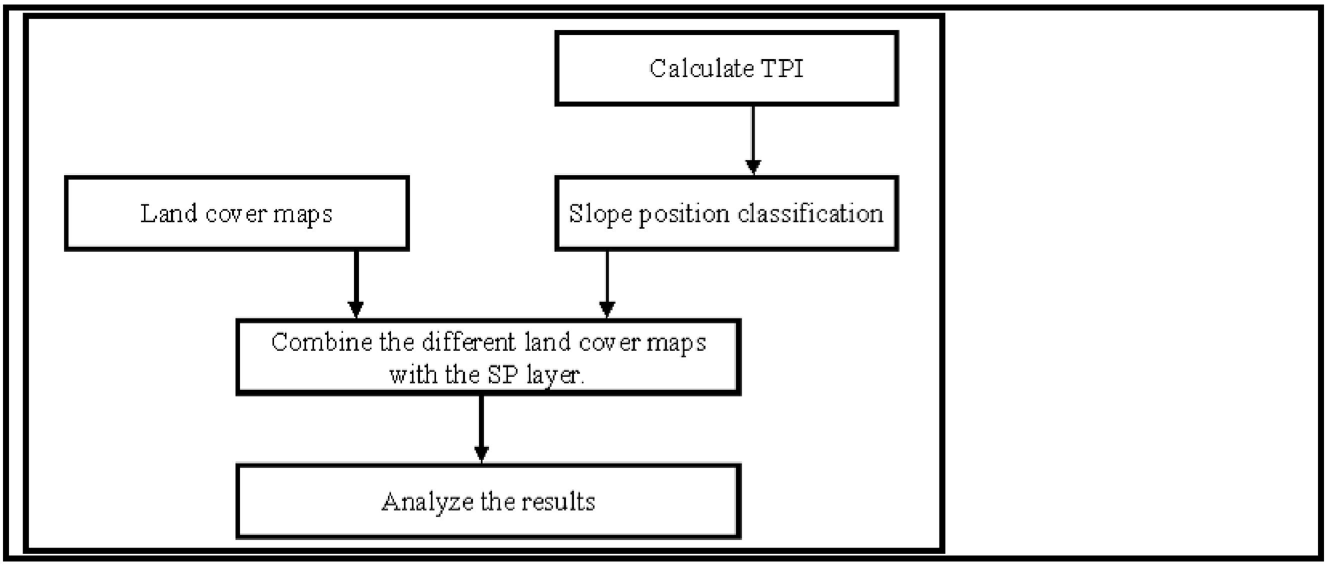


Figure 3.8 The procedures for slope position-land cover analysis

exported to a database file and the analyses performed in Excel. The model designed to create the SP-land cover combination layers appears in Figure 3.9. The original SP classification model was created by Jenness (2006) and performed here through the resample tool in ArcGIS. In sequence,

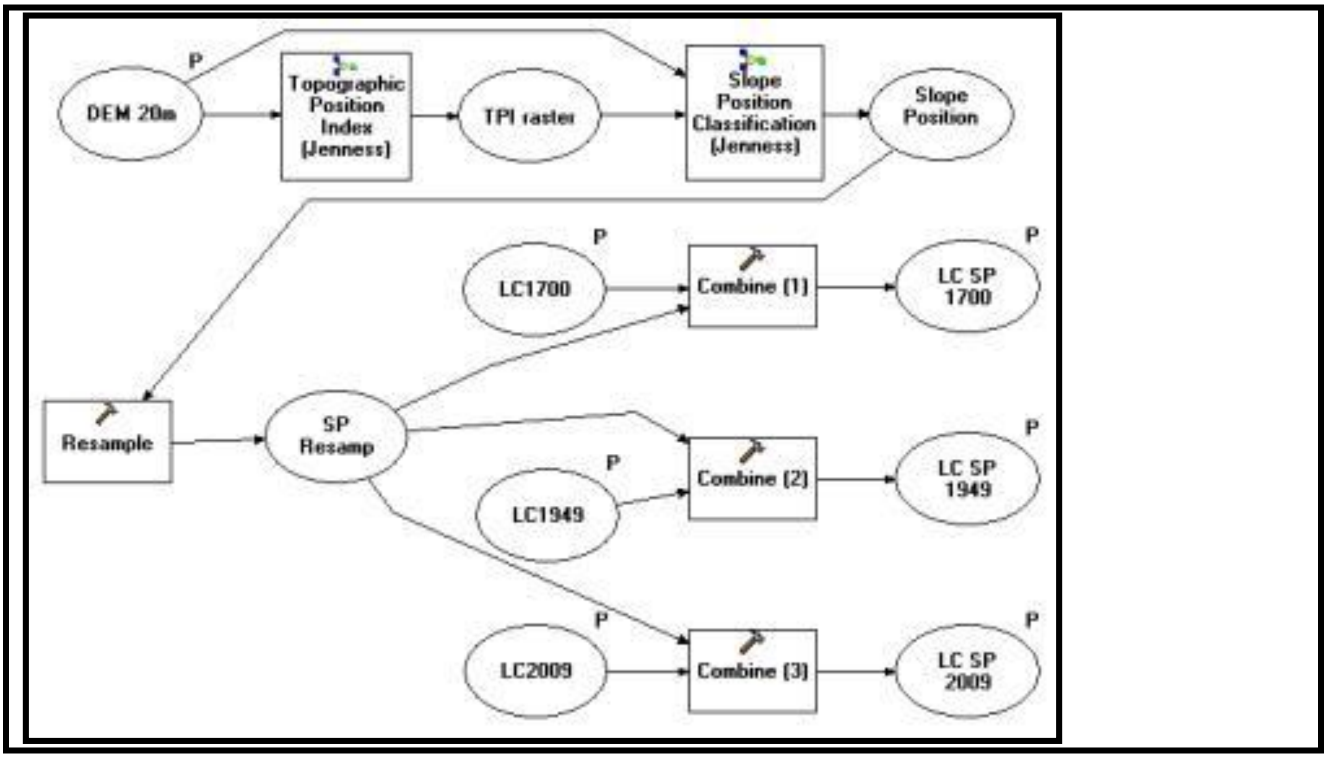


Figure 3.9 Slope position calculation and land cover combination model

the Topographic Position Index (developed by Jenness 2006) tool was applied to a 3x3 matrix on the DEM to calculate TPI. The Slope Position Classification (developed by Jenness 2006) tool was similarly applied with the TPI layer to derive SP (classified as in Table 3.1). To standardise cell size across SP and land cover layers to 2.5-m cell resolution, the Resample tool in ArcGIS was employed. The Combine tool in ArcGIS was used to combine the classified SP layer with each of the land cover layers.

3.2.5.2 Landform and land cover analysis

The procedures followed to perform the landform-land cover analysis are sequenced in Figure 3.10. With the 20-m DEM as data source, landform was calculated using the Landform Classification tool (Jenness 2006) in ArcGIS and as clarified in Section 3.1.4.2. This entailed the application to 3x3- and 15x15-cell matrixes as neighbourhoods in the DEM and landforms

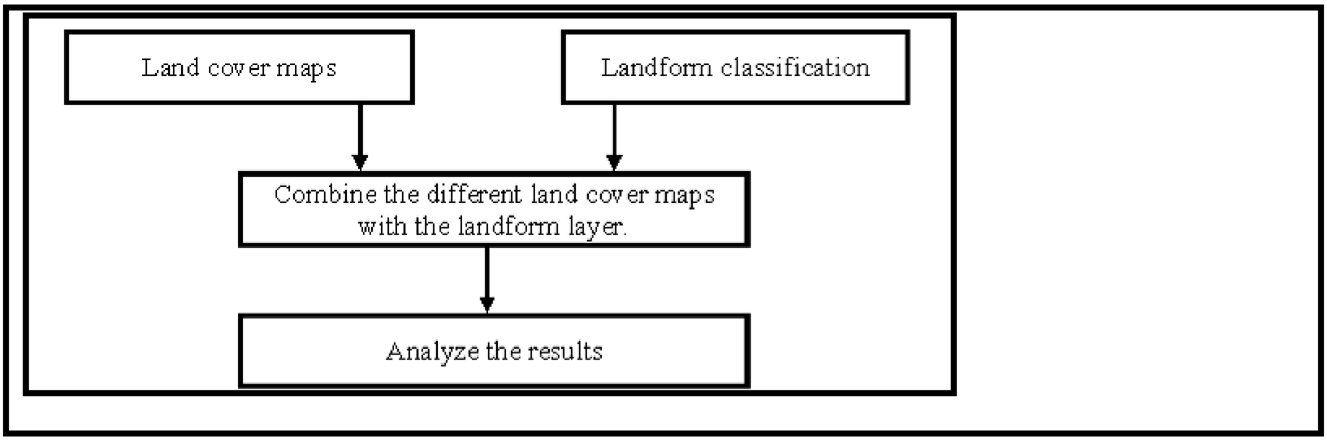


Figure 3.10 The procedures for landform-land cover analysis

classified as indicated in Table 3.2. To standardise cell size across landform and land cover to 2.5-m cell resolution, the Resample tool in ArcGIS was employed. The Combine tool in ArcGIS was used to combine the classified landform layer with each of the land cover layers and the resulting database file was exported and the analyses performed in Excel.

3.2.6 Proximity of agriculture to water sources

Image layers for each of the three target years were created sequentially following the procedures shown in Figure 3.11. The model allowed for extraction of features of interest from each land cover layer, using the Classify tool in ArcGIS. These raster layers were converted to vector format (Raster to Polygon tool) and multiple distance buffers in metres were generated using the Multiple Ring Buffer tool. The classes were: 0-100 (close); 101-200 (intermediate); 201-500 (mid-distance); 501-1000 (distant); >1000 (far distant). The resulting buffer layers were converted

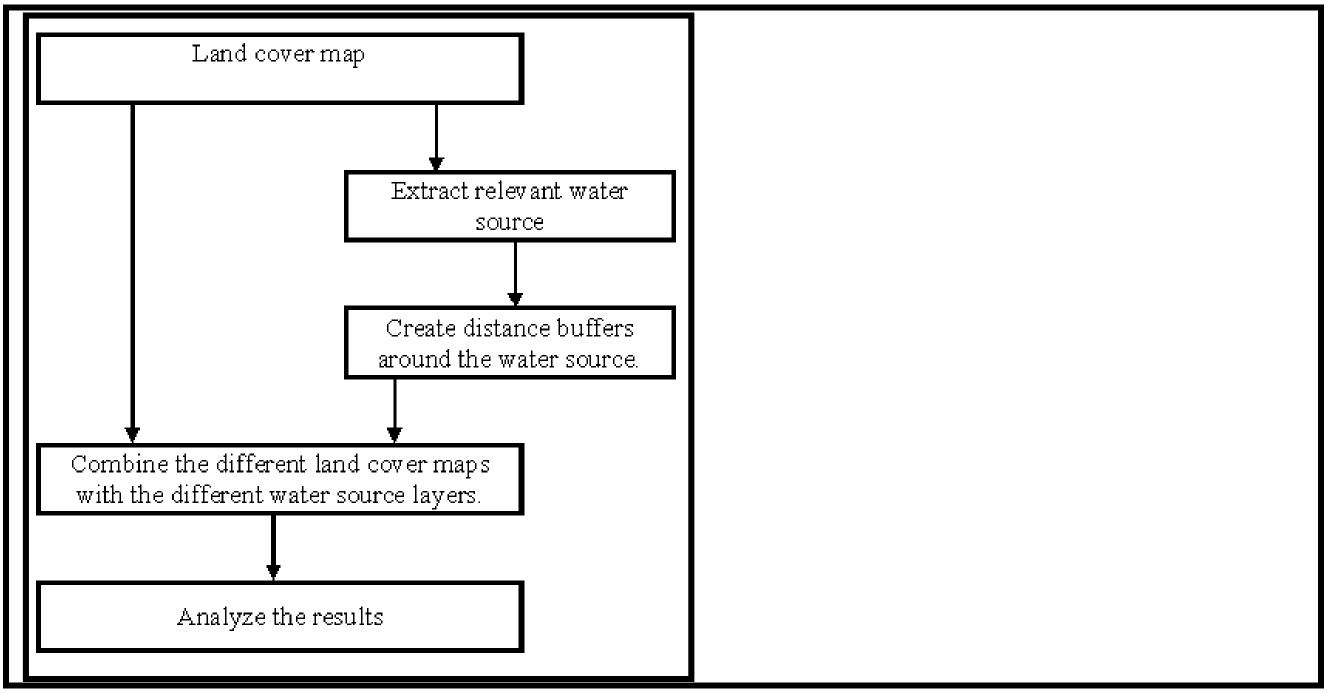


Figure 3.11 The procedures for water source distance to agriculture analysis

to raster and combined with the land cover layer using the Combine tool in ArcGIS and the attribute table was exported to Excel for analysis,

3.3 KOUE BOKKEVELD LANDSCAPE STRUCTURE AND LAND COVER ASSOCIATION

In this section the methods described in the foregoing sections are applied to the Koue Bokkeveld landscape. The associations between the temporal and spatial land cover patterns and each landscape structural element – slope, aspect, curvature, topographical position, slope position, landform (similar to those used in Tagil & Jenness, 2008) and proximity of agriculture to water sources – are explored by subregion.

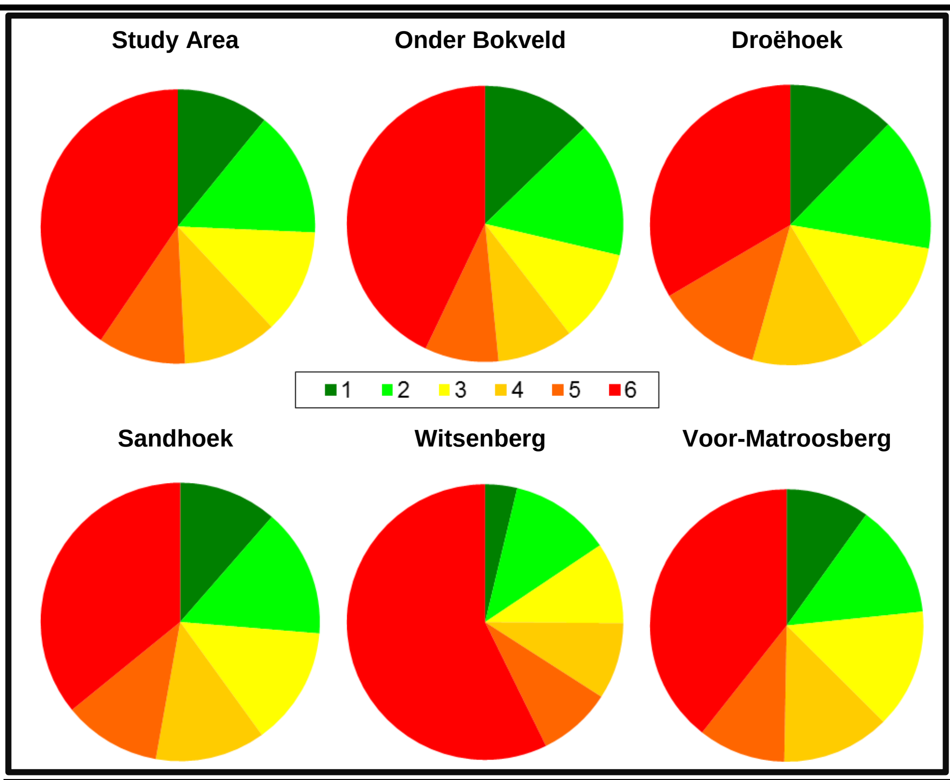
3.3.1 Slope: Spatial comparisons

Slope steepness determines the location of land development in the Koue Bokkeveld, with agriculture congregating in flat valley bottoms while leaving the steeper sloping hills and mountains in their natural state. These results concur with findings in Tagil & Jenness (2008) and Wondie et al. (2012). Because some 60% of the total Koue Bokkeveld area is legally cultivable (slope <20%), it is worthwhile analysing slope's relationship with land cover at subregional and regional scale.

Slope is a foremost determinant of where agriculture can be practiced, so that slope classes are reliable indicators of the suitability of land for large-scale agriculture and, conversely, the threat to natural vegetation. The more suitable a valley is for agriculture, the more threatened are the wetlands and other vegetation types in that valley. Table 3.4 and Figure 3.12 report the slope regimes of each subregion. Agriculture requires relatively level land, especially annual agriculture,

Table 3.4 Slope distribution in subregions

Slope %	Total		Onder-Bokveld		Droëhoek		Sandhoek		Witsenberg		Voor-Matroosberg	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
<2	26 872	10.9	9 333	12.8	7 678	12.3	6 941	11.4	1 267	3.7	1 657	9.9
2-5	36 636	14.8	11 626	15.9	9 640	15.4	9 092	14.9	4 015	11.9	2 260	13.5
6-9	30 530	12.4	7 973	10.9	8 593	13.7	8 369	13.7	3 224	9.5	2 367	14.1
10-14	27 539	11.1	6 486	8.9	8 091	12.9	7 773	12.8	3 041	9.0	2 146	12.8
15-20	25 487	10.3	6 309	8.6	7 631	12.2	6 893	11.3	2 924	8.6	1 732	10.3
>20	100 145	40.5	31 383	42.9	20 918	33.4	21 858	35.9	19 387	57.3	6 601	39.4
Total (ha)	247 210	100.0	73 110	100.0	62 551	100.0	60 926	100.0	33 858	100.0	16 763	100.0



1	<2% (Flat)	2	2-5% Undulating, nearly flat	3	6-9% Lower hill slopes
4	10-14% Medial hill slopes	5	15-20% Steep hill slopes	6	>20% Steep mountain slopes

Figure 3.2 Slope classes by subregion

since heavy tillage and harvesting machinery are used in modern practice. Voor-Matroosberg and Witsenberg have the least flat (highly cultivable, slope <5%) land and, by contrast, the most non-cultivable (steeply sloping, slope >20%) land – almost 60% of Witsenberg's area is non-cultivable. Droëhoek, Sandhoek and Onder-Bokveld have the least steeply sloping land so that it is not surprising to see proportionally large tracts of perennial agriculture in Witsenberg and large cereal (annual agricultural) fields in the latter three subregions.

Judging by location on legally cultivable slopes, the imminent threat to specific groups of natural vegetation is clear from Table 3.5, with more than 80% of Kouebokkeveld Shale and Alluvium Fynbos, Ceres Shale Renosterveld, Tanqua Wash Riviere and all wetland types in cultivable areas. Not surprisingly, early agricultural development (1949) was largely concentrated on such

Table 3.5 Land cover by cultivable slope over time

(% of area)	**Reference State**		**1949**		**2009**	
Land cover code *	**Cultivable**	**Non-cultivable**	**Cultivable**	**Non-cultivable**	**Cultivable**	**Non-cultivable**
WS	46.4	53.6	46.0	54.1	43.7	56.3
CF	43.5	56.5	43.0	57.0	41.0	59.0
SQ	58.5	41.5	58.2	41.8	58.2	41.8
KS	82.1	17.9	76.5	23.5	68.0	32.0
KA	99.0	1.1	98.8	1.2	97.9	2.1
CR	93.3	6.7	91.6	8.4	90.2	9.8
NI	19.2	80.8	18.8	81.2	17.9	82.1
MS	79.6	20.5	74.8	25.2	70.9	29.1
NH	45.2	54.8	44.9	55.1	42.5	57.5
WA	15.8	84.2	15.8	84.2	15.8	84.2
TW	93.2	6.8	93.2	6.8	93.2	6.8
SH	32.4	67.6	32.4	67.6	32.4	67.6
WC	84.4	15.6	84.5	15.5	79.1	20.9
WF	99.2	0.8	99.3	0.7	97.6	2.4
CD	---	---	98.4	1.7	97.0	3.0
TD	---	---	98.8	1.2	94.8	5.2
PT	---	---	93.5	6.5	83.7	16.3
AA	---	---	97.1	2.9	98.1	1.9
PA	---	---	97.3	2.7	96.3	3.7
Bu	---	---	93.5	6.5	94.7	5.3
T	---	---	---	---	99.5	0.5

* See Table 2.1 for the legend to land cover and land use category codes.

cultivable (flat) lands. Plantations and certain built-up spaces occupied steeper lands. The case of forestry accords with its development elsewhere in the Western Cape province where pine plantations especially had been planted on mountainsides, this practice incidentally coming under criticism for the forests' negative effect on run-off generation. That most of the agrarian activities occurred within the legal slope limit, so curbing erosion and soil-loss is a positive sign for the Koue Bokkeveld environment. The decreases registered in Kouebokkeveld Alluvium and Shale Fynbos, wetland flats, Ceres Shale Renosterveld and Matjiesfontein Shale Renosterveld and the increases in clear-water dams, annual agriculture and perennial agriculture noted earlier all occurred in areas where a cultivation is allowed regarding slope – a compliment to the Koue Bokkeveld's farmers.

3.3.2 Aspect and land cover association

The concept of terroir in viticulture offers a case in point of aspect influencing land cover, species or cultivar location and pattern in an area, due to differential radiation, wind direction or temperature exposure of crops. Enquiries made locally (Gibson 2012, Pers com), could not, however, confirm such preferences in perennial or annual cultivation proclivities for given aspect directions in the Koue Bokkeveld. Table 3.6 summarises overall exposure to aspect directions for the study area and shows a fairly even spread, except to the south and south-east, most likely due to

Table 3.6 Aspect distribution in the Koue Bokkeveld

Code	Aspect	Area (%)	Code	Aspect	Area (%)
1	North	13.4	**5**	South	9.1
2	North-east	14.8	**6**	South-west	14.6
3	East	14.3	**7**	West	13.6
4	South-east	8.5	**8**	North-west	11.7
Total					100.0

the general axial direction of the region's geological folding and hydrological tilting to the north. Given that southern slopes are colder than northern slopes in the southern hemisphere, and thus assumed to be less suitable for agricultural production, this factor might be seen as beneficial to agricultural development. Wondie et al. (2012), for example, found that agriculture occurs mostly on south-west, south-east and south aspects in the northern hemisphere, so that a reversal, i.e. north-west, north-east and north, would be expected in the southern hemisphere. However, given the dominance of Koue Bokkeveld agriculture on flat slopes, aspect does not appear to be a dominant locational determinant here.

The refined level of analysis shown in Figure 3.13 offers a number of finer insights – especially with reference to the occurrence and sensitivities of natural vegetation. Some communities (North Hex Sandstone, Western Altimontane Sandstone Fynbos, Tanqua Wash Riviere and South Hex Sandstone Fynbos) are present in too small and generally flat areas to draw any worthwhile conclusions. Where vegetation coverage has been altered over time, as in the case of Kouebokkeveld Shale and Alluvium Fynbos and in the renosterveld communities, their pattern of aspect had shifted. This can be ascribed to these low-lying areas having been put to the plough more extensively and the remaining stands of natural vegetation having survived only in the more rugged (steep) areas. Perhaps, even finer analysis at a local scale might illuminate further meaningful relationships with aspect in this complex landscape.

3.3.3 Curvature and land cover association

A complex mountain-and-valley region like the Koue Bokkeveld is not expected to be dominated by a specific class of curvature. However, the region's overall curvature (Table 3.7) is more concave (relatively lower-lying and water collecting) than convex (high-lying, water-shedding) in form with negligible neutral curvature. This is to be expected of a fairly rugged landscape. The relationship between land cover type and landscape curvature is quantified in Table 3.8, from which

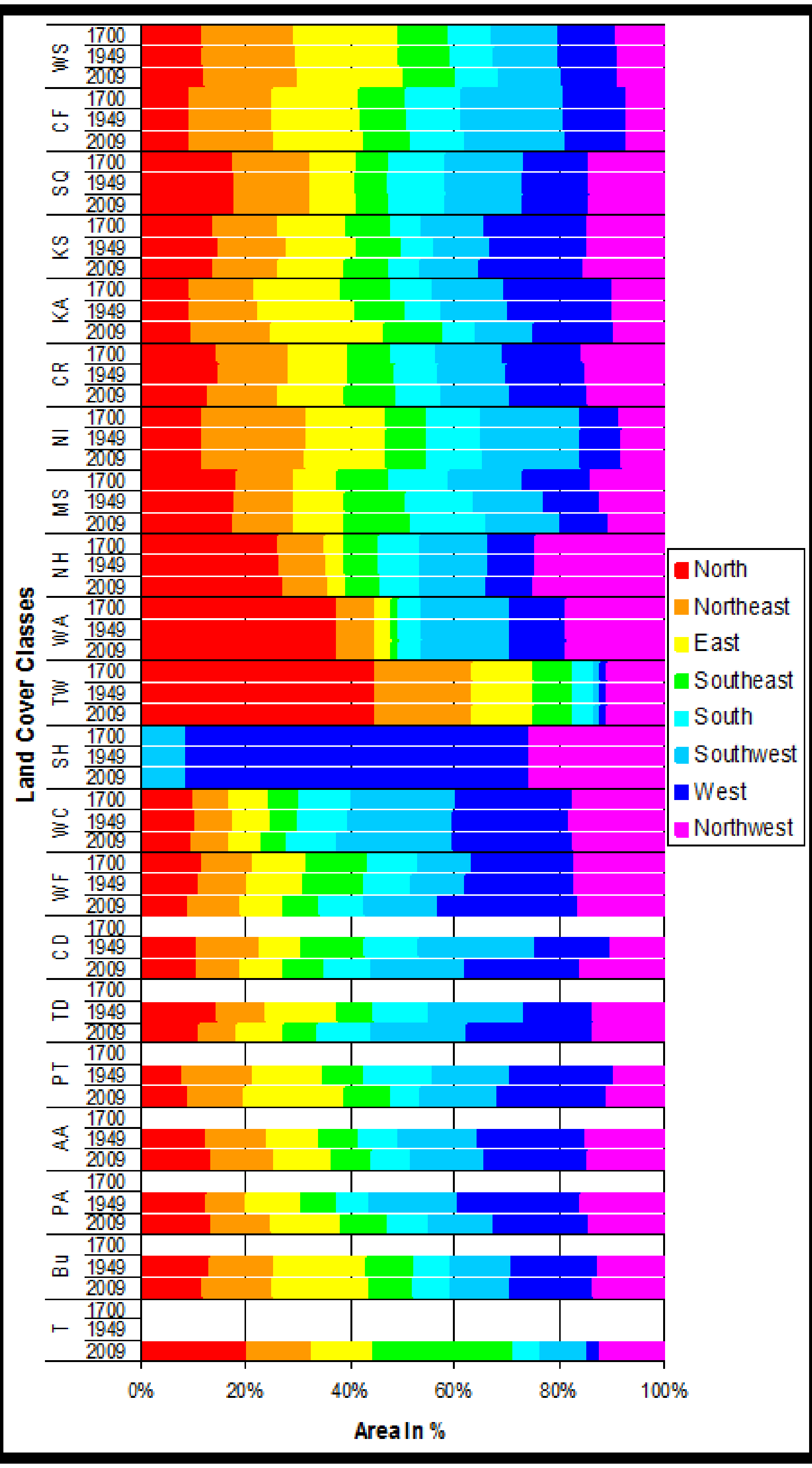


Figure 3.33 Land cover-aspect association in the Koue Bokkeveld

Table 3.7 Distribution of curvature classes in the Koue Bokkeveld

Curvature	**Proportion of area (%)**
Concave	55.2
Neutral	0.1
Convex	44.7
Total	100.0

Table 3.8 Curvature by land cover over time in the Koue Bokkeveld

Land cover code*	Curvature: Proportion of land cover class area (%)								
	Reference State			1949			2009		
	Concave	**Neutral**	**Convex**	**Concave**	**Neutral**	**Convex**	**Concave**	**Neutral**	**Convex**
WS	51.50	0.02	48.48	51.39	0.02	48.59	51.04	0.02	48.94
CF	50.07	0.03	49.90	50.01	0.03	49.96	49.77	0.02	50.21
SQ	49.71	0.03	50.26	49.66	0.02	50.32	49.62	0.02	50.36
KS	54.81	0.09	45.10	53.60	0.08	46.32	54.32	0.04	45.64
KA	65.41	0.30	34.29	64.99	0.32	34.69	66.25	0.27	33.48
CR	58.05	0.17	41.78	56.94	0.16	42.90	55.54	0.11	44.35
NI	57.83	0.01	42.16	57.82	0.01	42.17	57.66	0.01	42.33
MS	54.21	0.06	45.73	51.63	0.03	48.34	51.02	0.02	48.96
NH	47.34	0.02	52.64	47.32	0.02	52.66	46.82	0.02	53.16
WA	41.01	---	58.99	41.01	---	58.99	41.01	---	58.99
TW	73.79	---	26.21	73.79	---	26.21	73.79	---	26.21
SH	25.03	---	74.97	25.03	---	74.97	25.03	---	74.97
WC	60.34	0.13	39.53	59.89	0.14	39.97	59.55	0.10	40.35
WF	67.85	0.42	31.73	68.80	0.44	30.76	69.65	0.61	29.74
CD	---	---	---	63.60	0.25	36.15	64.77	0.27	34.96
TD	---	---	---	63.99	0.18	35.83	60.19	0.07	39.74
PT	---	---	---	60.19	0.15	39.66	52.15	0.07	47.78
AA	---	---	---	60.03	0.16	39.81	60.76	0.24	39.00
PA	---	---	---	64.67	0.16	35.17	56.87	0.12	43.01
Bu	---	---	---	65.56	0.08	34.36	58.30	0.14	41.56
T	---	---	---	---	---	---	55.49	0.30	44.21

* See Table 2.1 for the legend to land cover and land use category codes.

a number of significant observations can be made. It is evident that, by and large, the natural vegetation communities are fairly equally divided between convex and concave forms of land curvature. Wetlands are dominantly located on concave curvatures as are the shale- (including renosterveld) and alluvium-related communities in their lower-lying, valley-bottom and more gently-sloping environments that are rather concavely curved where water collects. High-mountain communities (WA, SH), again, are located on convexly curved landforms that shed water. Subtly evident are communities (e.g. renosterveld and shale-parented types) that are more vulnerable to large-scale invasion by agriculture that tends to concentrate on level and lower-lying concave locations, showing proportional reductions on concave (invaded) areas and some increases on areas with convex (retention) land curvature.

Agricultural development manifests a more insightful relationship with curvature. By 1949 all agricultural developments had predominated (>60%) on concave curves, clearly lower-lying, valley-bottom and more gently-sloping environments. While agriculture largely maintained this tendency (even increasing in the case of clear-water dams) all the other classes had increased incidences in convex-curved area, i.e. the shift of perennial crops onto valley sides and hills established earlier. Perennial agriculture, as well as plantations and trees, are now developed on steeper slopes as a consequence of technological advances in agricultural practices.

3.3.4 Topographical position, landform and land cover association

Topographical position in landscapes allows a more intuitive grasp of the subtleties determining development and potential impacts of land use in a landscape. Slope position, as it manifested in land use over time, and landform type are considered next to shed light on associations in the Koue Bokkeveld.

3.3.4.1 Slope position and land cover association

The Koue Bokkeveld, though often defined as generally mountainous in nature is, slopewise, a landscape of predominantly flat and mid-slope elements (Table 3.9). More than one-third of the area is flat, hence most suitable for agriculture, while the visually-intrusive mountains are

Table 3.9 Distribution of slope position classes in the Koue Bokkeveld

SP Code	SP label	Area (%)	SP Code	SP label	Area %
1	Valley	3.4	**4**	Mid-slope	42. 8
2	Toe-slope	7.0	**5**	Upper slope	6.7
3	Flat	36.5	**6**	Ridge	3.7
	Total (ha)	*247 210*		*Total (%)*	*100.0*

so defined by only about 10% upper-slopes and ridge positions and a similar proportion of valley- and toe-slope positions. The contents of this table are useful as benchmarks for analysing various land cover types by their variation in slope position.

Considering the association between land cover type and slope position for three historical study dates, as set out in Table 3.10, and by reflecting only on those land cover codes for which values differ from the regional average in Table 3.9 by approximately double the percentage, some salient observations are justified. The narrow belt of Northern Inland shale band vegetation (NI) is the only type that is over-represented on three positions (valley, toe- and mid-slope), but this can be explained by its precise appearance on a unique geological formation that stretches far beyond the study region. The South and North Hex Sandstone Fynbos (SH, NH) are similarly located on high-altitudes, ridge positions but both have limited extents. Exceptional cases of concentration on flat locations are recorded for three of the most vulnerable shale- and alluvium-based vegetation groups (KS, KA, CR) and wetlands that have been noted for their exposure to agricultural development. It is not very surprising that by 1949, and even more so by 2009, this flat slope position had become favoured by almost every type of agricultural development, including irrigation dams. Pressure by agrarian development on these positions caused natural vegetation to be accorded reduced occupation by 2009. Forestry plantations are the only modern land use that is significantly

Table 3.10 Slope position and land cover: Historical overview

Land cover code *	Reference state						
	Slope position area (row %)						
	Valley	Toe slope	Flat	Mid-slope	Upper slope	Ridge	Total
WS	4.79	9.09	21.30	50.40	8.66	5.76	100.00
CF	4.58	9.54	18.00	53.05	9.64	5.19	100.00
SQ	3.62	7.42	26.28	51.24	8.06	3.38	100.00
KS	0.66	3.21	60.58	31.95	2.78	0.82	100.00
KA	0.09	0.57	95.33	3.87	0.11	0.03	100.00
CR	0.45	1.64	84.04	11.80	1.31	0.76	100.00
NI	6.31	13.73	5.17	62.11	8.44	4.24	100.00
MS	1.46	4.25	50.40	38.63	3.90	1.36	100.00
NH	6.03	7.59	19.97	51.82	8.78	5.81	100.00
WA	3.75	9.54	2.51	60.39	14.41	9.40	100.00
TW	2.08	5.13	55.24	36.21	1.08	0.26	100.00
SH	1.16	5.59	4.81	60.18	16.77	11.49	100.00
WC	1.75	3.53	65.14	25.03	3.26	1.29	100.00
WF	0.04	0.23	96.46	3.04	0.19	0.04	100.00
1949							
WS	4.83	9.15	20.74	50.73	8.73	5.82	100.00
CF	4.62	9.61	17.49	53.31	9.73	5.24	100.00
SQ	3.63	7.46	25.91	51.50	8.10	3.40	100.00
KS	0.80	4.03	52.06	38.62	3.45	1.04	100.00
KA	0.11	0.64	94.97	4.13	0.12	0.03	100.00
CR	0.56	2.07	80.18	14.65	1.61	0.93	100.00
NI	6.34	13.79	4.89	62.23	8.49	4.26	100.00
MS	1.81	5.14	41.51	45.12	4.75	1.67	100.00
NH	6.07	7.62	19.94	51.69	8.83	5.85	100.00
WA	3.75	9.54	2.51	60.39	14.41	9.40	100.00
TW	2.08	5.13	55.24	36.22	1.07	0.26	100.00
SH	1.16	5.59	4.81	60.18	16.77	11.49	100.00
WC	1.74	3.51	65.33	24.91	3.23	1.28	100.00
WF	0.04	0.21	96.96	2.60	0.16	0.03	100.00
CD	0.00	0.14	94.51	4.81	0.42	0.12	100.00
TD	0.19	1.05	91.60	6.87	0.28	0.01	100.00
PT	0.53	1.63	78.60	17.62	1.22	0.40	100.00
AA	0.18	0.88	86.97	11.03	0.72	0.22	100.00
PA	0.27	0.73	87.67	10.49	0.68	0.16	100.00
Bu	0.38	1.60	76.65	19.58	1.45	0.34	100.00
2009							
WS	5.02	9.48	18.04	52.30	9.08	6.08	100.00
CF	4.77	9.91	14.97	54.84	10.08	5.44	100.00
SQ	3.64	7.46	25.82	51.55	8.12	3.41	100.00
KS	1.00	5.22	39.71	48.26	4.45	1.35	100.00
KA	0.17	1.03	91.64	6.94	0.18	0.04	100.00
CR	0.65	2.36	77.80	16.28	1.84	1.07	100.00
NI	6.40	13.90	4.10	62.73	8.56	4.30	100.00
MS	2.10	5.91	34.54	50.09	5.44	1.93	100.00
NH	6.36	7.90	17.56	52.85	9.22	6.12	100.00
WA	3.75	9.54	2.51	60.39	14.41	9.40	100.00
TW	2.08	5.13	55.24	36.22	1.08	0.26	100.00
SH	1.16	5.59	4.81	60.18	16.77	11.49	100.00
WC	2.95	4.94	55.52	30.71	4.21	1.67	100.00
WF	0.18	0.53	94.13	4.33	0.63	0.21	100.00
CD	0.22	0.85	89.73	8.19	0.78	0.24	100.00
TD	0.39	1.65	82.02	14.40	1.21	0.32	100.00
PT	1.35	3.70	51.77	38.96	3.17	1.06	100.00
AA	0.12	0.63	90.89	7.85	0.41	0.10	100.00
PA	0.31	1.27	82.39	14.71	1.02	0.29	100.00
Bu	0.51	1.79	78.77	17.39	1.12	0.41	100.00
T	0.30	1.44	67.34	27.79	2.90	0.24	100.00

* See Table 2.1 for the legend to land cover and land use category codes.

occupying mid-slope and even upper-slope positions in the landscape, as elsewhere in the province. Clear- and turbid-water dams mostly occur on flat areas where they compete for space with agriculture, but since they serve to irrigate cultivated crops, they are unlikely to be replaced by agriculture. Built-up farmsteads and townlands are mainly on flat areas.

3.3.4.2 Landform and land cover association

Landforms are more suitable descriptors of the Koue Bokkeveld landscape at regional than subregional scale. Table 3.11 shows the generally mountainous topography (nearly one third is upper-slopes, mountain tops and ridges) with open, flat plains (almost one quarter) interspersed between mountain ranges into which narrow U-shaped, or perhaps rather V-shaped, valleys (about one third) had been cut. These valleys developed along fracture zones or fault lines resulting from

Table 3.12 Distribution of landform types in the Koue Bokkeveld

Landform code	**Landform description**	**Area (%)**	**Landform code**	**Landform description**	**Area (%)**
1	Canyons, deeply incised streams	3.24	**6**	Open slopes	8.50
2	Mid-slope drainages, shallow valleys	0.05	**7**	Upper-slopes, mesas	28.15
3	Upland drainages, headwaters	0.08	**8**	Local ridges, hills in valleys	0.07
4	U-shaped valleys	32.15	**9**	Mid-slope ridges, small hills in plains	0.06
5	Plains	24.16	**10**	Mountaintops, high ridges	3.54
				Total (%)	100.00

intense folding and differential erosion of hard and resistant Table Mountain and Witteberg sandstones of the mountains and the softer, more easily transformed Bokkeveld shales along the valleys.

By considering the association between land cover type and landform distribution for three historical study dates, as presented in Table 3.12, and by reflecting only on those landform types that differ from the regional average in Table 3.11 by approximately double the percentage, some salient observations present themselves.

The fairly limited dissected landforms (canyons and incised streams) are located in the high mountains, hence occupied prominently by high sandstone fynbos and some shale band stands. These vegetation communities are located in remote areas where they have remained secluded from development over time. Valleys are spatially more prolific in occurrence and they are very strongly associated with some high-altitude, very stable vegetation types, although valleys also have strong representation in almost all the other natural vegetation communities, some of which are subject to development pressures of agriculture. Plains call for elaboration. Not only do significant areas of alluvium fynbos, renosterveld and wetlands occur on the plains, and have remained so over time, but most agricultural development has also taken place on plains as reported earlier. These natural vegetation communities are under severe threat by agriculture as clearly demonstrated by their

Table 3.13 Landform by land cover: Historical overview

Land cover code *	Reference state										
	Landform**/area (row %)										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
WS	4.56	0.09	0.15	36.91	10.69	9.75	32.10	0.10	0.08	5.58	100.00
CF	4.41	0.07	0.10	36.08	9.04	9.76	35.36	0.06	0.06	5.07	100.00
SQ	3.49	0.06	0.07	33.76	12.78	10.17	36.29	0.09	0.07	3.23	100.00
KS	0.64	0.01	0.01	28.32	42.21	7.71	20.28	0.01	0.01	0.79	100.00
KA	0.09	0.00	---	15.27	81.66	0.76	2.19	0.00	0.00	0.03	100.00
CR	0.43	0.01	0.01	18.28	66.51	2.68	11.32	0.01	0.01	0.75	100.00
NI	6.22	0.04	0.04	50.22	1.40	9.99	27.85	0.09	0.05	4.10	100.00
MS	1.43	0.02	0.01	32.31	29.74	9.88	25.25	0.05	0.04	1.27	100.00
NH	5.81	0.08	0.14	30.95	9.44	11.83	35.93	0.25	0.15	5.41	100.00
WA	3.29	0.16	0.30	23.68	0.18	10.23	52.77	0.06	0.12	9.22	100.00
TW	2.08	---	---	66.65	16.13	9.79	5.10	---	0.04	0.22	100.00
SH	1.16	---	---	3.92	---	4.61	78.82	---	---	11.49	100.00
WC	1.73	0.01	0.01	27.77	48.16	5.86	15.16	0.08	0.05	1.16	100.00
WF	0.04	---	---	6.00	90.41	0.85	2.67	0.00	0.00	0.03	100.00
	1949										
WS	4.60	0.09	0.15	36.98	10.26	9.80	32.31	0.10	0.08	5.63	100.00
CF	4.45	0.07	0.10	36.12	8.64	9.77	35.60	0.06	0.06	5.12	100.00
SQ	3.50	0.06	0.07	33.87	12.38	10.23	36.47	0.09	0.07	3.24	100.00
KS	0.78	0.01	0.01	30.99	34.95	9.15	23.08	0.01	0.02	1.00	100.00
KA	0.11	0.00	---	15.68	81.10	0.75	2.33	0.00	0.00	0.03	100.00
CR	0.53	0.01	0.01	20.50	61.61	3.37	13.02	0.01	0.01	0.91	100.00
NI	6.26	0.04	0.04	50.26	1.24	9.99	27.92	0.09	0.05	4.12	100.00
MS	1.77	0.02	0.02	34.62	21.06	11.21	29.62	0.06	0.05	1.57	100.00
NH	5.85	0.08	0.14	30.91	9.47	11.79	35.91	0.25	0.16	5.45	100.00
WA	3.29	0.16	0.30	23.68	0.18	10.23	52.77	0.06	0.12	9.22	100.00
TW	2.08	---	---	66.65	16.13	9.79	5.10	---	0.04	0.22	100.00
SH	1.16	---	---	3.92	---	4.61	78.82	---	---	11.49	100.00
WC	1.72	0.01	0.01	27.66	48.26	5.86	15.20	0.08	0.05	1.15	100.00
WF	0.04	---	---	5.11	91.68	0.72	2.42	0.00	0.00	0.03	100.00
CD	0.00	---	---	10.99	81.51	1.85	5.54	---	---	0.11	100.00
TD	0.19	---	---	19.71	72.78	2.08	5.23	---	---	0.01	100.00
PT	0.53	---	0.01	23.07	60.83	3.61	11.55	0.00	---	0.40	100.00
AA	0.18	0.00	0.00	18.89	68.06	3.08	9.57	0.00	0.00	0.21	100.00
PA	0.27	0.00	0.00	18.08	71.65	3.23	6.61	0.01	0.01	0.14	100.00
Bu	0.37	---	0.02	30.14	54.88	4.33	9.93	---	0.01	0.33	100.00
	2009										
WS	4.77	0.09	0.15	37.29	8.21	10.03	33.37	0.11	0.09	5.88	100.00
CF	4.60	0.07	0.10	36.71	6.49	10.03	36.56	0.07	0.07	5.31	100.00
SQ	3.51	0.06	0.07	33.81	12.37	10.24	36.53	0.09	0.07	3.25	100.00
KS	0.97	0.02	0.02	37.09	23.47	11.00	26.08	0.01	0.02	1.32	100.00
KA	0.16	0.00	---	24.54	71.39	1.21	2.66	0.00	0.00	0.04	100.00
CR	0.62	0.02	0.01	22.16	58.03	3.59	14.50	0.01	0.01	1.05	100.00
NI	6.32	0.04	0.04	50.21	0.91	10.06	28.12	0.09	0.05	4.16	100.00
MS	2.05	0.02	0.02	36.73	15.46	12.13	31.65	0.06	0.06	1.80	100.00
NH	6.13	0.09	0.15	30.76	7.72	11.82	37.23	0.26	0.16	5.69	100.00
WA	3.29	0.16	0.30	23.68	0.18	10.23	52.77	0.06	0.12	9.22	100.00
TW	2.08	---	---	66.65	16.13	9.79	5.10	---	0.04	0.22	100.00
SH	1.16	---	---	3.92	---	4.61	78.82	---	---	11.49	100.00
WC	2.92	0.01	0.02	32.65	38.24	6.91	17.58	0.12	0.06	1.49	100.00
WF	0.17	0.00	0.00	8.63	85.68	0.97	4.34	0.00	0.01	0.20	100.00
CD	0.21	0.01	0.00	16.70	73.15	2.07	7.62	0.00	0.00	0.23	100.00
TD	0.38	0.00	0.01	24.87	60.02	4.02	10.38	0.01	0.01	0.31	100.00
PT	1.33	0.01	0.01	31.51	29.70	10.36	26.02	0.02	0.04	0.99	100.00
AA	0.12	0.00	0.00	13.77	76.73	2.29	6.98	0.00	0.01	0.09	100.00
PA	0.30	0.01	0.00	20.70	61.69	4.44	12.56	0.00	0.00	0.29	100.00
Bu	0.49	0.02	0.01	25.19	57.71	4.39	11.78	0.03	0.02	0.36	100.00
T	0.30	---	---	16.42	48.24	7.06	27.75	---	---	0.24	100.00

* See Table 2.1 for the legend to land cover and land use category codes.
** See Table 3.2 for the legend to landform category codes.

diminishing areas on plains areas over the last fifty years. Agriculture is almost exclusively restricted to plains (confirming observations by Tagil & Jenness 2008) and, moreover, every land use type shows an expanding grip on the plains over time. Upper-slopes and mesas, although significant in areal coverage, are at present not now subject to development pressures, hence the special vegetation communities colonising mountain locations are not under any great threat.

The examination of landform associations with land cover has been limited to the Koue Bokkeveld as a whole with no subregional refinement. Some exploratory analyses at catchment level were done but, aside from the reality that the subregions and individual catchments in them do differ in character and, therefore the associations among landform and land cover and land use too, the results did not shed any new conceptual or practical light on the relationships so that they are not interrogated further in this subsection.

3.3.5 Proximity of agriculture to water source association

Because of the long dry summers experienced in this winter-rainfall area, agriculture in the Koue Bokkeveld has been dependent on irrigation water since its inception as an agrarian region. For field-grown crops to become established beside livestock-farming as an industry, ingenious irrigation schemes had to be established in the area. Mostly small-scale and privately driven by individual farmowners, these schemes underwent a definitive development path to which only perfunctory attention is paid here. In short, it entailed private individual schemes and small-scale cooperative schemes between neighbouring farms (see Smit & Jacobs (2004) for a description of such an operation as a typical example elsewhere in the province) eventually complemented by larger government-sponsored schemes during the 20th century. The first schemes were built by using hand tools and animal-draught equipment. Since the latter part of the 20th century these schemes have become much larger-scale operations (machine-built canals, pipelines, large reservoirs) owing to the adoption of engineering and irrigation innovations and use of specialised earth-moving contractors. The earlier irrigation schemes had relied on gravity-driven water, small dam walls in stream channels and furrows to convey stored water to cultivated fields where irrigation took the form of manually-guided flood irrigation. Modern irrigation schemes rely on large dam walls in or away from stream channels and pipelines to convey stored water to crop fields where irrigation is done by sprinkler and/or micro and drip irrigation. This evolution should be evident in the relationship between cultivated (especially perennial) croplands and the distance to water sources (wetland channels and dams).

Regarding landscapes, crop location is no longer dependent on close proximity to water and water storage sources – circumstance that may profoundly influence the vulnerability of specific natural vegetation communities that were most likely better protected from risk in the past. Table 3.13 confirms the expected association between each of three land use types and distance to wetland channels. In 1949 more than half of all planted fields were located within 200 m of streamlines but

Table 3.43 Proximity of agricultural land cover to wetland channels: 1949-2009

Distance (m)	Plantations/Trees		Annual Agriculture		Perennial Agriculture	
	Ha	%	ha	%	ha	%
	1949					
0-100 (close)	246	36.1	5235	35.4	872	45.8
101-200 (intermediate distance)	147	21.6	3116	21.1	460	24.1
201-500 (fairly distant)	221	32.4	3996	27.0	433	22.8
501-1000 (distant)	49	7.1	1917	12.9	118	6.2
>1000 (far distant)	20	2.9	537	3.6	22	1.2
Total	683	100.0	14801	100.0	1904	100.0
	2009					
0-100 (close)	91	8.7	2609	10.0	769	9.8
101-200 (intermediate distance)	82	7.8	2742	10.5	796	10.1
201-500 (fairly distant)	257	24.4	6885	26.3	1986	25.3
501-1000 (distant)	275	26.2	7537	28.7	1847	23.5
>1000 (far distant)	346	33.0	6453	24.6	2462	31.3
Total	1051	100.0	26226	100.0	7860	100.0

by 2009 half the fields were located at least 500 m from these sources. This is more pronounced in the case of perennial crops (orchards) where almost one third had become to be located beyond one kilometre from stream sources – clearly a victory of pump and pipeline over landscape.

In 1949 large parts of the study area still had no dams, so this irrigation feature should show interesting trends associations with agricultural development given their later arrival in the landscape. In Table 3.14 the measured distances between agriculture and dams confirm some expectations. The forestry plantations and trees, not being irrigated, show no changing proximity

Table 3.14 Proximity of agricultural land cover to dams: 1949-2009

Distance (m)	Plantations / Trees		Annual Agriculture		Perennial Agriculture	
	ha	%	Ha	%	ha	%
	1949					
<100 (close)	63	9.3	473	3.2	141	7.4
100-200 (intermediate distance)	89	13.1	919	6.2	292	15.3
201-500 (fairly distant)	261	38.2	4 011	27.1	789	41.4
501-1000 (distant)	175	25.6	5 243	35.4	496	26.1
>1000 (far distant)	95	13.9	4 155	28.1	187	9.8
Total	683	100.0	14 801	100.0	1 904	100.0
	2009					
<100 (Close)	168	16.0	2 161	8.2	806	10.3
100-200 (intermediate distance)	152	14.4	3 399	13.0	1 432	18.2
201-500 (fairly distant)	339	32.2	10 204	38.9	3 604	45.9
501-1000 (distant)	275	26.2	7 674	29.3	1 635	20.8
>1000 (far distant)	118	11.2	2 789	10.6	382	4.9
Total	1 051	100.0	26 226	100.0	7 860	100.0

relationship to dams over time. Plantations may occur in the vicinity of dams without any direct relationship with them. Annual agriculture, being predominantly extensive in area and irrigated only if it is vegetable crops (i.e. irrigated onions and potatoes but not cereals, which are rain-fed winter crops) is characteristically spread out and, hence, has yielded reservoir area to dam construction. This is evident from the relatively low proportion of annual agriculture that was more than one kilometre from dams in 2009 as opposed to the nearly 60% closer than 500 m from dams, and up by more than 24% on 1949. Perennial agriculture has a slightly different relationship, with dams and orchards having moved closer to one another over time. By 2009 nearly three quarters of orchards were closer than 500 m from dams – up by 10% on 1949. This suggests that the ability to engineer orchard and dam locations had enabled farmers to locate developments in productivity-driven and cost-effective configurations.

A combination of distance to wetland channels and dams (Table 3.15) confirms the dependence of land uses on water-proximate locations in 1949 (75% of perennial croplands closer than 200 m) but since then the Koue Bokkeveld has seen a loosening of this dependence (only 44% of croplands closer than 200 m in 2009). This land use is now located farther away from water sources (56% at 200 m or more) where technological advances allow efficiency to dictate where land can be irrigated in the landscape. This observation is even more significant in light of the large increases in annual (almost double) and perennial (more than four times) land areas devoted to these uses.

Table 3.15 Proximity of agricultural land cover to wetland channels and dams: 1949-2009

Distance (m)	Plantations/Trees		Annual Agriculture		Perennial Agriculture	
	ha	%	ha	%	ha	%
	1949					
<100 (close)	284	41.6	5 456	36.9	932	49.0
100-200 (intermediate distance)	166	24.2	3 300	22.3	509	26.7
201-500 (fairly distant)	203	29.7	4 121	27.8	384	20.2
501-1000 (distant)	18	2.7	1 683	11.4	78	4.1
>1000 (far distant)	12	1.8	241	1.6	2	0.1
Total	683	100.0	14 801	100.0	1 904	100.0
	2009					
<100 (close)	249	23.7	4 583	17.5	1 512	19.2
100-200 (intermediate distance)	196	18.7	5 300	20.2	1 920	24.4
201-500 (fairly distant)	353	33.6	10 798	41.2	3 437	43.7
501-1000 (distant)	208	19.8	4 865	18.5	925	11.8
>1000 (far distant)	45	4.3	680	2.6	67	0.9
Total	1 051	100.0	26 226	100.0	7 861	100.0

This chapter has expanded on the previous chapter's examination of the evolution of the land cover distribution and patterns in the Koue Bokkeveld by considering a number of landscape structural and morphological features as explanatory variables. Furthermore, with landscape morphological concepts and theory as basis land cover and landform characteristics were combined in GIS overlay format to establish the morphological interactions between land cover and land use in the region. A major finding was that areas suitable for agriculture coincide with areas of natural vegetation that are at risk to expanding and intensifying agriculture. The findings provide insights to inform decisionmaking about landscape development, conservation and management.

The topic explored in the next chapter determines the extent to which the morphological and areal alterations to the landscape have the potential to influence the natural functioning of the Koue Bokkeveld as a resource region.

CHAPTER 4 LAND COVER CHANGE AND LANDSCAPE FUNCTION IN THE KOUE BOKKEVELD

In the previous chapter, measurable factors controlling the form of the landscape as they influence relationships between the landscape and its use for agriculture, were considered. However, the various characteristics of the landscape are intricately interrelated and changes in observable, measurable aspects are known to affect other aspects of landscape that are mostly invisible, albeit measurable. These latter aspects relate to landscape structure and landscape functions (Cowling et al. 2008; Egoh et al. 2008). This chapter investigates the contention that because land cover and land cover change are partly governed by landscape form, the changing land cover and uses affect the inherent ecological functioning of the landscape (Le Maitre et al. 2007; Reyers et al. 2009). A large part of this chapter relies on further analyses of DEM and land cover data. The chapter begins by introducing the concept of landscape ecological function and justifying the selection of key functions (rainfall run-off, biodiversity, carbon sequestration) for analyses. Each function is treated with a theoretical exposition, explanation of its appraisal and measurement, and a report on the analytical results when applied to the Koue Bokkeveld.

4.1 LANDSCAPE FUNCTION SELECTION

Landscape functions provide resources for living organisms: humans, animals and plants (De Groot & Hein 2007; De Groot et al. 2010; Willemen et al. 2010). De Groot, Wilson & Boumans (2002) give a handy conceptual framework and typology by which to describe, classify and value ecosystem functions, goods and services. They recognise 23 functions, ordered in four groups as summarised in Table 4.1. Three salient functions were gleaned from the list for detailed study in the peculiar Koue Bokkeveld landscape. Some of the tabulated functions have greater global or universal appeal to humankind (De Groot 2006), while others are directly relevant to the local scale of a region, as indicated in the table. Demonstrations of determining ecological function value are available from studies on themes as diverse as landscape aesthetics, biological diversity and hydrology at global (Costanza et al. 1997) and regional scales (Le Maitre et al. 2007; Li et al. 2007; O'Farrell, Donaldson & Hoffman 2007; Reyers et al. 2009). Fourie (2005) has demonstrated this functional diversity by applying GIS in an evaluation of landscape aesthetics as an ecological function at a core regional site in the Koue Bokkeveld. Landscape aesthetics is a place and space based (Syrbe & Walz 2012) planning necessity also substantiated by Frank et al. (2012; 2013). Qualifying criteria were used to decide on crucial landscape functions to be chosen for this study. Ease and readiness of access to measured information with a definite spatial address (Egoh et al. 2008) that would suite the scientific mode of inquiry was decided upon for this research. It was

Table 4.1 Ecological landscape function groups

Function group	*Scope: Universal*	*Scope: Local landscape-specific*
Regulation functions – Maintenance of essential ecological processes and life-support systems (11 functions)	Air/gas-related; Mainly influence global climate	Water: Flood control, run-off quantity, quality; Soil: Formation, erosion, nutrients, toxicity; Biological: Pollination, pests
Habitat functions – Providing suitable living space for wild plant and animal species (maintenance of biological and genetic diversity (2 functions)	Species refugium; Biological reproduction integrity	Commercial harvests of wild species
Production functions – Providing natural resources (5 functions)	Raw materials for genetic, medicinal purposes	Subsistence: Food, timber, fuel, ornamental. Limited relevance in a commercial agri-environment/fynbos biome
Information functions – Providing opportunities for cognitive development (5 functions)	Landscape-dependent aesthetic, cultural, spiritual, recreational, scientific value	Tourism value: Growing relevance in a commercial agri-environment/fynbos biome

Source: Adapted from De Groot (2002)

deemed appropriate to select services that are spatially relevant; would be affected by agricultural land cover change (Tscharntke et al. 2005; 2012); be locally measurable; and both universally and locally relevant. The selection was thus limited to the regulation and habitat functions in Table 4.1, namely water (run-off), biodiversity and carbon sequestration potential.

Landscape functions such as biodiversity can be permanently impaired by the elimination of species and the replacement of natural vegetation by mono-cultural agriculture (Gotelli 2001; Bohensky, Reyers & Van Jaarsveld 2006). Moreover, some landscape functions compete with one another, as often happens with biodiversity and carbon storage (Chisholm 2010). In the next sections, water run-off, biodiversity and carbon storage are treated by considering the basic principles, value determination and measurement of each one – all in the living landscape of the Koue Bokkeveld.

4.2 RAINFALL RUN-OFF AS LANDSCAPE FUNCTION

The Koue Bokkeveld is located in a winter rainfall region where much winter precipitation run-off is captured and stored in large irrigation dams to sustain thousands of hectares of fruit orchards and vegetable fields. While rainfall is the main source of run-off in most catchments (Segond, Wheater & Onof 2007) the Koue Bokkeveld receives regular snowfalls, hence references to precipitation are understood to include this form of natural water delivery. Sustainable filling of the region's dams from run-off is a life-sustaining necessity which, if affected by land cover change, should be quantified and understood to inform relevant management practices. The following subsections cover some theoretical aspects of rainfall run-off, the way in which run-off is appraised and measured and with the quantification of run-off trends over time in the Koue Bokkeveld.

4.2.1 The principles determining rainfall run-off

Rainfall run-off is, without a doubt, the most important ecological function in this region with its emphasis on irrigated agriculture. Rainfall run-off is an ecological service that delivers ecosystem value through the amount and quality of water it provides in the form of surface flow channelled through streams and rivers, and infiltration to feed and replenish groundwater reservoirs. Service availability is determined through precipitation (amount, nature, seasonality) and the structural nature of the receiving earth surface (slope, surface and bedrock type, soil type, land cover type) that either restricts or enhances run-off production. These elements can be modelled to estimate probable run-off production in a given regional climatic setting (Grantham, Merenlender & Resh 2010).

Landscape functions are important to the healthy functioning of a landscape and the development of the landscape for human needs. To qualify as a landscape function, rainfall run-off must provide a service to the various elements of a landscape and its users. Some of these services are water to plants during rainstorms, filling of aquifers by infiltrating the ground, filling streams and rivers through run-off and providing water to animals, people and plants lower down river systems (Heathwaite 2010). Land cover change is one of the main drivers of change in landscape functions (Reyers et al. 2009; Verburg et al. 2009). Despite the large amount of literature on the relationship between land cover change and its influence on landscape functions, the local consequences of land cover change on landscape functions are not fully understood (Le Maitre et al. 2007; Reyers et al. 2009).

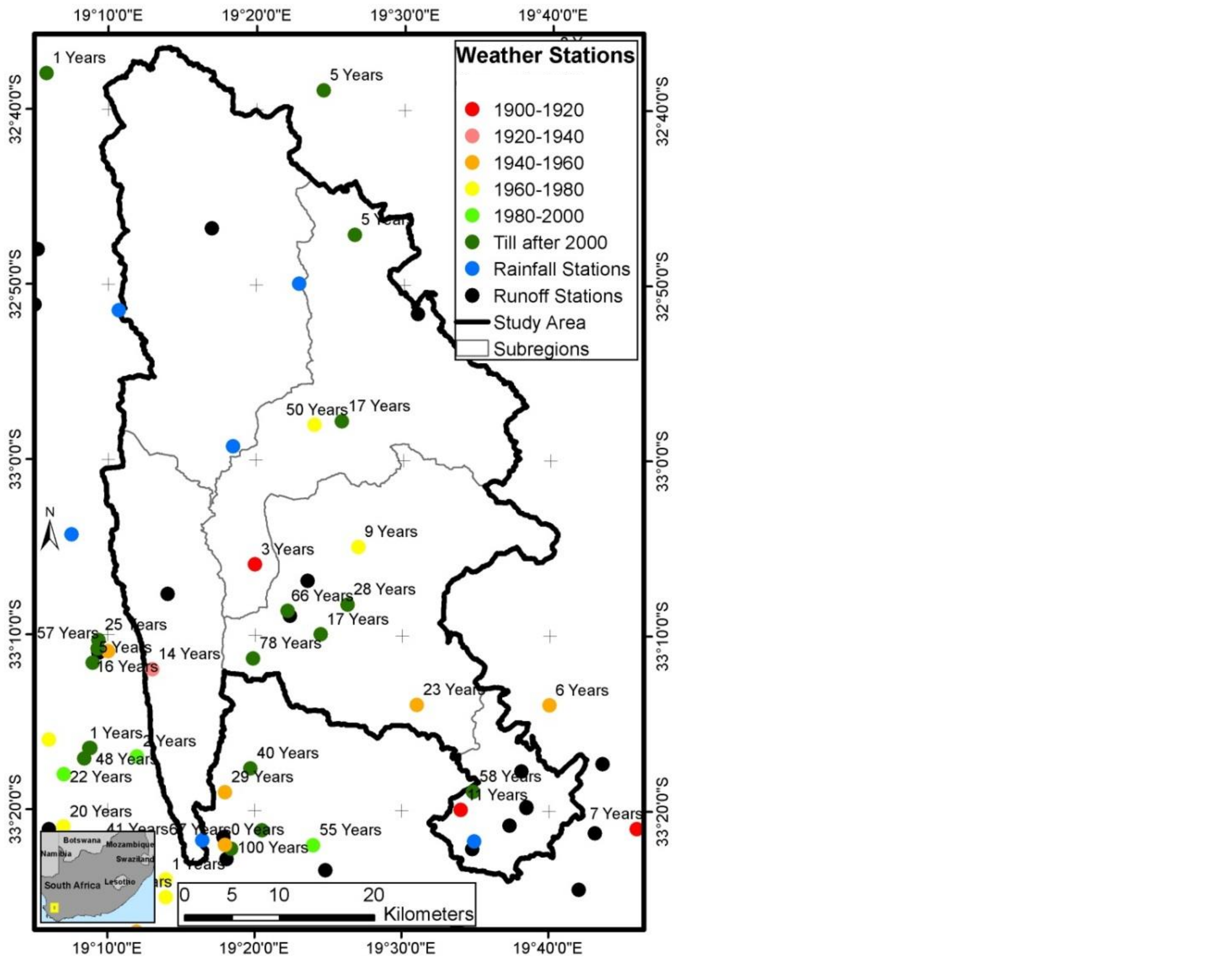
Rainfall run-off is one of the landscape functions that can change in response to land cover changes. Increases in run-off can mean less water entering local groundwater systems which can lead to river flow interruptions earlier in and during dry seasons. Because landscape functions and services influence one another, more functions are collaterally affected by run-off change (Millennium Ecosystem Assessment 2005). An altered run-off regime may inhibit stream-flow, hence insufficient volumes for storage and for maintaining basic biological functions in streams and wetlands downstream (Palmer, Menninger & Bernhardt 2010; Tockner et al. 2010). Likewise, altered run-off may lead to increased run-off causing flooding or increased soil erosion and lower water quality for storage. The Koue Bokkeveld lies at the core of the winter-rainfall region of South Africa where it is exposed to the (negative) effects of climate change, decreased rainfall and run-off as well as anthropogenic interference with run-off regimes through large-scale storage, artificial channelling and interbasin transfers.

4.2.2 Rainfall run-off value appraisal

Water is a prerequisite for most life forms on earth so that access to a sufficient amount and quality of water is guaranteed as a human right in the South African Constitution. As such, water has existence value as well as utility value (Bateman 1995; Bohensky, Reyers & Van Jaarsveld 2006). While the function of rainfall and run-off to provide water for human use has always been known, and in many instances has had a provision or delivery price attached as indicator of value, price and value of water have always been severely mismatched. Effort to ascribe a comprehensible value to water (independent of its price) only became urgent when the cost of maintaining the ecological integrity of run-off and water in ecosystems became the target of policy and research (Arthington et al. 2010). Van Wilgen, Cowling & Burgers (1996) have specifically accounted for the value of the water resource in fynbos environments by calculating proxy values of restoring catchments invaded by alien vegetation (and therefore seriously reducing run-off amounts) compared to management costs of pristine catchments. The value of run-off as a production commodity in the Koue Bokkeveld is seldom quantified but it can safely be claimed that, given that the area is fully reliant on irrigated crop production, the value of stored run-off is the equivalent of all cultivated products produced annually. Given this situation, the effects a changing environment, and anthropogenically altered land cover in particular, have on this vital ecological resource must be measured and monitored constantly (Bohensky, Reyers & Van Jaarsveld 2006; Davis, Sim & Chambers 2010; Hart & Calhoun 2010). These two requirements – measuring and monitoring – are treated in the following sections.

4.2.3 Rainfall run-off measurement: Data availability

Rainfall run-off as a landscape function is difficult to monitor and measure consistently over time in a regional landscape – especially when a historical trajectory needs to be traced. This complication means that in run-off as a variable more than one phenomenon can be gauged – either directly through physical gauging or indirectly through mathematical modelling. First, rainfall can be measured directly over time through gauges located at fixed points – requiring a reliable fixed network of gauges located in scientifically-selected locations (typically weather stations) to represent a range of locational variations that allow reliable interpolation of run-off values to intermediate areas between gauge stations. Second, is to gauge and record run-off directly at network of streamflow gauges constructed on the main stream network in a region. Figure 4.1 demonstrates that two complications were encountered in the Koue Bokkeveld, namely the rainfall and run-off stations are unreliable due to their uneven spatial spread and differences in periods of operation. Only five widely-dispersed weather stations have been in operation up to 2009. Consequently, rainfall data for the study area were derived from the web-based *South Africa*



Source: Derived from DWA (2012a; 2012b; 2012c; 2012d; 2012e; 2012f; 2012g; 2012h).

Figure 4.1 Weather station and run-off gauge locations in the Koue Bokkeveld

rain atlas (Zucchini, Nenadić & Kratz 2003) where data are provided on a minute-square resolution for South Africa and is considered the best regional source for this type of information (Zucchini & Nenadić 2006). The atlas is available on the Internet and statistics can be downloaded from the website. These downloaded values were used to calculate the rainfall raster for the Koue Bokkeveld at a 5-minute raster scale. Likewise, the seven run-off gauges were too thinly spread over the area for representative measurement in all five subregions – but they could be used as representative sample points with limited historical records to confirm some recent trends only.

Since the interconnectivity between hydrology and structure flow direction, river flow and hydrological functions of groundwater flow and recharge (Hornberger et al. 1998; Kennedy 2006) is influenced by topography as a structure function, a DEM is a useful data source from which to extract flow characteristics (Gruber & Peckham 2009) and the topographic attributes (Tagil & Jenness 2008; Wu, Li & Huang 2008). Although most studies still use DEM for this purpose, Kenny & Matthews (2005) consider its accuracy to be insufficient for fine-scale hydrological analysis. Because this is not a valid objection considering the scale used in this research, and following the example of Tagil & Jenness (2008), the available DEM (see Chapter 1) and the hydraulic tools in ArcGIS were used to extract catchment boundaries and correct an error detected on the quaternary catchment map offloaded earlier.

4.2.4 Rainfall run-off modelling

To obtain historical approximations of run-off trends in reaction to a changing land cover regime, the research had to resort to run-off modelling in which land cover change could be factored. Two families of modelling techniques were considered: The more complex group relying on measured run-off data and the less complicated United States Soil Conservation Service (SCS)-curve number (CN) method.

The more accurate models (confirmed in Water Research Commission (WRC) 2009) considered were the Pitman, Hughes and the Soil and Water Assessment Tool (SWAT) models. Pitman (1973) developed his well-used model (examples available in BNWMP 1991a; 1991b; Stipinovich 2005; Hughes et al. 2006; Tsheko 2006; Wilk et al. 2006; Hughes, Kingston & Todd 2011) to calculate rainfall run-off. The Pitman model requires more than ten different model parameters among which precipitation, total or potential evaporation and soil moisture storage (Pitman 1973; Stipinovich 2005; Tsheko 2006). Even in simplified form the model remains complex in nature (Hughes et al. 2006). The Hughes model accesses utilisable streamflow from borehole and other water extraction values (Hughes 2006) held in the WARMS (Water Use Authorization Management System) database, but this database is often inaccurate (DWAF 2006) because it depends on assumptions that National Water Act requirements to register all boreholes (DWAF 1998) are met (which is not the case). The SWAT model has been operative since 2005 as a popular hydrological program to analyse rainfall run-off (Gassman et al. 2007; Mengistu 2009; Neisch et al. 2009). SWAT also uses various detailed parameters including soil, rainfall, temperature and evaporation data. The accurate yet complex ACRU agrohydrological model is physically based conceptual rainfall-run-off model that integrates various water-budgeting and run-off-producing components of the terrestrial hydrological systems, Bayesian inference and Monte Carlo simulation (WRC 2009). Some models determine marginally related phenomena, like the landscape wetness potential (LWP) that uses flow accumulation data for landscapes to identify particular water-related landforms – wetlands in particular (Thompson et al. 2002; Münch & Conrad 2007; Weller 2008).

Suffice it to say that the more sophisticated models yield more accurate, localised results based on highly accurate, fine-scale data that are seldom available for a region the size of and as diverse as the Koue Bokkeveld. As such, these models were not considered suitable for the fairly coarse regional level at which this research aimed to estimate historical run-off trends and, furthermore, the concern here was to establish a basis for comparison over time and not so much accurate run-off statistics. Consequently, the SCS method was selected for application.

The SCS curve number run-off model, developed in the 1980s, is considered accurate for run-off calculation, uses few variables and has been employed in many catchments (Zhan & Huang 2004; Shi et al. 2007; Soulis, Valiantzas & Dercas 2009). The model's data requirement to calculate run-off is limited to soil types, rainfall and curve numbers for the soil-hydro groups and land cover type. Curve numbers range from zero to 100 reflecting the amount of rainfall that will run off the particular surface. Curve numbers differ slightly by region and soil-hydro group in each land cover type. Equations 4.1 and 4.2 show the calculation of run-off using SCS as derived from Zhan & Huang (2004), Shi et al. (2007) and Soulis, Valiantzas & Dercas (2009) and where the value *S* is the standard variable value for calculating run-off on each curve number. Run-off volume is measured in cubic metres per annum (m^3/a).

$$\text{run} - \text{off} = \frac{(\text{rainfall} - 0.2\text{S})^2}{(\text{rainfall} + 0.8\text{S})} \quad if\ rainfall > 0.2S$$

Equation 4.1

$$\text{run} - \text{off} = 0 \quad if\ rainfall \leq 0.2S$$

$$S = \frac{25400}{\text{CN}} - 254$$

Equation 4.2

Since neither the hydrologic groups for soils in South Africa nor the actual soils types at the required scale were available, land cover was proxied for this variable by employing mean curve numbers per cover type. Given the assumption that rainfall had remained constant over the study period and discounting real water storage and extraction, potential run-off could be calculated for the three experimental time slices and summed for the various catchments. Table 4.2 shows the curve numbers by land cover type as they were empirically established mostly in USA studies from the sources indicated in the table. Four soil-hydro groups (A-D), each with its own CN value for the cover type on that soil group are distinguished. By assuming equivalence of the land cover types in this research and accounting for fynbos being highly soil-type specific (Mucina & Rutherford 2006), a mean curve number value could be calculated for each cover type. These values are higher for 'hard', more artificial land cover types because of higher precipitation run-off, while 'natural' land cover retains run-off (lower CN values). Kouebokkeveld Shale (KS) and Alluvium (KA) Fynbos were classified as degraded and obtained that mean value, while all other fynbos types were asigned the intact mean value. Although the Ceres Shale Renosterveld (CR) is regarded as vulnerable, it is not sufficiently fragmented to warrant classification as degraded.

The methodological workflow of steps to derive run-off predictions for the study area at each time slice is shown in Figure 4.2. It entailed downloading the *South Africa rain atlas* (Zucchini,

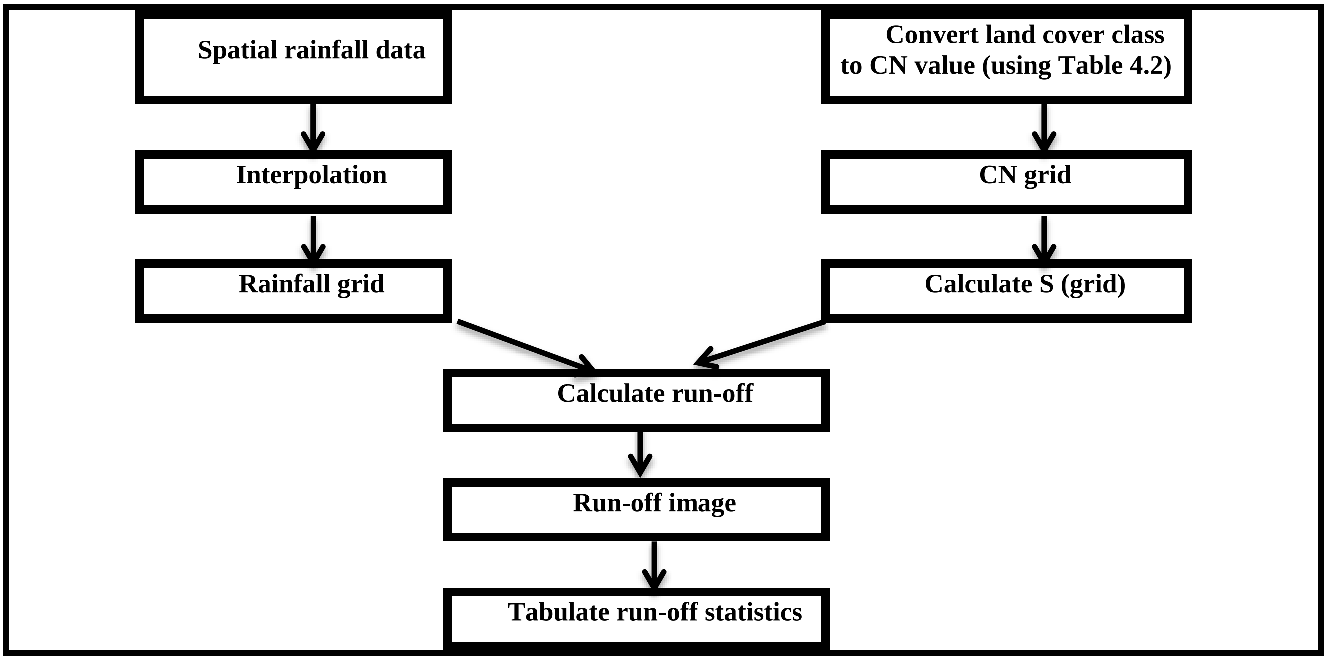


Figure 4.2 Workflow for performing run-off analysis

Nenadić & Kratz 2003) data to a 5-degree-minute matrix and interpolating with the inverse distance weighted (IDW) interpolation method to a 500-m resolution raster image. Land cover image values were converted to curve number values using the means in Table 4.2 and the standard S values as in Equation 4.2. All spatial manipulations occurred in ArcGIS. The resultant run-off data output was grouped by catchment using catchment shape file in the Zonal Statistics tool in ArcGIS. The resulting tabled output was exported to Excel for historical analyses of run-off trends between primary catchments and subregions.

4.2.5 Land cover change and rainfall run-off in the Koue Bokkeveld

The results of the SCS run-off analysis are presented at various levels of generalisation and in several display formats. First, the total run-off generated in the region, compared at various historical times is provided, followed by the same results but separated by catchment and subregion for comparative purposes. Figure 4.3 and Table 4.3 summarise the relevant run-off patterns, figures and ratios per secondary catchment and for the five subregions.

The spatial patterns in Figure 4.3 confirm the western high-rainfall area as the spatial centre for run-off generation and contribution to two (Breede, Olifants/Doring) of the three major rivers fed from the study region. While at the reference stage (Figure 4.3a) the major centre of run-off generation was due to the higher rainfall in the western mountain chain, the contribution of increased run-off from agriculturally tilled and developed land becomes abundantly clear in the map for 1949 (Figure 4.3b). By 2009 (Figure 4.3c) the effect of agricultural development has moved increased run-off generation to the valley centres bordering the undisturbed mountain complexes

Table 4.2 Derived and mean curve numbers by land cover type

LAND COVER TYPE	SOIL-HYDRO GROUP VALUE					SOURCE
	A	**B**	**C**	**D**	**Mean**	
Fynbos intact (All fynbos except KA, KS)	**33**	**53**	**68**	**76**	**58**	
Brush (Fair)	35	56	70	77		USDA (1986)
Brush (Good)	30	48	65	73		USDA (1986)
Shrub and Brush Rangeland	35	56	70	77		USDA (1986)
Fynbos degraded (KA, KS)	**48**	**67**	**77**	**83**	**69**	
Brush (Poor)	48	67	77	83		USDA (1986)
WC	**98**	**98**	**98**	**98**	**98**	
Water	98	98	98	98		Shi et al. (2007)
WF	**31**	**58**	**72**	**79**	**60**	
Nonforested wetland	30	58	71	78		Zhan & Huang (2004)
Wetland	32	58	72	79		Shi et al. (2007)
CD/TD	**0**	**0**	**0**	**0**	**0**	
Reservoirs	0	0	0	0		USDA (1986)
PT	**45**	**66**	**77**	**83**	**68**	
Orchards, groves, vineyards, nurseries and ornamental horticulture	45	66	77	83		USDA (1986)
AA	**63**	**74**	**82**	**85**	**76**	
Cropland and pasture	49	69	79	84		USDA (1986)
Fallow (CR – Good)	74	83	88	90		USDA (1986)
Other agricultural land	59	74	82	86		USDA (1986)
Row crop (C – Good)	65	75	82	86		USDA (1986)
Row crop (C – Poor)	70	79	84	88		USDA (1986)
Row crop (C & T – Good)	62	71	78	81		USDA (1986)
Row crop (C & T – Poor)	66	74	80	82		USDA (1986)
Row crop (C & T + Ceres Shale Renosterveld – Good)	61	70	77	80		USDA (1986)
Row crop (C & T + Ceres Shale Renosterveld – Poor)	65	73	79	81		USDA (1986)
Row crop (C + Ceres Shale Renosterveld – Good)	64	74	81	85		USDA (1986)
Row crop (C + Ceres Shale Renosterveld – Poor)	69	78	83	87		USDA (1986)
Row crop (SR – Good)	67	78	85	89		USDA (1986)
Row crop (SR – Poor)	72	81	88	91		USDA (1986)
Row crop (SR + Ceres Shale Renosterveld – Good)	64	75	82	85		USDA (1986)
Row crop (SR + Ceres Shale Renosterveld – Poor)	71	80	87	90		USDA (1986)
Small grain (C – Good)	61	73	81	84		USDA (1986)
Small grain (C – Poor)	63	74	82	85		USDA (1986)
Small grain (C & T – Good)	59	70	78	81		USDA (1986)
Small grain (C & T – Poor)	61	72	79	82		USDA (1986)
Small grain (C & T + Ceres Shale Renosterveld – Good)	58	69	77	80		USDA (1986)
Small grain (C & T + Ceres Shale Renosterveld – Poor)	60	71	78	81		USDA (1986)
Small grain (C + Ceres Shale Renosterveld – Good)	60	72	80	83		USDA (1986)
Small grain (C + Ceres Shale Renosterveld – Poor)	62	73	81	84		USDA (1986)
Small grain (SR – Good)	63	75	83	87		Miller et al. (2007)
Small grain (SR – Poor)	65	76	84	88		USDA (1986)
Small grain (SR + Ceres Shale Renosterveld – Good)	60	72	80	84		USDA (1986)
Small grain (SR + Ceres Shale Renosterveld – Poor)	64	75	83	86		USDA (1986)
Legumes (SR)	58	72	81	85		Atkinson (2001)
PA	**43**	**64**	**77**	**83**	**66**	
Orchards, groves, vineyards, nurseries, ornamental horticulture	45	66	77	83		Zhan & Huang (2004)
Orchard	40	62	76	82		Shi et al. (2007)
Bu	**59**	**74**	**82**	**86**	**75**	
Farmstead	59	74	82	86		USDA (1986)
T	**67**	**79**	**86**	**89**	**80**	
Other urban, built-up land	63	77	85	88		USDA (1986)
Mixed urban, built-up land	81	88	91	93		USDA (1986)
Residential	57	72	81	86		USDA (1986)

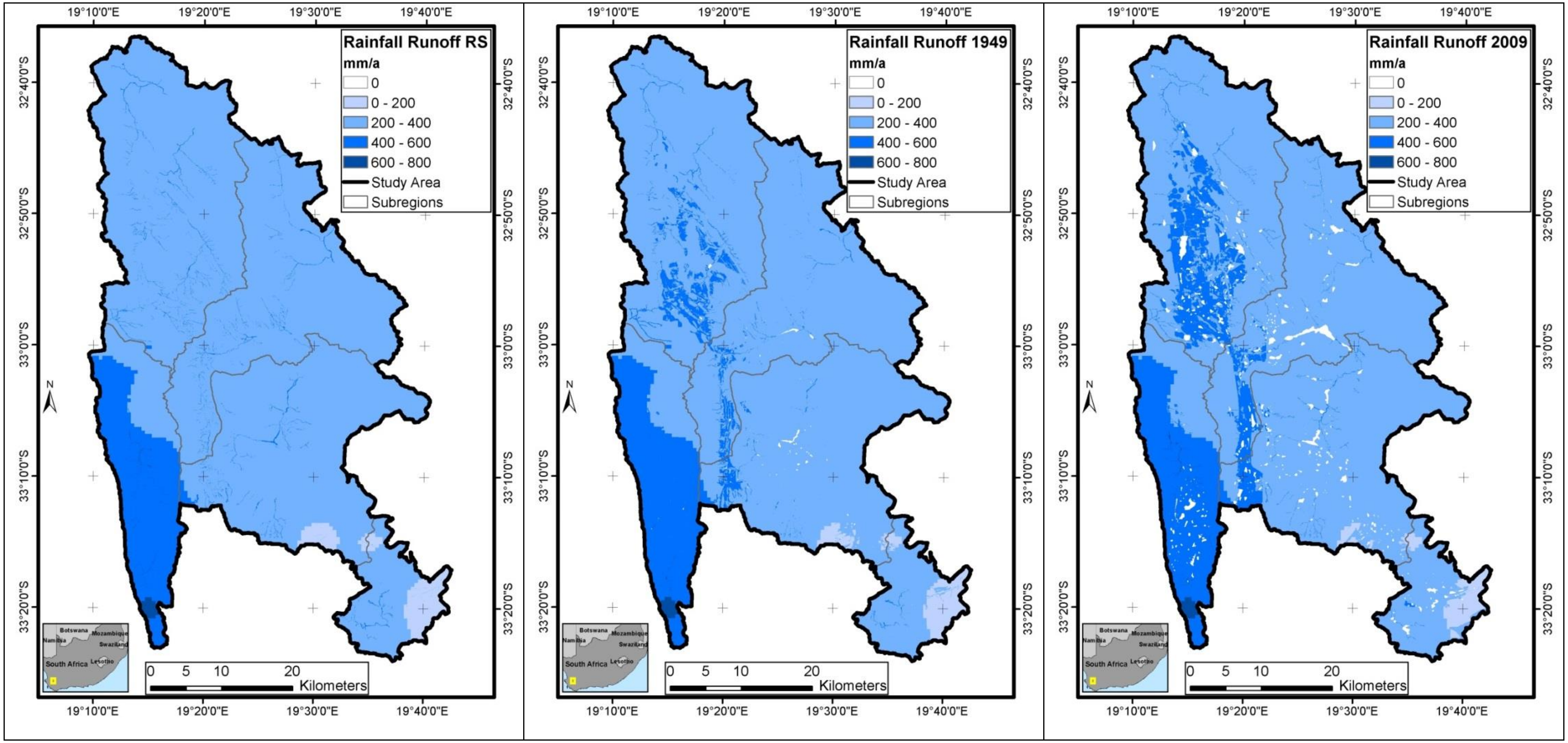
where run-off has remained stable – to be expected given the assumption of stable precipitation over time.

When attention is turned to the modelled output figures in Table 4.3, the importance of the region as run-off generator becomes evident. The study region contributed nearly 790 million cubic metres (m^3) of run-off in 2009. Of this total, nearly 91% of run off is to the Olifants/Doring system, nearly 9% to the Breede system and a mere 0.4% to the Gourits. Nearly 65% of the total run-off in the Olifants/Doring system (1 108 million m^3) originates here, underscoring the importance of the Koue Bokkeveld as regional provider of this vital ecological service. When the different catchments are considered, it becomes clear that five sub-basins (E10A, E21D, E21E, E21G, E21H) dominate run-off yield – each producing more than 10% of the total run-off. Subregionally, this means that the Onder-Bokveld yields nearly one third of all run-off and Voor-Matroosberg less than 4%. The other three subregions each contribute about 20%. (E21D in Sandhoek produces more than 40% of the total into the upper Doring, while E21G provides more than 13%.

Of course, since the study area is physically and developmentally diverse, various subregions generate different amounts of run-off per unit area. The mean run-off/area ratio (expressed in m^3/yr per km^2) was just over 3 000, but reached maxima far above 4 000 (E10A, H10C) and dropped to minima below 2 000 (H20C, J12A). Not surprisingly, the latter two catchments were located in the extreme south-east (Voor-Matroosberg) and the former two in the extreme south-west (Witsenberg), so cementing the expectations about subregional performance.

Temporally, trends in run-off yield reflect the impact that development has had – numerically and spatially. With the exception of two catchments (E10C, E21A), all catchments registered fairly consistent increases in run-off yield over time since the undisturbed reference state. The scope of change has been marked – just short of 20 million m^3/yr, or 2.6%. Here, catchments E21G and E21D catch the eye with nearly 40% and 14% of total change registered there respectively. It is noteworthy that four catchments (E10B, E21D, E21G, E22C) registered increased yields above 100 m^3/yr per km^2, indeed large figures that may suggest potential problems concerning water quality or soil erosion in parts of Sandhoek and Onder-Bokveld.

Clearly, run-off production as an ecological service in all catchments and subregions had been affected to some degree, and positively so regarding yield. The question is whether increased run-off is accompanied by improvement in the concomitant services of biodiversity and carbon storage, because the performance of these services may not be positively associated (Strassburg et al. 2010). The issue of biodiversity as landscape function is pursued in the next section.



a) Reference state b) 1949 c) 2009

Figure 4.3 Modelled historical run-off patterns

Table 4.3 Rainfall run-off in the Koue Bokkeveld: Reference state to 2009

Primary catchment	Area (km^2)	Run-off (m^3/yr)			Run-off change (%)			Run-off/Area ratio (m^3/yr per km^2)		
		Reference State	**1949**	**2009**	RS-1949	1949-2009	**RS-2009**	**Reference State**	**1949**	**2009**
E (Olifants/Doring)										
E10A	22 735	95 675 625	96 030 000	96 793 750	0.37	0.80	1.17	4 208.2	4 223.8	4 257.4
E10B	9 515	35 529 688	36 759 375	37 023 813	3.46	0.72	4.21	3 734.3	3 863.5	3 891.3
E10C	820	2 935 094	2 935 094	2 924 388	0.00	-0.36	-0.36	3 581.1	3 581.1	3 568.1
E21A	19 309	58 168 313	59 707 750	58 796 375	2.65	-1.53	1.08	3 012.4	3 092.2	3 045.0
E21B	19 048	42 604 313	43 761 125	43 887 688	2.72	0.29	3.01	2 236.7	2 297.4	2 304.1
E21C	24 194	64 095 000	64 301 875	64 885 000	0.32	0.91	1.23	2 649.2	2 657.7	2 681.8
E21D	23 843	78 418 750	80 091 875	81 080 000	2.13	1.23	3.39	3 288.9	3 359.1	3 400.6
E21E	28 154	81 976 875	82 520 625	82 967 500	0.66	0.54	1.21	2 911.7	2 931.0	2 946.9
E21F	8 929	25 935 063	25 979 875	26 176 125	0.17	0.76	0.93	2 904.7	2 909.7	2 931.7
E21G	26 087	87 763 125	91 124 375	95 815 625	3.83	5.15	9.18	3 364.2	3 493.1	3 672.9
E21H	36 689	114 352 500	114 593 750	115 055 000	0.21	0.40	0.61	3 116.8	3 123.4	3 136.0
E22C	5 064	10 431 000	10 626 188	10 952 250	1.87	3.07	5.00	2 059.9	2 098.4	2 162.8
H (Breede)										
H10C	11 122	54 175 313	54 659 938	54 763 625	0.89	0.19	1.09	4 870.8	4 914.4	4 923.7
H20C	8 122	10 431 000	10 626 188	10 952 250	1.87	3.07	5.00	1 284.4	1 308.4	1 348.6
H20D	1 529	3 388 119	3 388 119	3 484 900	0.00	2.86	2.86	2 215.5	2 215.5	2 278.8
J (Gouritz) J12A	2 049	3 574 825	3 607 463	3 718 169	0.91	3.07	4.01	1 744.3	1 760.3	1 814.3
Total	**247 210**	**769 454 603**	**780 713 615**	**789 276 458**	**1.46**	**1.10**	**2.58**	**3 112.6**	**3 158.1**	**3 192.7**
Subregions										
Witsenberg	33 858	149 850 938	150 689 938	151 557 375	0.56	0.58	1.14	4 425.9	4 450.7	4 476.3
Droëhoek	62 552	164 867 626	167 770 750	167 569 063	1.76	-0.12	1.64	2 635.7	2 682.1	2 678.9
Sandhoek	60 926	186 330 688	188 592 375	190 223 625	1.21	0.86	2.09	3 058.3	3 095.4	3 122.2
Onder-Bokveld	73 110	240 580 407	245 412 594	250 818 826	2.01	2.20	4.26	3 290.7	3 356.7	3 430.7
Voor-Matroosberg	16 764	27 824 944	28 247 958	29 107 569	1.52	3.04	4.61	1 659.8	1 685.0	1 736.3

4.3 BIODIVERSITY AS LANDSCAPE FUNCTION

The Koue Bokkeveld is located along the central north-eastern edge of the fynbos biome in the Western Cape. As such, the diversity of natural vegetation in this area and the maintenance of biodiversity is of primary importance to ensure efficient landscape functioning and the concomitant economic development and production in the region. The following subsections cover the essential theoretical aspects of biodiversity as a landscape function in an agroregion and the way in which biodiversity is spatially appraised and measured through analysis of landscape structure. The section concludes with two subsections on the quantification results of biodiversity indicators over time in the Koue Bokkeveld.

4.3.1 The biodiversity principles

> “The most unique feature of Earth is the existence of life, and the most extraordinary feature of life is its diversity” (Cardinale et al. 2012: 59).

Since the signing of the Convention on Biological Diversity in 1992, the tantalising research question has remained how loss of biological diversity alters the functioning of ecosystems and their ability to provide society with the goods and services needed to prosper. In reviewing two decades of research since 1992, Cardinale et al. (2012) published definitive answers in *Nature* – conclusions to which this narrative will return in this section.

In any ecosystem, biodiversity refers to all occurring and interacting species of plants, animals and micro-organisms. Altieri (1999) and Olson & Wäckers (2007) have expounded the intricacy of biodiversity assessment, especially in agroecosystems where the natural system provides valuable plants and animals, allowing biodiversity to perform ecological services like vegetative cover preventing soil erosion, replenishing groundwater and controlling flooding by enhanced infiltration and reduction of water run-off. All of this despite earlier disputed claims that losses may be sustained because of ecological redundancy (Walker 1992). Cardinale et al. (2012) concluded unequivocally that biodiversity loss reduces the efficiency by which ecological communities capture biologically essential resources, produce biomass, decompose and recycle biologically essential nutrients. Specifically relevant to this study region, in agricultural systems, biodiversity performs ecosystem services beyond the direct production of food, fibre, fuel and income by recycling nutrients, controlling local microclimate, regulating local hydrological processes, regulating the undesirable organisms, and detoxifying noxious chemicals. These ecosystem services are largely biological, requiring maintenance of biological diversity to ensure their persistence. Natural services may be lost through agriculture-induced biological simplification, causing economic and environmental costs that reduce quality of life (Tscharntke et al. 2012). Cardinale et al. (2012) also confirm abundant evidence that biodiversity increases the stability of ecosystem functions through time. Biodiversity simplification for agricultural purposes generates an artificial ecosystem that requires constant human intervention to enhance "functional landscape heterogeneity" (Fahrig et al. 2011:101). In Western Cape farming, the trend towards monoculture cropping (extensive orchards, vineyards, cereal fields) transforms natural fynbos habitat and so places a special responsibility on farmers, who own most of the land (Giliomee 2006) to aid government in complying with the signing of the Convention on Biological Diversity, adopted in 1992 in Nairobi.

In natural ecosystems, internal function regulation is a product of plant biodiversity through energy and nutrient flows, i.e. control progressively lost under agricultural intensification (Tscharntke et al. 2012). Even decomposition is altered because new plant growth is harvested and soil fertility maintained through fertilisers. Thus, modern agricultural systems have become productive but only by high dependency on external inputs. A growing fear for the long-term sustainability of such ecologically simplified food production systems is triggered by observed loss of biodiversity, land lost through soil erosion and heavy reliance on chemical fertilisers and pesticides. Furthermore, Cardinale et al. (2012) concludes that biodiversity impact on ecosystem processes is non-linear, implying that change accelerates with increased biodiversity loss.

Two enhancement strategies of biodiversity operate in agroecosystems: planned and associated biodiversity. New agroecological technologies and systems emphasise the conservation-regeneration of biodiversity, soil, water and other resources. In a fruit-growing region the 'new' biodiversity is introduced via each new fruit or cereal variety planted. The role of natural biodiversity (through predators, parasites and soil microflora and microfauna) in securing crop protection and soil fertility is clear: planned biodiversity (the farmer manages the agroecosystem) and associated natural biodiversity (colonising the agroecosystem after farming commences) and how they promote ecosystem functions (Altieri 1999) is therefore quite possible to analyse in a wide array of aspects at greatly varying levels of detail (Poiani et al. 2000). In this thesis, following several authors (Herzog et al. 2001; Cardinale et al. 2012; Frank et al. 2012; Tscharntke et al. 2012), the focus is on employing enhanced understanding of how landscape structure contributes to the provision of ecosystem services, through a simplified comparison of readily obtained spatial indicators derived from land cover mapping in GIS. Various dimensions of spatial landscape pattern are used as indicators of biodiversity at the landscape scale of this research.

4.3.2 Biodiversity appraisal

The value of biodiversity and the landscape-related ecological services associated with it can be calculated directly in economic and monetary terms and by proxy in terms of the level of concern over the vulnerability status of various natural elements of the landscape. Both these appraisal modes are considered here with reference to the broader fynbos region in which the Koue Bokkeveld is located and in terms of those vegetation communities uniquely located inside its borders.

The real value derived from ecological services can be complex to arrive at (Costanza et al. 1997; Li et al. 2007). Cardinale et al. (2012) provide a comprehensive overview of biodiversity valuation approaches helpful to structure such inquiry. They suggest that a variety of issues be monetised: society's willingness to pay for services (e.g. water), the marginal values and trade-offs (cost of genetic losses, carbon sequestration), the effect of differences in spatial and temporal scales and market value of ecosystems. In fynbos, value is ascribed to five sources, namely the collection and processing of fynbos products (wildflowers, herbs, thatching reeds, medicines); the cultivation of fynbos plants for commercial harvest (rooibos, proteas, garden plants); water supply release and run-off; ecotourism revenue; and genetic storage (Van Wilgen, Cowling & Burgers 1996; Higgins et al. 1997). These sources agree with the simplified framework for integrated assessment of ecological services and socio-economic benefits of natural and semi-natural ecosystems and landscapes suggested by De Groot (2006) to determine functional values.

However, "in a society that seems to value only what illustrates a profit on a balance sheet" (Ashwell et al. 2006: 153), it is necessary to attach real values to ecological services. Such valuations have been rather sketchily attempted since around the turn of the century and were fairly focused on particular spatial elements, such as fynbos wetlands (Turpie 2010), fynbos industries (Ashwell et al. 2006), water provision (Higgins et al. 1997), fynbos in general (Van Wilgen, Cowling & Burgers 1996; Turpie, Heydenrych & Lamberth 2003; Ashwell et al. 2006) or in regional settings (Fourie, De Wit & Van der Merwe 2013). Real values are rather dated, and varied estimates for distinguished commodities are reported (see Ashwell et al. (2006) and Van der Merwe (2013) for fynbos flower and oils industry, honeybees' honey and essential pollination services to deciduous fruit production and specialised ecotourism). However, the annual value of all fynbos services has been set at R10bn for the biome in the late 1990s – equated to 10% of regional GGP of the Western Cape (Turpie, Heydenrych & Lamberth 2003; Ashwell et al. 2006). This figure might be adjusted for inflation and generalised to local area dimensions for an approximated value – bound to be impressive to local farmowners and to encourage improved management of environmental resources.

The foregoing represents an effort to account for the real use value of the 'natural capital' inherent to the fynbos biome resource. However, fynbos provides both market and non-market (use and non-use) values (Van der Merwe 2013) – much of which could be considered 'bequest values' (Bateman 1995), i.e. the knowledge that something valuable exists without yielding direct benefit. Pristine fynbos is partly a bequest concern and as such measured and assessed in non-monetary terms through classification of irreplaceability and endangerment or vulnerability to eradication loss by scientific determination such as that provided by SANBI (Mucina & Rutherford 2006; SANBI 2009a; 2009b).

4.3.3 Biodiversity measurement

Having established the value of biodiversity, attention next shifts to how this concept might be measured and quantified in a particular, and extensive, regional setting such as the Koue Bokkeveld. Two methods present: first, extensive species composition counts might be carried out, typically in designated signal indicator vegetation communities or, second, by spatially analysing the structure of a heavily affected landscape and deducing relevant biodiversity status from it. The latter is the obvious, direct empirical option to follow in this case. After unpacking a conceptual approach to landscape structure analysis, the procedural approach followed in this research is sketched.

4.3.3.1 The principles of landscape structure analysis

By accepting as a basic thesis that environmental patterns strongly influence ecological processes, and that change, especially from anthropogenic activities, disrupts the structural integrity of landscapes and ecological flows of organisms across the landscape, compromising its functional integrity by interfering with critical ecological processes necessary for population persistence and the maintenance of biodiversity and ecosystem health (McGarigal 2014), implies that measuring such patterns allows monitoring of landscape and hence biodiversity integrity (Clerici et al. 2007). A plethora of established researchers (McGarigal & McComb 1995; Tinker et al. 1998; Jaeger 2000; Griffith, Martinko & Price 2000; McGarigal 2000; Neel, McGarigal & Cushman 2004) attest to this developing interest in the recent past. It has been established that a landscape is a heterogeneous land area composed of a cluster of interacting ecosystems that may be defined as land containing a mosaic of habitat patches. In map format, such a landscape can be analysed in terms of its point, line and surface (patch) patterns – the latter captured in thematic (choropleth) maps. Land cover maps wherein vector polygons or grid cells (raster) are classified into discrete land cover classes, are excellent examples with each separate class occurrence forming a patch in the landscape. The major landscape elements typically recognised to define the extent and grain of landscape patterns are patches delimited by boundaries that are scale-dependent, so forming a mosaic. When considering single patch classes, the rest of the landscape may be assumed to act as the matrix in which the particular class is embedded. Considering agricultural development as class type allows all natural vegetation in a landscape to be regarded as the matrix (McGarigal 2014).

Purposely leaving aside a host of complicating, yet measurable aspects of the ecological model, like landscape corridor connectivity and the edge effect inherent to patches and species movement in a landscape (Gotelli 2001; Cushman et al. 2013), the assumption here is that the landscape is analysed in terms of the *landscape mosaic model* instead of the *island biogeographic model* (McGarigal 2014). Furthermore, the scope of analysis in this case is not small-scale (Hou & Walz 2013) 'patch-centric' ('focal'), or neighbourhood structure focused, but on the global landscape structure. Analysis therefore does not use cell- or patch-level metrics, rather class- or landscape-level metrics. The metrics referred to are those values that are calculated as indicators of landscape structure, especially relevant to regional or temporal comparisons. Landscape metrics refer to myriad numerical indices (Li & Wu 2004; Dramstad 2009; Lozano, Suárez-Seoane & De Luis 2010) that quantify categorical map patterns (or patch mosaics) and include either those that quantify the *composition* of the map (applicable at landscape-level only) or those that quantify the *spatial configuration* (spatial character and arrangement, position or orientation of patches within the class or landscape) of the map. Composition metrics determine the *abundance* (proportion of each class relative to the entire map), *richness* (number of different patch types), *evenness* (level of dominance) or *diversity* (a composite measure) of classes. Configuration metrics are more difficult to calculate and refer to the spatial character, arrangement, shape, position or orientation of patches – hence simply quantify for the class or landscape as a whole, some statistical attribute such as mean, maximum or variance of the characteristic, like size or shape.

It is now accepted that biodiversity decreases with decreasing patch size viability and landscape fragmentation, increasing organism endangerment or extinction (Gotelli 2001). "Such metrics represent recognition that ecological processes and organisms are affected by the overall configuration of patches and patch types within the broader patch mosaic" (McGarigal 2014: 19). Example metrics quantify aspects of patch area and edge, patch shape complexity, core area, contrast, degree of aggregation or clumping of patch types, landscape division and patch isolation. Increased patch numbers imply more fragmented landscape (Abdullah & Nakagoshi 2006; Mas, Gao & Pacheco 2010) and similarly smaller mean patch area (Gotelli 2001; Abdullah & Nakagoshi 2006; McGarigal, Tagil & Cushman 2009). Higher largest patch index values (percentage of the total area occupied by the largest patch) (Schindler, Poirazidis & Wrbka 2008) indicate less fragmentation and higher habitat survival rates. Larger mean patch perimeter-area ratios (Long, Nelson & Wulder 2010) quantify more complicated patch edge length and vulnerability from external influence. Even more complex are surface metrics in an ever developing field of ecological metrics not attempted or relevant to this research. The decision here was to confine analyses to structural metrics, rather than functional metrics that would have implied some relevance to an organism or process under consideration (McGarigal 2014).

4.3.3.2 Landscape structure measurement procedures

The research was tailored to provide answers to a set of rather simplified issues about the development of the Koue Bokkeveld landscape over time at this particular scale and resolution, namely:

- How secure is the integrity or intactness of each natural vegetation community over time (how pristine or fragmented?); and
- Does the monoculture nature or compactness of the agriculture and human settlement and development footprint interfere with a natural vegetation matrix with intact natural patch patterns?

Pursuing these questions based on the arguments from the previous section, only five metrics were calculated for each land cover class, as indicated in Table 4.4. This decision complies with

Table 4.4 Selected landscape metrics calculated for the Koue Bokkeveld

Landscape metric	Unit	Indicator of
(Class area)	(Class % of total landscape – Table 2.3)	(Class prominence)
Patch count	Total number of class and landscape patches	Patch and edge density; Fragmentation level; Landscape complexity
Patch perimeter	Average perimeter length of class and landscape patches (metres)	Sinuousness; Intrusion vulnerability
Patch area	Average area of class and landscape patches (ha)	Overall landscape dominance
Perimeter/area ratio	Class and landscape values (m/ha)	Patch shape; Landscape complexity
Largest patch index	% of total class area in landscape covered by single largest class patch	Area distribution; Dominance in the landscape; Intrusion vulnerability; Adjacency/Clumpedness

Sources: Rutledge (2003); Kupfer (2012); McGarigal (2014).

the findings of redundancy and need for parsimony in metrics selection (Riitters et al. 2002; Cunningham & Johnson 2011), because almost 90% of landscape variation was statistically accounted for by these metrics. A further potential complication in the landscape- and scale-specific mapping techniques and the raster size (Lechner et al. 2013; Liu & Weng 2013; Lü et al. 2013; Schindler et al. 2013) was accounted for.

The calculation procedure necessitated some preparatory work on the target imagery, specifically to incorporate the fragmentation process introduced by road construction (Gotelli 2001) throughout the study region. Roads overlays were created for each time period – digitised for 1949 and derived from 1:50 000 map overlays for 2009. Roads were buffered according to five road classes confirmed from DTPW (2006) and DRT (2010) – tracks (5 m), tertiary (10 m), secondary (15 m), main and arterial (tarred) roads at 20 m. Procedurally, the roads vector layers were first rasterised and then merged with the relevant (1949, 2009) land cover layers in preparation for the metrics calculation.

A number of landscape fragmentation analytical tools are available, among which the Fragstats program (McGarigal & Marks 1995; McGarigal 2014) is perhaps best known. However, most standard image analysis programs like ArcGIS (Parent & Hurd 2008), IDRISI (IDRISI 2009d) and others (Riitters et al. 2002; Kozak, Estreguil & Vogt 2007; Vogt et al. 2007; Parent & Hurd s.a.), have been adapted to perform such analyses. For patch fragmentation analyses in this research the time slice land cover raster layers were converted to vector using the ArcGIS Raster to Feature and the Multipart to Singlepart tools. Consequently, all landscape metric parameters were calculated with the ArcGIS tools in ArcMap: area and perimeter with the Calculate Geometry tool; perimeter/area with the Field Calculator; and average patch area and perimeter, area ratio, count and largest area for the different land cover types with the Summarise tool (in the ArcMap attribute table). All results were tabled and the graphs were created in Excel. The same procedures were followed For KA, KS, CR and WF for each of the Koue Bokkeveld subregions.

Vulnerability judgments of the various natural vegetation communities were obtained from SANBI (Mucina & Rutherford 2006). This source determined the proportion (expressed as %) of the total of each vegetation type in South Africa that remained in a pristine locational and remnant quality condition as well as the proportion formally or statutorily protected. By clipping the study region from the national vegetation map, the representation of each vegetation community in the study area could be determined and the national vulnerability status simply transferred to each community. In this manner some authoritative empirical expression of biodiversity status in the study region was derived.

4.3.4 Landscape structure integrity and biodiversity in the Koue Bokkeveld

The results are first discussed in terms of the summary fractal statistics for the Koue Bokkeveld as a region in total, followed by the subregional comparisons to get a spatial perspective. In reviewing more than 300 journal papers, Uuemaa et al. (2009) recorded consistent associations between landscape pattern and biodiversity of vegetation, mammal, bird and insect species from all over the world. Clearly, agricultural activities have major effects on floral and faunal species richness in anthropogenic landscapes like the Koue Bokkeveld. In short, the more fragmented the landscape (more, smaller patches, larger perimeters, smaller core areas), the stronger the edge effect, hence the larger the risk of biodiversity loss. The results in Table 4.5 should be interpreted against this backdrop. Keep in mind, though, that three natural vegetation groups (Winterhoek Sandstone Fynbos (WS), Cederberg Sandstone Fynbos (CF), Swartruggens Quartzite Fynbos(SQ)) and annual agriculture dominate the Koue Bokkeveld landscape (see Table 2.3) – jointly covering more than 70% of regional space. Yet, the much smaller Kouebokkeveld Shale Fynbos (KS),

Table 4.5 Selected landscape metrics results for the Koue Bokkeveld

Code *	Patch count			Average patch perimeter (m)			Average patch area (ha)			Patch perimeter/area ratio (m/ha)			Largest patch index (%)		
	RefSt	1949	2009	RefSt	1949	2009	RefSt	1949	2009	RefSt	1949	2009	RefSt	1949	2009
WS	134	641	5 295	7 690	1 990	417	476.2	98.6	11.3	16.2	20.2	36.8	56.0	55.3	45.5
CF	144	432	4 589	5 214	2 179	333	336.6	111.0	10.0	15.5	19.6	33.3	51.9	36.8	34.6
SQ	51	114	225	7 312	3 667	2 667	866.8	385.4	194.6	8.4	9.5	13.7	95.9	88.0	97.6
KS	269	6 023	29 154	4 535	422	136	109.9	3.4	0.5	41.3	122.6	279.8	49.9	24.2	31.6
KA	390	2 174	11 108	2 178	527	166	36.6	5.2	0.5	59.5	100.6	310.3	20.0	22.0	9.7
CR	143	2 689	4 885	3 779	470	240	91.1	3.6	1.7	41.5	129.7	141.1	21.2	12.2	16.0
NI	5667	810	788	111	733	812	1.5	10.4	10.5	74.6	70.5	77.2	18.3	18.2	17.8
MS	32	1 198	1 335	8 926	470	410	250.6	5.4	4.2	35.6	87.5	98.5	100.0	61.5	67.8
NH	86	127	402	2 213	1 732	809	82.9	55.6	16.8	26.7	31.1	48.2	78.8	65.0	33.0
WA	6	6	6	8 149	8 149	8 267	184.4	184.4	184.4	44.2	44.2	44.8	50.4	50.4	50.3
TW	3	3	5	2 903	2 903	1 885	32.9	32.9	19.7	88.2	88.2	95.6	93.9	93.9	91.8
SH	1	1	1	1 084	1 084	1 084	3.4	3.4	3.4	314.8	314.8	314.8	100.0	100.0	100.0
WC	1816	1 217	833	1 523	2 415	2 313	1.7	2.5	2.8	915.5	965.3	820.1	13.3	7.8	3.7
WF	543	539	435	1 086	1 197	1 285	11.0	9.9	4.4	98.4	120.5	289.5	20.7	16.1	20.8
CD	0	105	422	0	613	1 252	0.0	3.0	9.2	0.0	204.7	135.7	0.0	30.5	11.4
TD	0	202	195	0	470	1 030	0.0	1.5	6.0	0.0	308.5	170.5	0.0	7.9	8.5
PT	0	603	653	0	446	615	0.0	1.1	1.6	0.0	393.5	382.0	0.0	3.4	8.3
AA	0	2 179	1 550	0	1 420	2 235	0.0	6.8	16.9	0.0	209.1	132.0	0.0	1.8	3.7
PA	0	442	2 496	0	947	824	0.0	4.3	3.2	0.0	219.9	261.7	0.0	3.6	1.3
Bu	0	383	686	0	313	704	0.0	0.6	1.8	0.0	504.4	391.3	0.0	3.0	2.7
T	0	0	5	0	0	1 618	0.0	0.0	6.7	0.0	0.0	240.9	0.0	0.0	44.1
Rd	0	3 586	13 631	0	439	379	0.0	0.1	0.1	0.0	3 420.2	3 719.4	0.00	3.84	1.37

* See Table 2.1 for legend to the land cover and land use category codes.

Kouebokkeveld Alluvium Fynbos (KA) and Ceres Shale Renosterveld (CR) were identified as the most threatened communities. If technical influences that may account for some raised metric values (vector rasterisation, narrow, linear nature of features like roads) are discounted, the question arises: Are these trends confirmed by the landscape structure patterns as reflected in salient summary statistics over time as presented in Table 4.5?

The change in patch numbers (count) since the reference state show notable and constant increases for all natural vegetation communities except the stable and isolated Western Altimontane

Sandstone Fynbos (WA), Tanqua Wash Riviere (TW), South Hex Sandstone Fynbos (SH) and Northern Inland shaleband (NI) – the latter actually showing a decline in patch numbers. Notably, all other metrics display the same stability for these four vegetation communities, indicating stable biodiversity conditions for them. Concerning the remaining eight vegetation groups, patch numbers have generally increased dramatically, denoting disturbing fragmentation trends. As expected, reciprocal trends are noted in the other four metrics for these groups: sharply declining patch perimeters and areas (evidence of smaller patches), increasing perimeter/area ratios (more patch edge exposure per unit of area) and declining largest patch indices (decreasing large intact areas to serve as group ecological reserves). The biodiversity health for wetlands (WF) and especially that of low-lying communities impacted by agriculture (Kouebokkeveld Shale Fynbos (KS), Kouebokkeveld Alluvium Fynbos (KA), Ceres Shale Renosterveld (CR) and Matjiesfontein Shale Renosterveld (MS)) has clearly declined sharply. The metrics denote consistently lowered potential species mobility space, greater stand isolation and hence lowered diversity maintenance potential.

All man-made land cover types intruded into the landscape since the reference state in a pattern of high fragmentation: high and increasing patch numbers and long patch perimeters (the latter denoting some extent of monoculture stands, especially in annual agriculture). Patch areas are relatively small due to the high development costs of permanent agriculture and the largest patch index values are small as expected because agricultural patches are fairly evenly distributed throughout the lower-lying regions of the study area. Of course, none of the biodiversity concerns appears in terms of patterns inherent to agricultural patches, aside from its obvious collateral damage effect of how it finely segments the naturally occurring vegetation communities and the landscape more broadly.

How these deductions hold when subregional analyses are performed, is demonstrated next. In Figure 4.3 the selected metrics for each subregion for the second-most affected natural vegetation group that occurs in all subregions (Kouebokkeveld Shale Fynbos – KS) is temporally compared for the five subregions. The patch count in all of the subregions rises over time as this natural vegetation class gets dissected by development, but Witsenberg and Onder-Bokveld exceed the others – clear indication of intensified development impact there. Both average patch area and perimeter length decline drastically in all subregions, with Voor-Matroosberg slightly less affected by the severe fragmentation appearance of KS. However, the high perimeter/area ratio and low largest patch index value show emphatically that KS is under most severe stress in Witsenberg – a confined valley with most of the valley floor converted to agriculture and mere remnant islands of KS remaining. Somewhat contrarily, Droëhoek shows the least decline in largest patch index, probably due to some abandonment of annual agricultural fields and allowance to revert to KS. This

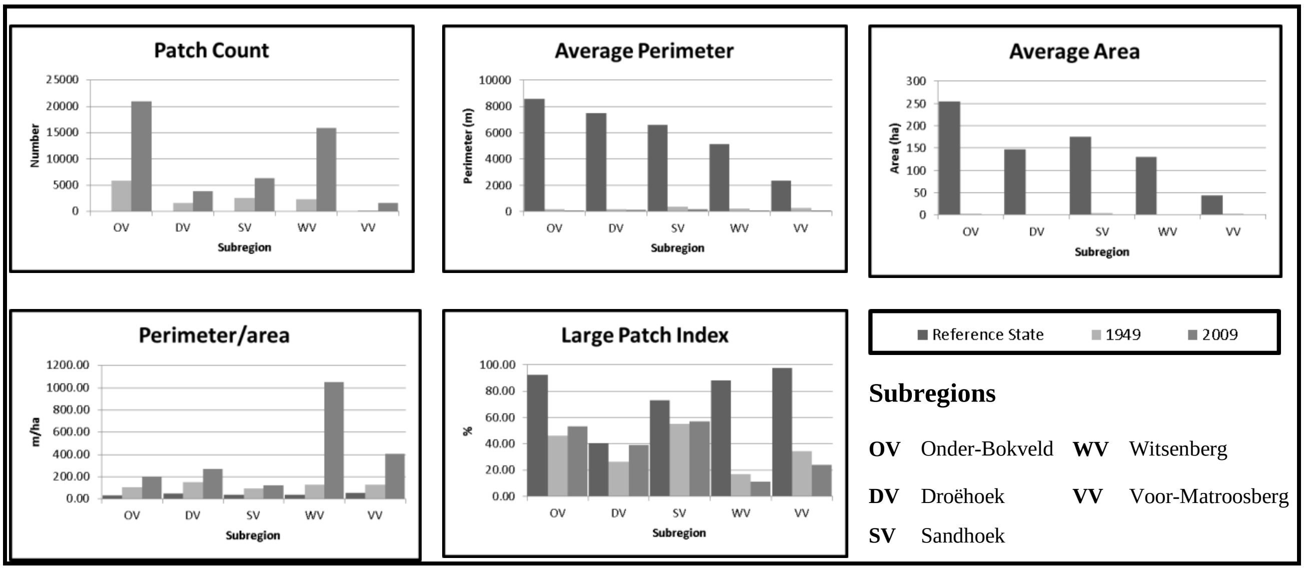


Figure 4.1Fragmentation of Kouebokkeveld Shale Fynbos in subregions

implies the Kouebokkeveld Shale Fynbos in the Droëhoek is the least threatened in the study area and may imply that reversal of biodiversity impact is a management option.

4.3.5 SANBI vulnerability rating of Koue Bokkeveld natural vegetation

Their diversity and unique vegetation communities in all South Africa's biomes contribute variable conservation concerns and they are continuously under professional ecological scrutiny (DEAT 2001; 2005). The country's natural vegetation is characterised by high counts of endemism and the threat of species extinction (Conservation International 2007), especially concerning the biodiverse and threatened Cape Floristic Region (Duffy 2008; Conservation International 2010a; 2010b; 2010c; 2010d). This recognition is reflected in a number of programmes instituted in the Western Cape to protect this rich biodiversity (CAPE Project Team 2000a; 2000b; Barodien 2005; CAPE Project Team 2006; Giliomee 2006; CapeNature 2007). SANBI, as reported in Table 4.6 according to Mucina & Rutherford (2006), provides rating statuses for all vegetation groups in South Africa in terms of vulnerability and formal protection status in statutory sanctuaries. GIS analysis of the SANBI map shows that the Koue Bokkeveld houses a majority of the Kouebokkeveld Alluvium Fynbos (KA, 100%) and Shale Fynbos (KS, three quarters) communities within its boundaries – implying a particular regional responsibility for its protection. Small wonder that these two communities are listed as endangered and suffering from a total absence of formal protection, largely because they are low-lying in the landscape, offer excellent soil conditions for agricultural development and have been systematically replaced over the past century. The Ceres Shale Renosterveld is poised to become a community of great concern. While having almost one

Table 4.6 Natural vegetation status in the Koue Bokkeveld

Land cover code *	Proportion of community in study area (%)	National vulnerability status **	National protection status **
WS	54.3	Least threatened	Moderately protected
CF	20.0	Least threatened	Moderately protected
SQ	27.0	Least threatened	Poorly protected
KS	75.0	Endangered	Not protected
KA	100.0	Endangered	Not protected
CR	28.3	Vulnerable	Hardly protected
NI	32.1	Least threatened	Moderately protected
MS	3.9	Least threatened	Poorly protected
NH	18.5	Least threatened	Well protected
WA	29.5	Least threatened	Well protected
TW	0.1	Least threatened	Moderately protected
SH	0.01	Least threatened	Moderately protected

* See Table 2.1 for the legend to land cover and land use category codes.
**Source: Mucina & Rutherford (2006).

third of its area in the Koue Bokkeveld, it is rated as vulnerable, enjoys very limited protection and in this region is incidentally protected only by its location in the lower rainfall shadow of the central Droëhoek region. However, this plant community suffers a lack of recognition of its biodiversity value and with refined irrigation technology being progressively employed, it is set to come under increased pressure in the future. It requires urgent and improved management attention.

4.4 CARBON STORAGE AS LANDSCAPE FUNCTION

The third landscape function considered is carbon storage. The Koue Bokkeveld is located in the fynbos biome in the Western Cape and as such its carbon storage potential is determined by the natural vegetation relics and the anthropogenic economic development and production markers in the region. The following subsections cover the essential theoretical aspects of carbon storage as a landscape function in an agroregion, the way in which it is spatially appraised and measured through analysis of land coverage and conclude with the quantification results of carbon storage volumes over time in the Koue Bokkeveld.

4.4.1 Carbon storage in principle

All living matter and the soil contain carbon. Plants capture or sequester carbon dioxide (CO_2) from the atmosphere and store it as carbon in parts of the plants (Hutchinson, Campbell & Desjardins 2007). Consequently, most carbon is stored in vegetation as the terrestrial medium with the highest biomass. When plants die and decompose, carbon returns to the soil and into the atmosphere as various greenhouse gases. Sequestration captures carbon for a limited period, the amounts varying according to species and climate zones (Hutchinson, Campbell & Desjardins 2007). Change in land cover therefore implies change in carbon storage in an area (Havemann 2009) as a basic air quality landscape function. The accumulation of greenhouse gasses like CO_2,

CH_4 (methane) and NO_2 (nitrogen dioxide) trapped in the atmosphere increases global temperatures and causes global warming (Sofo et al. 2005; Morgan et al. 2010), a (human-induced) natural phenomenon causing climate change and destructive, severe weather events.

Anthropogenic industrial activity emits greenhouse gases into the atmosphere through the burning of fossil fuels (oil, coal, gas), of which SASOL and ESKOM are major contributors in South Africa (Hietkamp et al. 2008; Osman, Coquelet & Ramjugernath 2014), and woody biomass – leading to landscape altering deforestation or desertification (Lemus & Lal 2005; Oliver 2014). While agriculture, bioenergy crops in particular (Lemus & Lal 2005), acts as an efficient carbon sink through its planted crops (Chisholm 2010), these crops might replace natural vegetation with higher carbon storage potential and so cancel its benevolent effect. Global initiatives have led to political action such as the Kyoto Protocol to kerb the problem (Havemann 2009; Henry 2010) and countries and industries ascribe to its principles to lower the carbon content of the atmosphere. By accepting the principle that carbon storage is a vital landscape service, it is inevitable that land cover change will affect it – but the question remains: What quantitative value can be ascribed to carbon storage and how is it to be measured and determined quantitatively in a given region?

4.4.2 Carbon storage appraisal

The quantitative appraisal of the value of stored carbon in a landscape has been facilitated by a range of international initiatives to provide monetary value to preserving or restoring high-yielding carbon-rich landscape resources such as forests (Oliver 2014). This action enables stored carbon to be traded on world markets to offset the effect of carbon emissions exceeding agreed levels on national bases among countries and industries as part of agreements such as the Kyoto Protocol. The calculation of a monetary value for species like pine or eucalyptus (Arroja, Dias & Capela 2006) is relatively straightforward, but for biodiversity in more complex biomes more innovative approaches are required. Turpie, Heydenrych & Lamberth (2003) have used an economic valuation principle (Bateman 1995) by estimating the price people are willing to pay (WTP) to protect various South African biomes, as presented in Table 4.7.

These figures for 2003 provide estimated intrinsic biome values according to how much people were willing to pay to have them protected. Fynbos value, at the current (August 2014) exchange rate of R10.50/\$US, approaches R500/km^2/yr and accommodates a clear proportional majority of carbon storage values for South Africa. Per unit area it is fairly modestly rated compared to forest and spekboom (*Portulacaria afra*) – the dominant species in the Albany Thicket biome. The latter was rated equal to forest values because of its similar carbon storage potential, potential to decrease soil erosion and high carrying capacity for naturally occurring herbivores (Le Maitre et al. 2007;

Table 4.7 Intrinsic value of South African biomes

Biome	***Percentage allocation (%)***	***US$ per km² per year***
Fynbos	39	46
Marine	19	64
Forest/Spekboom	15	2 227
Succulent Karoo	7	7
Nama Karoo	7	2
Grassland	7	2
Savanna	6	1

Source: Adapted from Turpie, Heydenrych & Lamberth (2003: 210)

Reyers et al. 2009). Despite its low relative value, SANBI (Le Maitre et al. 2007) even values the Karoo ecosystem – including non-use value of biodiversity – at R5500/km^2/yr.

The accurate assessment of fynbos biodiversity potential in South Africa, especially in different regions and among communities lags attention. Mills et al. (2012; 2013) have made recent inroads by comparing carbon storage in various coastal fynbos communities (including renosterveld) with that of cultivated crops (cereals, pastures, vineyards) to determine potential carbon trading advantages from restoration or conversion of fynbos. They concluded that coastal fynbos and renosterveld stored higher stocks of carbon than any cultivated land uses and that, especially in marginally productive, drier regions, significant benefits from fynbos restoration could be obtained from selling carbon credits. These observations concur with findings related to fynbos-equivalents elsewhere in the world (Luo et al. 2007). As a general indicator of monetary value, the consensual going rate of carbon credits was recently approximated at $US10-15 per credit (ton equivalent) (Paviour 2014).

4.4.3 Carbon storage measurement

Quantifying the carbon storage potential in a landscape can become an elaborate inventory exercise (Zhao, Horner & Sulik 2011) as the copious literature on the subject attests. The carbon storage potential of individual plant species is determined by field experiment and calculated as the sum of the various vegetation components:

Total organic carbon (TOC) stocks = Total below-ground carbon (TBGC, i.e., root carbon + soil C) + Total above-ground carbon (TAGC = herb carbon + litter carbon + woody C)

(Mills & Cowling 2006).

To measure soil carbon, a minimum of 30 plants must be sampled to get a mean CS (carbon storage) value for a species in a given region (Lemus & Lal 2005; Mills & Cowling 2006; 2010; Powell, Mills & Marais 2008; Powell 2009).

As Wani et al. (2012) and Rodríguez-Loinaz, Amezaga & Onaindia (2013) have pointed out, the assessment of the carbon sequestration potential (CSP) of native species in various regions is still in a nascent phase, and this is true of fynbos and especially its various communities. The aim here was therefore to simplify the procedure by not endeavouring to calculate species- or community-level storage potential empirically and put monetary values to carbon as a tradable commodity, but merely to determine a carbon storage mass value for the various land cover types by area and period and to use these for comparative purposes. In other words, the aim was not necessarily to produce accurate and absolute carbon storage figures, but to enable relative volume and ecological service delivery comparisons over time. The solution was to determine from the literature the realistic consensual carbon storage potential approximations for the various land cover types as simplified basis for comparison. For this reason, in this research total carbon storage (typically expressed as tons of carbon per hectare – $tCha^{-1}$) was used instead of carbon sequestration rates.

A summary of the empirically derived and averaged carbon storage figures from a host of studies, regions, assumed relevant species and vegetation types was compiled as listed in Table 4.8. Clearly, reported figures vary widely, because similar vegetation under different climatic and natural regimes and conditions (e.g. fire exposure, stand age, species composition, topography) and growth stages had been experimented with. This inevitably led to a somewhat bewildering and incomparable array of possible values and it was decided to approximate to the central value appearing in the last column of the table. In justification of the chosen value, the expressed aim to generate comparable values over time only, should be kept in mind.

Trees and plantations, as expected, have the highest carbon storage values in the area, fairly closely followed by perennial agriculture (fruit orchards in this case). The different annual agriculture crops and fynbos communities all have a much lower carbon storage value. While the chosen central value for fynbos might imply that this biome offers modest potential as a carbon storage medium, the available values vary rather wildly and seem to be conflicting. Indeed, the values reported by Mills et al. (2012; 2013) for a not-too-distant region approach that of deciduous fruit orchards. Note that, should absolute carbon storage figures be required for the purposes of trading, much refined calculations would have to be performed. For their comparative use in this study, the values are acceptable and were applied operationally.

Carbon storage potential data for the different land cover types in the Koue Bokkeveld region were calculated by multiplying each land cover area (ha) by the approximated per-unit storage figures (tCha) obtained from literature as reported in Table 4.8. By applying the per-hectare storage values to the various land cover images, carbon storage potential tables for the three time slices for each cover type could be generated and graphically prepared for later use. The calculated figures

Table 4.8 Literature-derived reported carbon storage values by land cover type

Land cover type	***Vegetation/Biome type***	***Reported values (tC/ha) ****	***Source***	***Applied value (tC/ha)*****
Natural vegetation	Fynbos (20 years post-fire)	3.2	García-Quijano et al. (2007); Chisholm (2010)	3.2
	Fynbos	1.5-4.0	Egoha et al. (2009)	
	Fynbos	42-81.0	Mills et al. (2005)	
	Fynbos	34-65.0	Mills & Fey (2004)	
	Fynbos	55 (average)	Paviour (2014)	
	Fynbos	92.4	Mills et al. (2012)	
	Fynbos	60.0	Marais (2013)	
	Sandstone fynbos	113.5	Mills et al. (2012)	
	Limestone fynbos	88.4	Mills et al. (2012)	
	Renosterveld	84.0	Mills et al. (2013)	
	Thicket biome (intact)	87.0	Powell (2009)	
	Thicket biome (degraded)	30.5	Powell (2009)	
	Karoo biome	21-50.0	Mills & Fey (2004)	
		30.0	Mills et al. (2005)	
	Acacia Karoo	30.3	Jindal, Swallow & Kerr (2008)	
	Grasslands	97-164.0	Mills & Fey (2004)	
Wetland channels	River & floodplain	0.0	Reyers et al. (2009)	0.0
	Freshwater stream & seepage areas	0.0	Reyers et al. (2009)	
Wetland flats	Wetlands	20 (Vegetation); 723 (Soil)	Lemus & Lal (2005)	20.0
Dams		0.0	Marais (2013)	0.0
Plantations and trees	Pine plantations	90 + fynbos	Chisholm (2010)	90.0
	Plantations	50% of forests	Lasco & Pulhin (2009)	
	Plantations	189 (average)	Marais (2013)	
	Agroforestry	95	Albrecht & Kandji (2003)	
	Mixed cropping to agroforestry	75	Kotto-Same et al. (1997)	
	Temperate agroforestry	15-198	Dixon et al. (1994)	
	Agroforestry	48.7 (above ground)	Nair et al. (2009)	
Annual agriculture	Gliridicia-maize	10-33	Wise & Cacho (2008)	10.0
	Cropland	2.0	Abberton, Conant & Batello (2010)	
	Agriculture	10-11	Avitabile et al. (2011)	
	Pastures	104.1	Mills et al. (2012)	
	Pastures	58.8 (average)	Marais (2013)	
	Active fields	68.8±19.5	Mills et al. (2013)	
	Crop fields	81.0 (average)	Marais (2013)	
	Fallow fields	28.7±1.95	Powell (2009)	
	Fallow fields	92.4±33.0	Mills et al. (2013)	
Perennial agriculture	Vineyard	97	Keightley (2011)	48.0
	Vineyard	69.1	Mills et al. (2012)	
	Peach orchard	16.7	Sofo et al. (2005)	
	Peach orchard	29.6	Sofo et al. (2005)	
	Perennial Agriculture	50% of forest	Lasco & Pulhin (2009)	
	Fruit trees	14 (average)	Marais (2013)	
Farmsteads	(25% tree cover)	91 (tree cover)	Kaya (2009)	23.0
Town	(10% tree cover)	91 (tree cover)	Kaya (2009)	9.0

* Empirically-derived or average values;

** Operational approximation for this research enabled the pivotal questions to be answered: How much carbon was stored? Did carbon storage change positively or negatively in the study area over time? Did subregional change, and hence ecological service delivery, occur evenly in the region?

4.4.4 Land cover change and carbon storage in the Koue Bokkeveld

The results are discussed first in terms of the summary carbon storage statistics for the Koue Bokkeveld as a region in total, during which change over time is also addressed, followed by subregional comparisons to gain spatial and ecological service delivery perspectives. Consistent associations between land cover change and biodiversity of vegetation and carbon storage have been reported from all over the world and locally (Le Maitre et al. 2007; Reyers et al. 2009). Clearly, agricultural activities have major effects on carbon storage through displacement of natural vegetation in landscapes like the Koue Bokkeveld. However, the more agriculturally developed the landscape, the more varied the effect on carbon storage because natural fynbos is a carbon sequester similar to cultivated species like orchards or forestry plantations. The results in Table 4.9 should be interpreted against this backdrop and remembering that all natural vegetation communities are statistically lumped together. The first noteworthy result is that at landscape level, very large

Table 4.9 Carbon storage by land cover type in the Koue Bokkeveld

Land cover type *	Capacity (tC/ha)	Total carbon storage (tons)		
		Reference State	1 949	2009
NV	3.2	762 226	705 795	644 654
WC	0.0	0	0	0
WF	20.0	119 849	107 118	38 623
CD	0.0	0	0	0
TD	0.0	0	0	0
PT	90.0	0	40 993	63 063
AA	10.0	0	148 009	262 259
PA	48.0	0	91 013	375 635
Bu	23.0	0	5 405	28 087
T	9.0	0	0	306
Total carbon stored		882 075	1 098 333	1 412 626

* See Table 2.1 for the legend to land cover and land use category codes.

amounts of carbon are stored in the vegetative forms showing up on land cover maps. It should therefore be evident that vegetative cover plays a major landscape service-providing role in curbing earth warming, climate change and ensuring clean air. Also, the role of natural vegetation, especially wetlands, in carbon storage has been diminished significantly over recent history. However, the addition of agricultural land cover has compensated for this loss by adding gross increases in carbon storage. In total, carbon storage increased by nearly 25% from the reference state to 1949 and by more than 28% over the past 50 years. Until 1949, annual agriculture had contributed most of the anthropogenic carbon storage after which perennial agriculture, in the form of extensive deciduous fruit orchards, provided the lion's share of the carbon storage additions.

As expected, the general regional trend does not hold across subregions. Carbon storage calculations for the five subregions, as reported in Table 4.10 and illustrated in Figure 4.4, show how differential development trends affect ecological service delivery differently in regional space.

Table 4.10 Carbon stored in the Koue Bokkeveld subregions

	t Carbon Stored			t Carbon/ha		
Subregion	**Reference S**	**1949**	**2009**	**Reference S**	**1949**	**2009**
Onder-Bokveld	254 866	333 351	448 700	3.5	4.6	6.1
Droëhoek	202 628	269 531	299 484	3.2	4.3	4.8
Sandhoek	238 669	275 593	303 124	3.9	4.5	5.0
Witsenberg	124 125	150 185	257 288	3.7	4.4	7.6
Voor-Matroosberg	61 787	69 673	104 030	3.7	4.2	6.2
Total: Study area	882 075	1 098 333	1 412 626	3.6	4.4	5.7

Carbon storage has increased in all of the subregions, but has more than doubled and nearly doubled in Witsenberg and Onder-Bokveld respectively. Storage increases have been slightest in Droëhoek and Sandhoek. There are notable trends in the proportional contribution to regional storage as highlighted by the pattern of change between the three time slices: Witsenberg and Voor-Matroosberg display down-up growth patterns since the reference state, signifying recent accelerated development affects, while Sandhoek displays a down-down pattern. The latter can probably be ascribed to the large dams built in that region's river valley so making no contributions to carbon storage, yet covering large areas of wetland. The Droëhoek up-down pattern should be

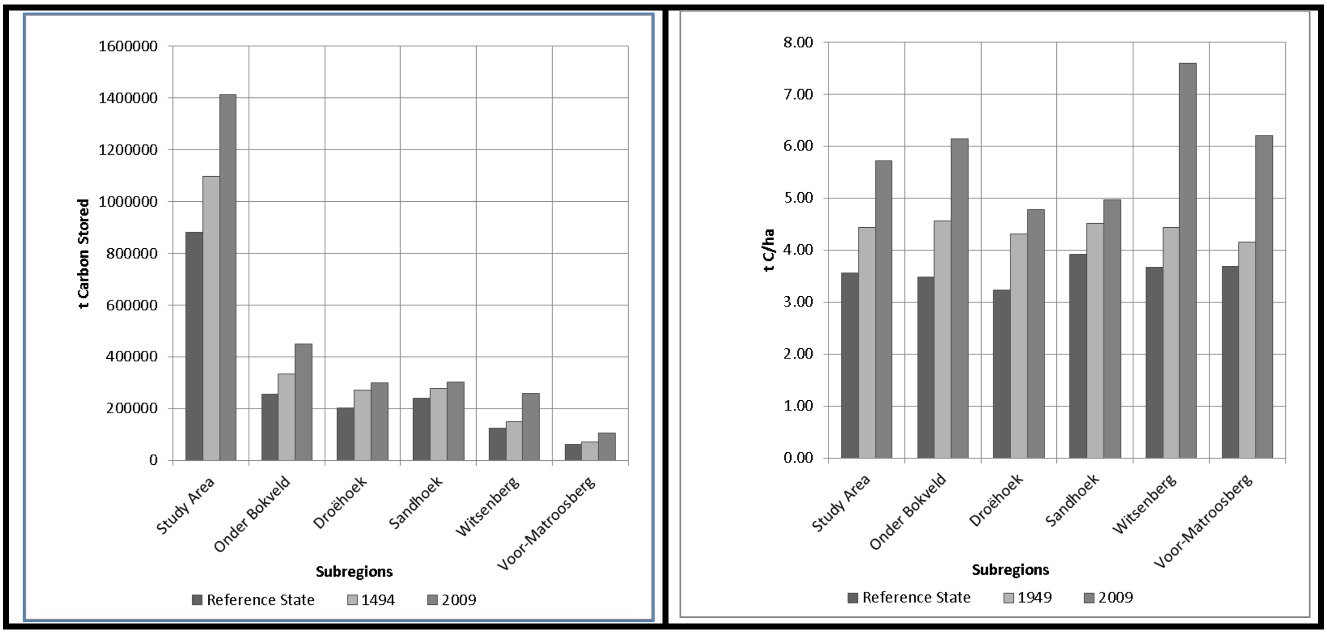


Figure 4.4 Carbon storage in the Koue Bokkeveld subregions

judged in light of the trend toward abandonment of extensive annual agriculture fields in this drier region, while Onder-Bokveld's up-up pattern points clearly to its being the most consistently developing region. These observations are borne out by the per-hectare storage results which show Onder-Bokveld, Voor-Matroosberg and Witsenberg consistently outperforming the other regions. It also shows the effect of absolute area: the larger subregions store less carbon per hectare than the smaller, more intensively developed deciduous fruit-growing and plantation forestry regions.

In conclusion, some general comments are in order: From the carbon storage prospective, the development of agriculture seems to benefit the Koue Bokkeveld and the world at large, since carbon storage is beneficial for the removal of greenhouse gasses from the atmosphere. However, because this increase is accompanied by an apparent decrease in biodiversity (previous section) the trend casts an ominous shadow. Some compromise between carbon storage and biodiversity should be affected to reconcile the preservation of both of these landscape functions – especially as foreseen in local integrated development planning (Witzenberg Municipality 2012). Although potential synergies between carbon storage and biodiversity exist and Strassburg et al. (2010) assert a strong association (R_S= 0.82) between carbon stocks and species richness, albeit unevenly distributed, they also warn that some high-biodiversity regions may not benefit from carbon-focused conservation. Perhaps a regional management solution, similar to that suggested by local scientists (Le Maitre et al. 2007; Reyers et al. 2009), could be found in systematically identifying less-effective carbon storage areas that can be converted to natural vegetation to boost the biodiversity of individual catchments. The reconversion of agricultural areas to natural vegetation is another avenue for consideration and further research. After all, "watershed ecosystems provide quantifiable benefits that can justify management expenditure" (Van Wilgen, Cowling & Burgers 1996: 184).

This concludes the empirical results part of the thesis, requiring a summary and reflective recapitulation of the research in the next, and final, chapter.

CHAPTER 5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The main aim of the research was to detect, capture, record and classify the spatial nature, extent and change dynamics of various landscape elements and functions due to change in land cover, allowing the determination of its effects on landscape functioning in the Koue Bokkeveld. This aim was reached through achieving the seven objectives of the study summarised under separate headings in the first main section of this chapter. Salient conclusions relevant to the economic development and conservation initiatives in the study region and recommendations for practical management steps are presented. The chapter concludes with suggested avenues for further research on landscape analysis and the effects of land use on landscapes in Geography and related sciences.

5.1 SUMMARY OF RESEARCH RESULTS

The research aim was reached through realising each of the seven research objectives stated in Chapter 1 and revisited in this section – under separate headings to ensure comprehensive coverage. However, eight subsections are distinguished here to allow land use change to be summarised separately due to its importance to other objectives. In most cases an indication is provided of the part of the thesis where the relevant objective had been explored and brought to fruition.

5.1.1 Spatial database assembly

The beginner-researchers' tendency to rely on the latest methods and software for data preparation and analysis independent of the available data had to be resisted in this research. Especially in areas of data paucity, such methods might not be the most appropriate. The latest software is often too expensive or unavailable to users, especially in developing countries where data availability is often low and the complex methods available demand data that are not obtainable. Consequently, less demanding methods should be used to allow and encourage the application of useful research methodology among a larger segment of researchers. This argument dictated methodological decision-making in this research.

Most land cover change detection is normally performed on data from single sources, an option eventually not possible in this study. As developed at length in Section 1.4, source data here consisted of an amalgam of maps, aerial photographs and satellite imagery. The preparation and processing of this data to base materials at comparable scales and format was the first objective. Several factors dictated a circumspect approach. The low quality of the 1949 aerial photography – a primary data source – and the lack of empirically measured observations for the reference state (circa 1700 and defined as the precolonial natural land cover) largely dictated the data preparation methods used. Diverging and disparate data sources (listed in Table 1.1), ranging from derived maps to high-resolution satellite imagery for 2009, precluded the use of the newest image comparison methods for direct comparison of images without classification, so necessitating the application of a variety of data preparation and comparison methods to the various data types.

The 1949 digital data set for the study region was created by scanning two series of differently scaled aerial photographs to resolutions matching those of the 2009 SPOT satellite imagery. The scanned photographs were geo-referenced and mosaicked using a SPOT digital orthophoto and ERDAS LPS. Because fiducial marks on many photographs were badly faded the non-framed camera option was used and the result deemed adequately accurate for the research. A SPOT 2006 image was used as the GCP source. Time differences between imagery sets complicated the finding of matching GCPs, so that recognisable landmarks, like visible roadways, crossings, unchanged cuttings, and natural river courses that remained spatially stable were used. The 2009 satellite images were rectified with the SPOT ortho-image used as GCP source. Rectification was performed using the LPS Photogrammetry suite in ERDAS. The rectified images were mosaicked to match the size of the 1949 photo mosaic. The natural vegetation image was obtained from SANBI in digital format and used to generate the reference state land cover image. Quaternary catchment data were the basis for delimiting the study area and five subregions (Table 2.2). Errors detected in the quaternary data were removed by applying a DEM and the hydrology tools in ArcGIS. Three accurate, matching and comparable time-slice land cover overlay images were created for the study region by clipping from the corrected catchment frame.

All landscape structure data were extracted from a DEM through various spatial analysis tools in ArcGIS. The simplified geology image was captured from the digital 1:250 000 geology map which was also the base for the natural vegetation image. Data obtained in electronic format were projected to the same coordinate system as the imagery to promote accurately registered overlaying operations in ArcGIS. The maps compiled from the main data sets are stored for reference in the accompanying DVD in ArcGIS format.

Tabulated data obtained for (e.g. climate, run-off) and generated in this research were stored and manipulated in Microsoft Excel. ERDAS LPS, ArcGIS and Microsoft Excel were the main software used for data gathering and manipulation. The data were purposely not stored in an esoteric geodatabase format so as to enable its future use, in and transportation among, different program platforms. Judged by its accuracy and functionality, the spatial data base that was created successfully realised the first objective and represents a benchmark to support regional research and development planning.

5.1.2 Land cover analyses of three time slices

The objective was to compile three synoptic land cover classification maps – reference state, 1949 and 2009 – and to analyse land cover change over time. The land cover distributions and patterns revealed in the maps and results of the land cover change analyses are recounted in the next two sections respectively.

5.1.2.1 Land cover patterns

A unique land cover classification system (see Table 2.1) of twelve natural and nine anthropogenic land cover classes was designed for this research and applied meticulously according to the methodology set out in Section 2.2. Numerical results are listed in Table 2.3. It was found that Winterhoek Sandstone Fynbos consistently covered about one-quarter of the study region, followed by Cederberg Sandstone Fynbos and Swartruggens Quartzite Fynbos at just below 20% respectively – giving a consistent dominance of 80% natural versus 20% (and growing) anthropogenic coverage. The absence of human spatial footprint at the reference state (mapped in Figure 2.8) constitute an appropriate point of departure, with natural vegetation dominating the landscape. Wetlands still dominate the shale fynbos and renosterveld areas in the valley bottoms, illustrating the rich vegetal biodiversity and intact landscape functioning in the study area. Wetlands, mainly occurring in these sensitive low-lying vegetation groups, stood out as vulnerable to the impending development of the region.

The potential for human impact on the landscape became evident in the pre-modern (1949) land cover reconstruction (mapped in Figure 2.9). The low-lying shale vegetation types were being replaced by agricultural activities, although wetlands were relatively free of agricultural encroachment. Irrigation dams were located in smaller streams and in wetlands, leaving areas farther away unaffected. Agricultural production was mainly annual crops (cereals, stockfeed) and mostly located along valleys sides away from the wetland flats in valley bottoms. Plantations, trees and perennial agriculture (orchards) were making their presence felt, but only on about 1% of the region's total land area. Subregional trends indicated that future perennial crop development would congregate in the better watered subregions (Witsenberg, Sandhoek, parts of Onder-Bokveld and Voor-Matroosberg).

The current (2009) land cover patterns (mapped in Figure 2.10), demonstrated a spatial explosion of human activity in the landscape. The natural vegetation that had dominated low-lying regions had become largely replaced by agriculture-related activities, so endangering the natural wetlands and shale vegetation. Irrigation dams (some very large) were scattered between agricultural blocks and little of the wetlands and shale vegetation remained visible. Technological developments and innovations in transportation, earth-moving, cold-storage, water storage, transportation and, especially, irrigation techniques fuelled accelerated agricultural intensification and expansion beyond the advantages offered by climate and related natural resources.

5.1.2.2 Land cover change

A thorough methodological approach (see Section 2.2.3) for land cover change matrix construction was done to simplify change analysis and to be more useful in indicating development trends. Change detection was performed in ArcGIS and statistical processing was performed in Excel to create graphs and tables. The change matrices were manipulated to gauge various aspects of change, of which the temporal changes in intensification and productivity among all land cover classes were paramount. Tables 2.6-2.9 display these trends.

Overall, the Koue Bokkeveld has become transformed from a pristine natural environment to a landscape of highly human-influenced, linear agricultural cores fringed by mountainous vestiges of pristine nature. By the mid-20th century the shale-resident natural vegetation types had been largely replaced by agricultural (mainly annual, and some perennial), dotted by smallish irrigation dams. Fruit-growing development was still slow due to the inability of deciduous (apples, pears) and stone (peaches, plums) fruits, as well as vegetables (potatoes, onions) to withstand transportation over dirt roads without being bruised. Grains and livestock escaped these limitations for extensive livestock-farming, pasturage and annual cereal production to dominate. The use of ever-larger machines caused the level, low-lying shale and alluvium soils to be targeted for cultivation. Waterlogged, heavy wetland soils, although rich in nutrients, presented challenges to cultivation, although limited draining of wetlands had commenced in the Koue Bokkeveld.

During the remainder of the 20th century and the beginning of the 21st century exceptional improvements in technology and general infrastructure networks had driven profound landscape change. Refrigeration, better transport, innovative irrigation technologies, advanced farm machinery and the consolidation of smaller farms all increased the profitability of capital-intensive perennial crop farming above that of livestock and cereals. Consequently, more profitable perennial agriculture had come to dominate the regional economy and this had driven land cover change. Half of the agricultural lands (some 10% of the total area) were covered by orchards, while abandonment of annual agriculture gave the impression that some previously ploughed lands had begun a return-to-nature trend. An intensification and permanence contrasting with a balancing of nature’s demands now dominated the broad pattern of land use.

Notable spatial trends were evident, both regionally and in the local landscapes. While gravity-fed irrigated agriculture had initially been confined to valley-bottom locations downstream from small storage dams on low-lying streamlines, orchard locations had changed markedly. Large storage dams, built with the aid of powerful machinery and fed by pipelines, came to use off-stream locations, some high in the mountains from where they provide gravity-feed irrigation water to micro-fed irrigation systems and fields. Furthermore, the national electricity grid had reached the region in the early 1960s, enabling pumping schemes to transfer large volumes of water across catchment divides. Consequently, micro-sprayer irrigation facilitated a migration of orchards out of valley bottom locations, to the better, high-lying, shale-rich soils free from spring frost. Valley bottoms, extensively drained through artificial stream channelling, became reserved for irrigated vegetables (onions, potatoes, green regimen and pumpkins). This cornucopia of agricultural commodities emanating from the Koue Bokkeveld now feed provincial, national and international markets. Infrastructural developments were a proliferation of electricity grids, tarred roads, modern processing-related facilities (cooling, packing, sawmills, workers' residential villages) constructed at extensive farmsteads. The occupied landscape had become a patchwork of farmstead clusters connected by a network of transportation routes traversing a landscape dominated by high-intensity vegetable fields and fruit orchards.

Understandably, this extensive intensification in land use profoundly impacted on the previously natural landscape. Low-lying fynbos on valley shales or alluvium fynbos and both types of inland renosterveld (CR and MS) were variously decimated by the agricultural activities. These regionally-unique vegetation communities were graded to the list of vulnerable types deserving of national concern. The profound land cover changes uncovered by the research raise serious questions about the continued functional health of the Koue Bokkeveld landscape.

5.1.3 Understanding the Koue Bokkeveld landscape

The objective to better comprehend the land cover dynamics unfolding in the Koue Bokkeveld, necessitated analyses of the morphology of the landscape to establish the relationships between land cover types and landscape. The outcomes of these efforts are comprehensively reported in Chapter 3 and are encapsulated in this section.

One way to resurrect regional geography is through the greater understanding of landscape offered by the analytical abilities inherent to GIT application. In its various guises GIT allows the creation of morphological landscape images for variables such as height above sea level directly from DEMs, calculation of slope, aspect, drainage and hydrology network connections, landform classification, slope position and distance to water sources for the region using the same basic DEM. These procedures were applied to better understand the peculiarities of land cover placement and change in the landscape. The comparisons entailed a relatively uncomplicated process of repeated combinations of basic image layers of land cover with various morphological layers.

The Koue Bokkeveld is a highland area dominated by the upper slopes of mountain ranges (nearly 30%) interspersed by broad plains and valleys (more than half of the total area). The mountain slopes are steep and thus unsuitable for development, so giving protection to the natural sandstone-related vegetation. The opposite applies on the flat valley bottoms. More than 80% of shale and alluvium fynbos, shale renosterveld, Tanqua Wash Riviere and wetlands are located on these gentle slopes and they are thus prime target areas for agricultural expansion. Most of the region's agriculture occurs on land below the legal 20%-slope limit above where deleterious erosion and soil loss impacts are normally encountered. Fortunately this reflects basically sound soil-management practices in the Koue Bokkeveld.

The valleys are mainly concave (relatively lower-lying, water collecting) with flat valley bottoms and cultivation along valleys and mountainsides (convex curvature, high-lying, water-shedding) that show no dominant or preferred aspect. The shape of individual valleys does, however, have an influence on agricultural development, the broader, plain-like valley forms accommodating more annual agriculture and the narrower valleys attracting the more profitable perennial agriculture.

The incorporation of simple morphological measures (slope and aspect) and more complex factors (slope position and landform) helped to comprehend land cover patterns. Analyses revealed the close association between various vegetation types (shaleband, sandstone and alluvial groups or renosterveld) on various landscape positions (ridge, valley, toe- and mid-slope) and unique geological formations and altitudes. Exceptional concentrations on flat locations were recorded for three of the most vulnerable shale and alluvium-based vegetation groups (KS, KA, CR) and wetlands that were noted for their exposure to agricultural development by 1949, and even more so by 2009. Development pressure caused the natural vegetation in these locations to record lower occupation rates by 2009. Forestry occupied mid-slope and even upper-slope positions, clearly a marginal use compared to agricultural production. Paradoxically, but not unexpectedly, built-up farmsteads and town lands are mostly on flat areas where they presumably compete with agriculture for space. The analyses of proximity of (mainly perennial) agricultural land cover types to water sources (wetlands, stream channels and dams) showed a growing liberation of the constriction of the cultivable suitability of land to proximity to water sources. In short, the transferability of water by pipeline has continually increased the distance between water storage and naturally available water channel locations and crop locations. This has unexpected implications for some vegetation communities previously protected from invasion by virtue of their topographical isolation.

5.1.4 Stability of landscape functions in the Koue Bokkeveld

A major outcome aimed for in the research was to gain an improved understanding of the potential impacts on the natural ecological functioning of the Koue Bokkeveld landscape exposed and attributable to the profound land use changes alluded to above. Three salient landscape functions (hydrological integrity, biodiversity stability and maintenance of carbon sequestration potential) that could be jeopardised by land cover change were analysed in Chapter 4 and the results are recapped in this section.

5.1.4.1 Hydrological functioning of catchments in the Koue Bokkeveld

The poor spatial and temporal distribution of weather stations and run-off gauges and incomplete records of precipitation and run-off data for the Koue Bokkeveld dictated the use of run-off modelling to determine trends in run-off and, coupled to land cover change, the effects on landscape functions. A lack of soil-hydro group information for the area was a further confounding factor in selecting an appropriate modelling method. The SCS-curve number method was selected as it is appropriate for simulation and obviates the lack of ready data. Derived and mean curve numbers were calculated for the region, while soil-hydro groups were assumed to remain stable over time.

The Koue Bokkeveld occupies the watersheds between three primary river systems in the Western Cape, the Olifants, Breede and Gouritz rivers. It is a main run-off generator for the Olifants/Doring river system so that run-off changes there will influence the system at large. Increased run-off or erosion potential can lead to siltation in the system, clogging up dams and so lowering water storage capacity further and reducing water availability for agriculture and human consumption. It is a landscape function of major import.

The modelled output figures (Table 4.3) underscore the importance of the region as run-off generator. It contributes nearly 790 million cubic metres (m^3) of run-off annually, of which more than 90% runs to the Olifants/Doring system, nearly 9% to the Breede system and only 0.4% to the Gourits. Nearly two thirds of the total run-off in the Olifants/Doring system originates here, thus underscoring the importance of the Koue Bokkeveld as a regional provider of this vital ecological service. It was found that five subbasins (E10A, E21D, E21E, E21G, E21H) dominate run-off yield, each producing more than 10% of total run-off. Subregionally, the Onder-Bokveld yields nearly one third of all run-off and Voor-Matroosberg less than 4%.

Temporal trends in the run-off yield reflect the numerical and spatial impacts that development has had. With the exception of two, all the catchments registered fairly consistent increases in run-off yield since the undisturbed reference state – all due to change in land cover. The scope of change was large and reached almost 20 million m^3/yr, or 2.6% in total. Specific catchments (E21G, E21D) registered more prominent total run-off increases and four catchments (E10B, E21D, E21G, E22C) registered increased yields above 100 m^3/km^2. Such large volumes suggest potential problems concerning water quality and/or soil erosion in parts of Sandhoek and Onder-Bokveld. Clearly, run-off production, as an ecological service, had been affected to some degree in all the catchments and subregions. This is positive in yield terms, but probably negative regarding its limiting effect on groundwater recharge.

5.1.4.2 Landscape pattern and biodiversity in the Koue Bokkeveld

In principle, spatial analysis of the structure of a landscape enables deductions to be made about biodiversity status. Environmental patterns influence ecological processes and changes driven by anthropogenic activities disrupt the structural integrity of landscapes. These disruptions compromise ecological flows of organisms across the landscape and its functional integrity, so interfering with critical ecological processes necessary for the survival of human, animal and plant populations, and the maintenance of biodiversity and ecosystem health. The fragmentation of the landscape by agriculture is vitally important because of the influence it has on biodiversity through patch ecology. Patch size and density patterns were thus analysed on the assumption that the landscape mosaic model applied accepts that biodiversity decreases as landscapes fragment (more, smaller patches, larger perimeters, smaller core areas) and a stronger edge effect raises the risk of biodiversity loss. Decreasing patch size and increasing landscape fragmentation raise organism endangerment and susceptibility to extinction. Five patch-descriptive metrics were used, namely: patch area (measuring landscape dominance), patch perimeter (intrusion vulnerability), patch count and area/perimeter ratio (complexity), and largest patch index (clumpedness). Various ArcGIS toolsets were used for the appropriate metric calculation.

The empirical results recorded in Table 4.5 indicated that patch number increased over time for all the natural vegetation communities, except the stable and isolated Western Altimontane Sandstone Fynbos (WA), Tanqua Wash Riviere (TW), South Hex Sandstone Fynbos (SH) and Northern Inland Shale Band (NI) vegetation. Notably, all the other metrics displayed the same stability for these four vegetation communities, an indication of stable biodiversity conditions. The other eight natural vegetation groups registered dramatically increased patch numbers, denoting alarming fragmentation dangers. Trends in the other four metrics for these groups point to consistently smaller patches and more perilous patch-edge exposure per unit area. The declining values of largest patch indices ominously imply decreasing large intact areas that must serve as ecological reserves for these communities. The biodiversity health of wetlands, especially that of low-lying natural communities impacted by agriculture (mainly KS, KA, CR and MS) has declined sharply. The metrics denote consistently lowered potential species mobility in space and growing stand isolation, hence lowered potential for maintenance of diversity.

Anthropogenic land cover classes intruded the landscape throughout the study period in a pattern of high fragmentation indicated by increasing patch numbers and long patch perimeters of monoculture blocks. In the regional landscape, patch areas are small due to the high development costs of permanent agriculture and the largest patch index values are small because agricultural patches are fairly evenly distributed throughout the lower-lying regions of the study area. Steady development of agricultural patches damages the naturally occurring vegetation communities and the landscape more broadly through segmentation. Subregionally, Witsenberg and Onder-Bokveld experienced increased landscape fragmentation through development impacts, therefore biodiversity vulnerability was heightened.

The analysis of Koue Bokkeveld-specific vegetation communities, as classified by SANBI (Table 4.6) confirmed the spatial vulnerability deduced from the landscape structure analysis. The Koue Bokkeveld houses a majority of the Kouebokkeveld Alluvium (KA, 100%) and Shale (KS, three quarters) Fynbos communities within its boundaries – implying a particular regional responsibility for their protection. These two communities are listed as endangered, they suffer from an absence of formal protection because they are low-lying in the landscape, they offer excellent soil conditions for agricultural development, and they have been systematically replaced over the past century. Moreover, the Ceres Shale Renosterveld is poised to become a community of concern because of its similar location and improved water transferability may bring it into the sights of agricultural development.

5.1.4.3 Carbon storage potential in the Koue Bokkeveld

Carbon storage (CS) and sequestration are related, yet dissimilar concepts. Both imply that living matter and soils contain carbon and that plants capture or sequester carbon dioxide (CO^2) from the atmosphere and store it as carbon in parts of the plants. Because carbon sequestration varies from region to region and according to climate potential, standard CS inherent to particular plant species, as reported in literature, were used in this research. Change in land cover implies change in CS in an area and to calculate the CS potential of the Koue Bokkeveld, the area of land cover classes can simply be multiplied by the per-area storage figures to determine total landscape CS values for the region.

Standard CS figures gleaned from published material were used to calculate CS volumes for three time slices studied in the Koue Bokkeveld, as reported in Table 4.9. It was found that the region contributes large amounts of CS that help alleviate regional and global warming trends due to the greenhouse effect – a clearly valuable landscape functional service. CS in the Koue Bokkeveld has increased continually since the reference state, mainly because of the planting of perennial crops (fruit trees) and timber plantations. CS in the region's natural vegetation has always been the largest contributor due to its overall spatial prevalence, but this share has diminished in accordance with its declining overall area. An accelerated natural burn cycle of fynbos in the affected area (as influenced by the agricultural development) will affect its CS potential – a management and planning concern. Subregionally, CS has increased in all of the subregions, but has more than doubled and near-doubled in Witsenberg and Onder-Bokveld respectively – the areas experiencing the greatest expansion of perennial agriculture.

5.2 SALIENT RESEARCH CONCLUSIONS

Salient research conclusions are drawn about the research methodology, data adequacy, phenomena analysed and the contribution of work to geography, particularly to the subdiscipline of regional geography. These conclusions are contemplated separately below.

5.2.1 Insights regarding geographical phenomena and research

The integrity of the natural vegetation of the Koue Bokkeveld raises some burning issues. Although the SANBI vegetation map and data suffice as a resource for determining locational distribution of communities, it has limitations about accurately determining the spatial vulnerability status of natural vegetation in a regional setting. For instance, wetlands per se are not identified on the map and neither does it comment on the regional extent of their vulnerability. Both shale-based natural vegetation in the Koue Bokkeveld and wetlands are at greater risk than evident from the SANBI sources. Some of these areas have been irreparably damaged and species loss in fynbos and renosterveld is already almost certain. Shale fynbos types have been severely affected through replacement and have been fragmented by agriculture because these communities occur largely or exclusively in the Koue Bokkeveld. Wetlands occur within the shale fynbos areas where they are equally endangered by replacement. Although it may be argued that storage dams in the area function as (new) replacement wetlands (according to official wetland definition they are classified as such) but they function as water storage mechanisms for agriculture, their levels fluctuate by season and can therefore not function as full replacement habitat for wetlands.

Ecological landscape functions in the Koue Bokkeveld are invariably interrelated (even symbiotically connected) and change in one is bound to have an effect on others. It does not mean that a positive change in a function (for example, carbon storage potential) will necessarily positively encourage biodiversity. In the Koue Bokkeveld the carbon storage/biodiversity relationship is an example where a positive increase in one may indeed negatively influence the other. The carbon storage/run-off and run-off/biodiversity interactions are less clearly defined, but because fynbos removal for agricultural expansion generates increased run-off, it might also increase carbon storage. The relationship is apparently positive, yet it is not clear from the research how these interactions function. This research has confirmed that a landscape is a complex interconnected system with the different aspects influencing each other in a variety of uncertain ways, especially downstream and even beyond the boundaries of the region itself.

As for the research methods employed, it should be emphasised that the software used was consciously selected to be unsophisticated and having limited data requirements. Complicated methods were avoided for the sake of simplicity and straightforward replication. To simplify the various classification and mapping processes, products in open GIS software were used. These considerations are important in low-budget or preliminary research projects and they suite research conditions prevailing in developing environments with limited data availability or uncertain quality.

5.2.2 Conclusions regarding disciplinary impact

According to Barnard (2001), from the 1950s geography as discipline has relinquished its regional geography approach because of its reputation of generality and lack of comparability between various empirical descriptions of the same area. It was regarded as belonging to the 19th-century era of travel description and because more scientific approaches rendered artificial regional boundaries meaningless. The descriptive nature of regional geography favoured the human geography approach which became increasingly foreign to specialist physical geographers. The subsequent split between human and physical geographers led to the neglect of regional geography as a field of focus and its apparent demise (Barnard 2001).

Today there is a focus in geographical research on understanding landscape and the interconnectedness of landscape elements for ensuring sustainable development. The use of GIT to simultaneously analyse landscape patterns broadly and at greater integrative depth through the factoring of complementary and interactive spatial variables, promotes insight into how the physical and human-economic dimensions create new landscape dynamics. Landscape boundaries are established to determine the effect of spatial development on surrounding areas – from human and natural perspectives. This new focus on sustainable development is not only bridging the gap between the two main branches of geography, but it is also leading to the resurrection of regional geography. Although regional descriptive methodology has changed, the new approach can still be considered regional geography in the sense that it concentrates on analysing and deepening understanding of all interacting human and natural phenomena related to one region. This research claims its niche contribution as belonging to the ‘new’ regional geography approach.

Not only is regional geography reviving but the divide between the human and physical geographical approach to geography is closing as attention focuses on the interconnectedness of all natural (plants, animals, rainfall, etc.) and manmade (buildings, roads, dams, etc.) elements. These elements influence each other and they are so integrated that changes in one inevitably influence the rest in a landscape setting. Economic and other human-made factors (e.g. administrative, legal, regulatory) also play a role in our conception of the functioning of contemporary landscapes.

5.3 RECOMMENDATIONS

The recommendations are split between those relevant to landscape management and economic conduct in landscapes and those relevant to future research in the landscape domain.

5.3.1 Land management in the Koue Bokkeveld

The pre-eminent recommendation emanating from this research addresses the vital import of ongoing sensitive management and conduct of agriculture, agricultural expansion and the interaction between a vibrant agricultural land cover regime and the maintenance of a fully functional and healthy matrix setting of natural vegetation unique to the Koue Bokkeveld. To protect the endangered natural vegetation types, farmers must be given useful current information and continued education on the species richness of their fynbos environment. To do this, continued research should be performed to establish the location and variety of species that occur in even the smallest remnant stands of these fynbos types. To help raise the value and to practically evaluate the potential monetary value of all vegetation patches, the system of carbon credit trading should be advanced among landowners. A system that takes the quality of vegetation patches and their species richness into consideration should be developed to encourage the implementation of practical conservation measures by and among landowners, apart from any statutorily sanctioned and encouraged formal measures and structures. Such a system will also help to resolve the conflicts between carbon storage and biodiversity in carbon-storage poor vegetation types, where such problems exist locally.

The active establishment (cultivation, rehabilitation) and maintenance of existing, connecting vegetation corridors could be done by the cultivation or leaving of remnant stands to provide ecologically-sound linkages between patches of natural vegetation islands. Invasive plants along road verges and in mountainous settings, especially those visibly spreading from established alien-tree plantations, can be removed to safeguard indigenous species of fynbos. To help save wetland areas and some of their habitat functionality, especially for waterbirds, irrigation dams should be designed and actively altered to function more as wetlands than just water storages. The provision of small ‘eco-islands’ comes to mind as a practical initiative.

5.3.2 Further research

The recommendations in this section address issues pointedly, because they relate to technical discoveries made and convictions reached during the research. The *availability of appropriate data*, especially in developing settings like Africa, that meet the requirements of sophisticated and accurate landscape models, remains a problem. This means that data sources for variable points in a landscape are often not homogeneous, so that recourse has to be taken to different sources for a particular region. Building and providing such environmental data sets for landscape-related features like run-off, climate and weather, should be targeted in research efforts. Models fit for use in less-developed settings should better allow for methods suitable for less precise data. Concerning *run-off analyses*, soil hydro-group data for South African soils is not freely available at present, thus greatly limiting run-off modelling options and their accuracy and usefulness. The building of such a database for all South Africa's soil types should be a priority, because it would expedite and render research more economical for local companies, government and students.

An improved understanding of the operational relationships between various *ecological landscape functions* is crucial and too little is known about this subject. Research to improve the predicted effects of land cover change on landscapes is urgently needed. More accurate predictive models are called for to support progress toward more sustainable development practices. The carbon storage-biodiversity dichotomy is a good example of negatively interacting landscape functioning that begs improved understanding.

The availability and appropriateness of *GIT software solutions* to conduct regional research remains a challenge. Many research entities use open software or cheaper packages of licenced software for GIS applications to overcome cost constraints. Easily adaptable application modules built for these more economical software platform options should be the focus in research to enhance the free availability of the technology.

Region-specific research offers rewarding research foci. For instance, while existing botanical knowledge concentrate on macro- (national) or micro- (individual plant) scales, knowledge useful to mesoscale for enterprise management on individual farms or planning districts, is often non-existent or lagging. Continued research should be performed to establish the location, composition and variety of species that occur in even the smallest remnant stands of, for instance, fynbos types in smaller regions. Geographers must advance the 'new' regional geography approach advocated and tentatively probed in this research.

Research should be undertaken to explore ways in which *farmers* can *reduce their impact on local vegetation* stands to preserve remnant vegetation still intact. A notable example is the shale-based vegetation communities in the Koue Bokkeveld.

Because the Koue Bokkeveld occupies the headwater catchments of three river systems, a more in-depth hydrological analysis is necessary of the development impacts that storage and irrigation practices, and the possible decline of groundwater recharge, have in the region and downstream along the affected river systems. A productive point of departure is to determine the ecological reserve for each secondary subcatchment to inform water-extraction decisions, planning and practices on a watershed basis.

It is believed that building on the insights emanating from this research and pursuing the recommendations, a functional and useful contribution to establishing and maintaining a healthy and sustainable Koue Bokkeveld landscape and economy can be assured for future generations who will dwell and prosper there.

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PERSONAL COMMUNICATIONS

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APPENDICES

APPENDIX A AERIAL PHOTOGRAPHIC COVERAGE

Job 225 – Strip 1

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Job 225 – Strip 2

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Job 225 – Strip 3

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Job 226 – Strip 16

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Job 226 – Strip 17

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Job 226 – Strip 18

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Job 226 – Strip 19

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Job 226 – Strip 20

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Job 226 – Strip 21

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Job 226 – Strip 22

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Job 226 – Strip 23

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Job 226 – Strip 24

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Job 226 – Strip 25

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Job 226 – Strip 26

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APPENDIX B SPOT 5 SATELLITE IMAGES

K/J: 119/417

Scene: 509022509113731874 119-0-417 20 November 2008

Scene: 509022509111383 2216 119-0-417 20 November 2008

Centre: S33°25 E19°17

K/J: 119/416

Scene: 5090225113909619 119-0-416 20 November 2008

Scene: 5090225113941269 119-0-416 20 November 2008

Centre: S32°55 E19°26

K/J: 120/417

Scene: 5090225114041057 120-0-417 21 December 2008

Scene: 5090225441442668 120-0-417 21 December 2008

Centre: S33°25 E19°52

Processing Level: L1A

WGS84

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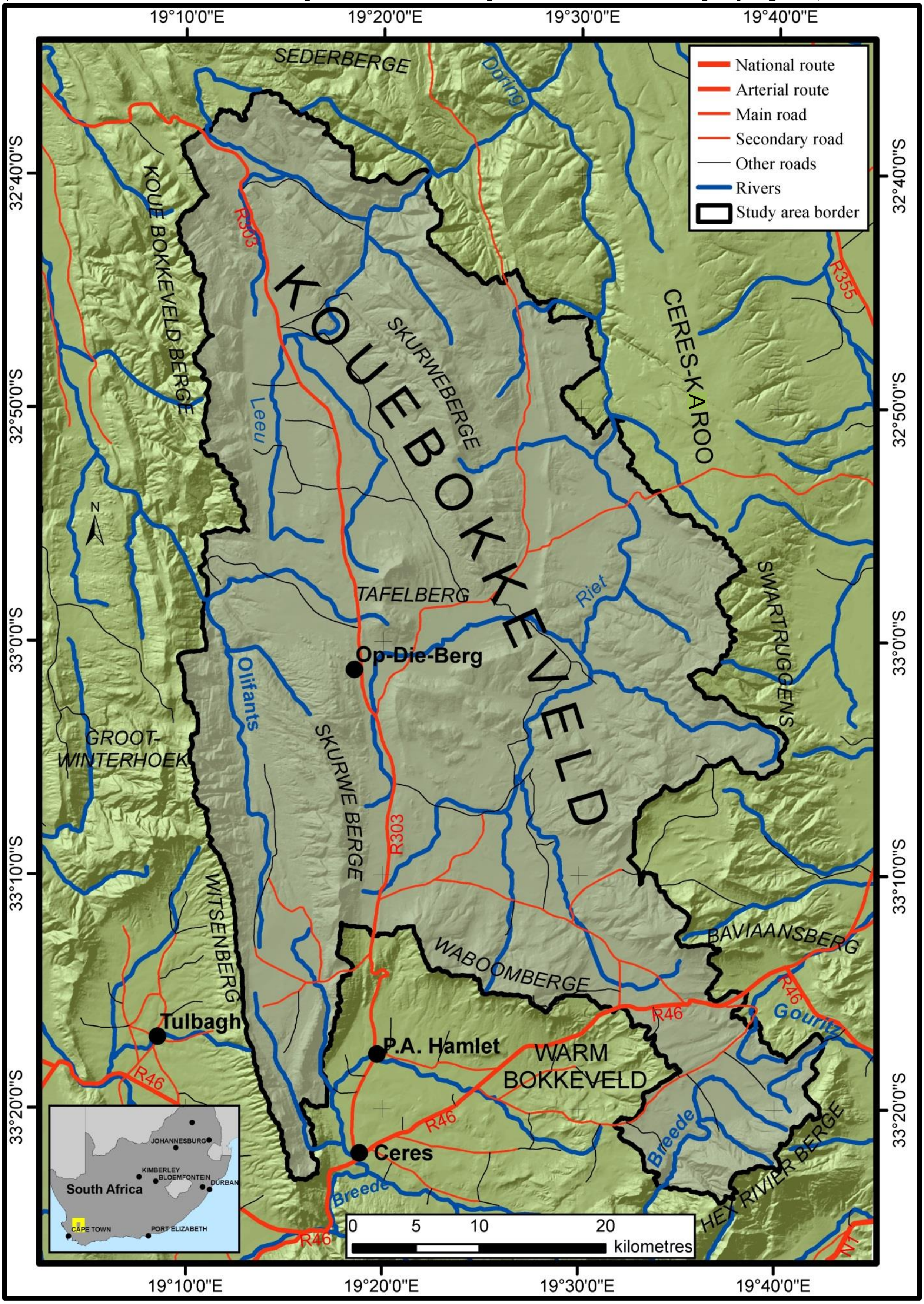
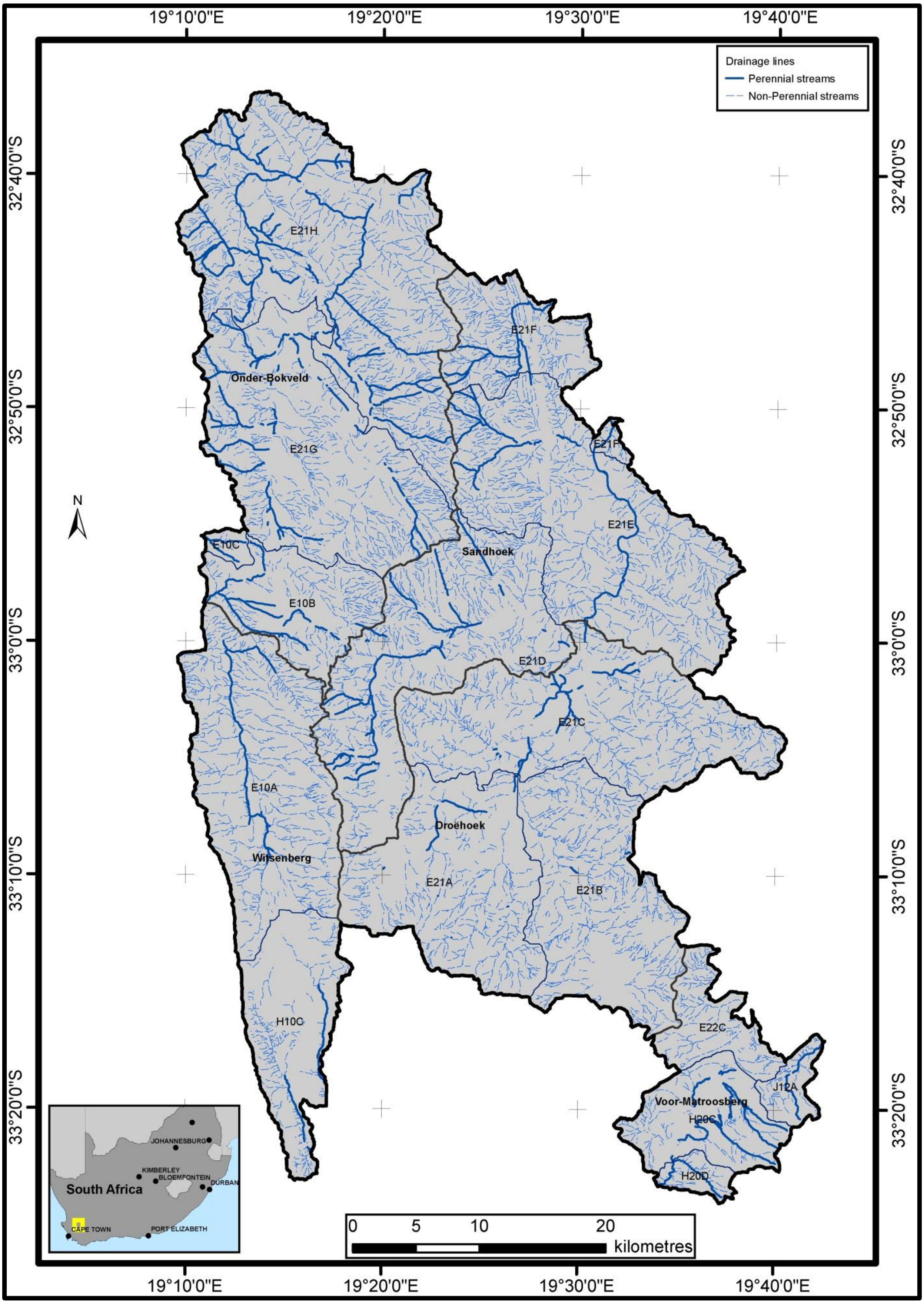
APPENDIX C GRAPHIC IMAGERY ON THE DVD

(Printed in A4 format here, and provided for A2 duplication on the accompanying CD)

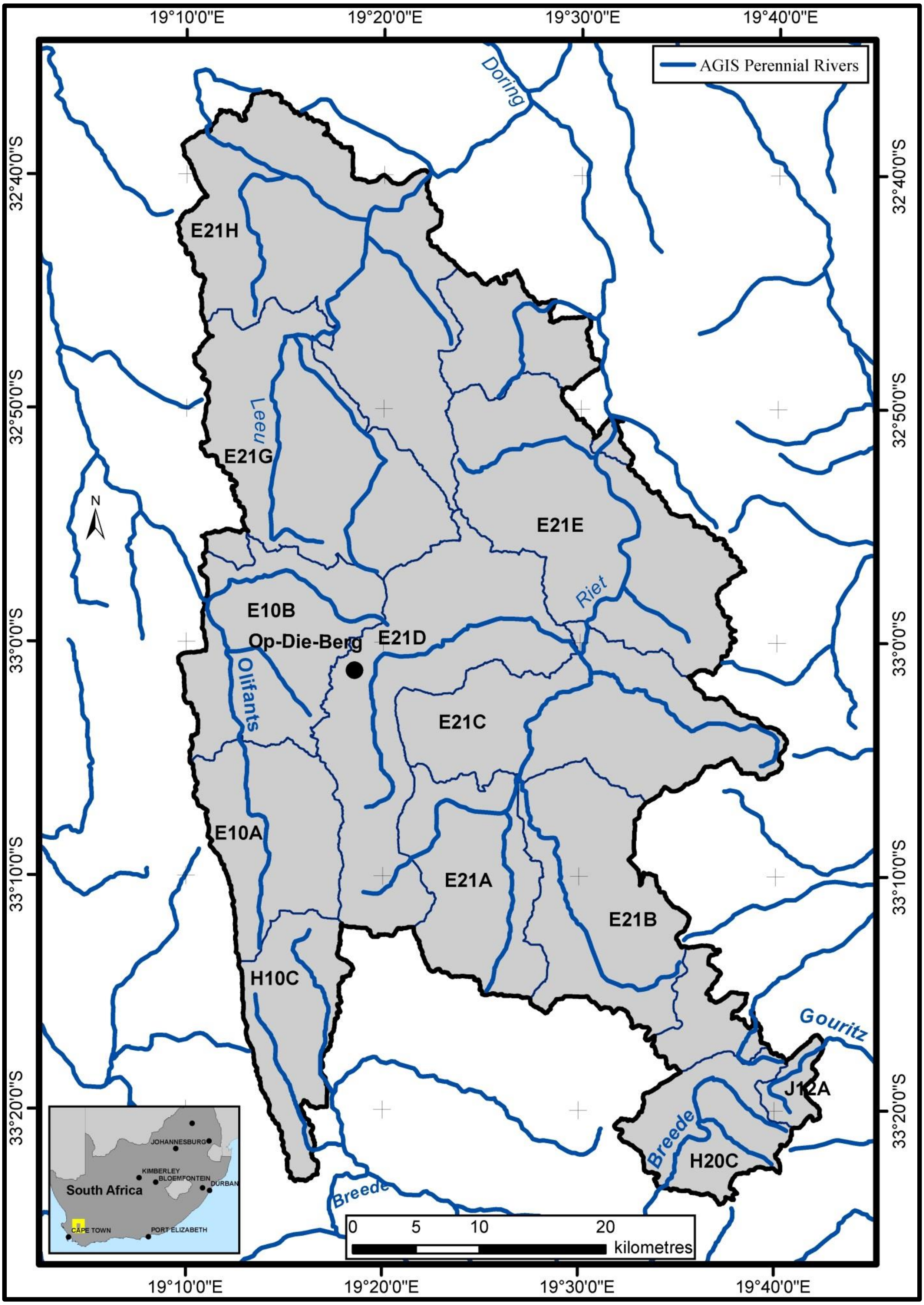


Appendix C 1: Detailed view of Koue Bokkeveld location



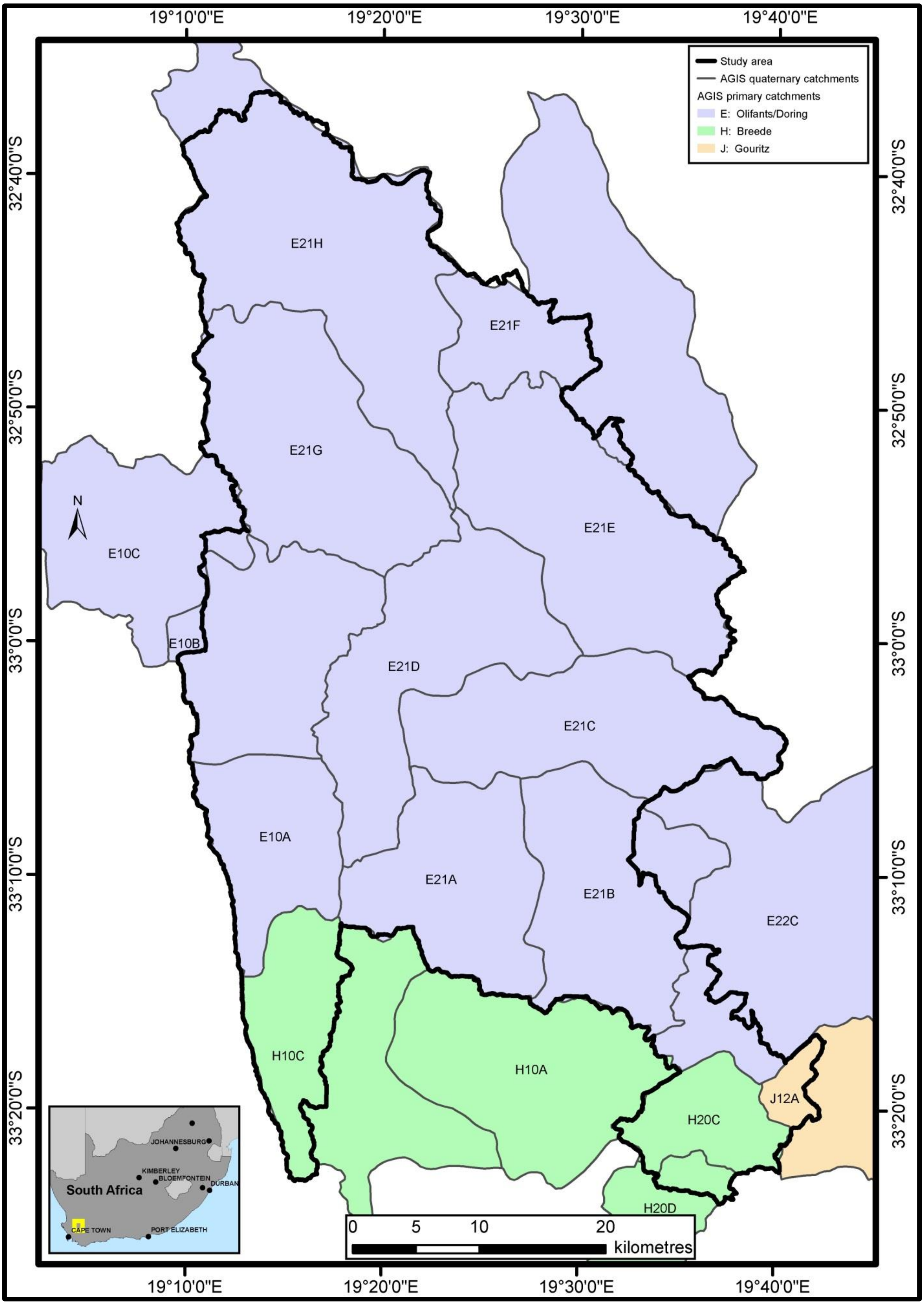
Source: 1:50 000 SA topographic

Appendix C 2: Koue Bokkeveld hydrology: All streams



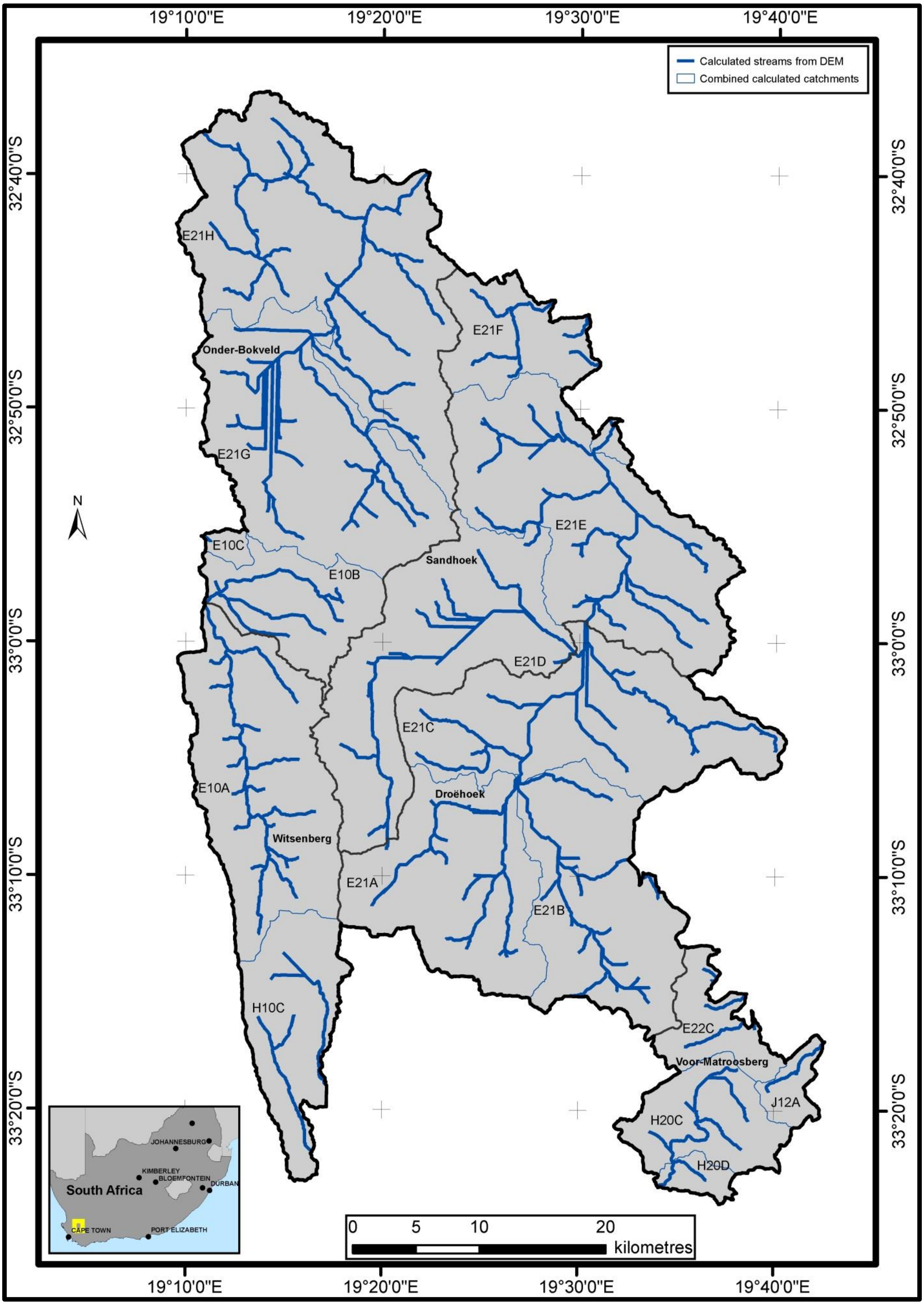
Source: AGIS

Appendix C 3: Koue Bokkeveld hydrology: Perennial streams

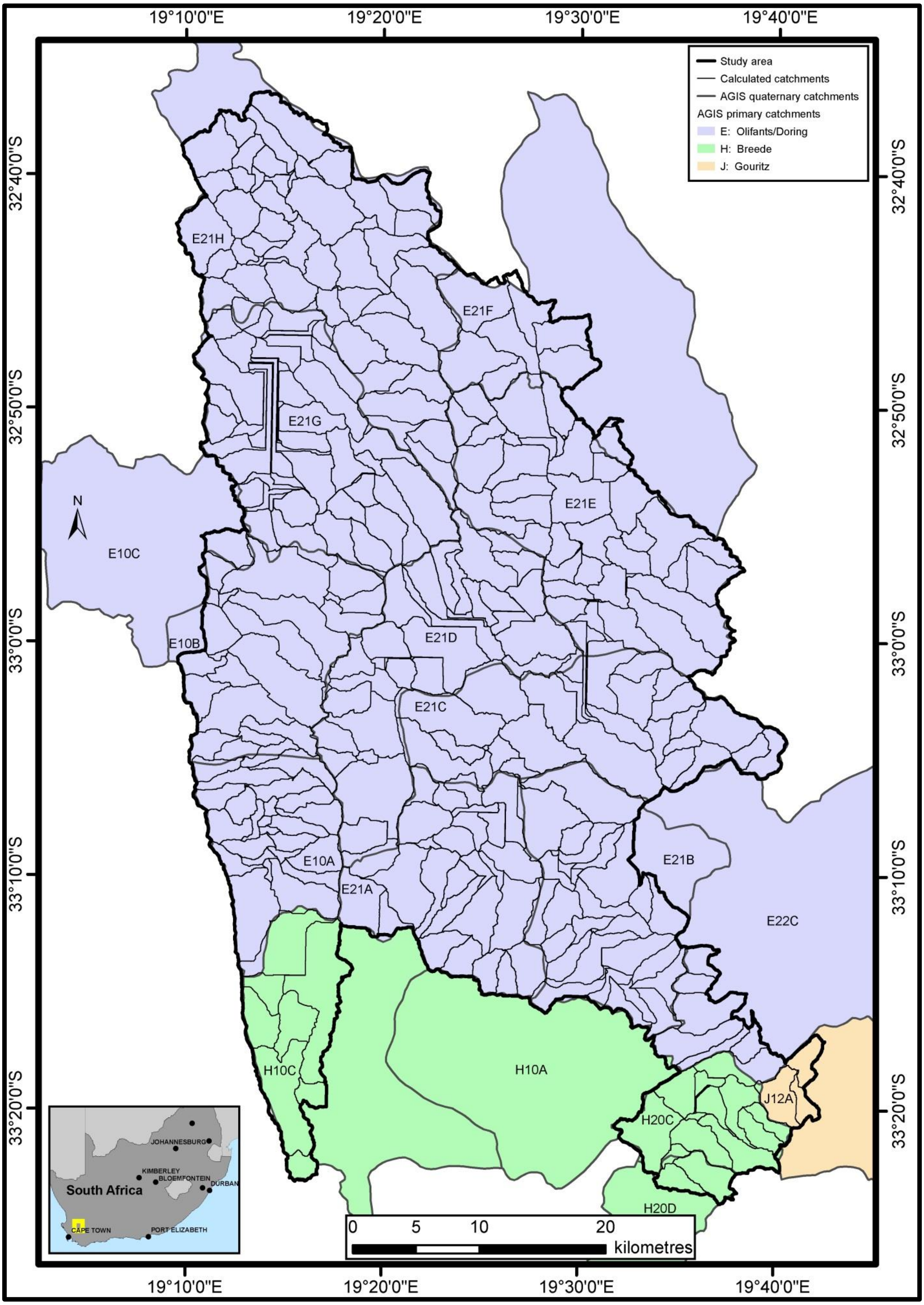


Source: AGIS

Appendix C 4: Koue Bokkeveld hydrology: Primary and Quaternary catchments

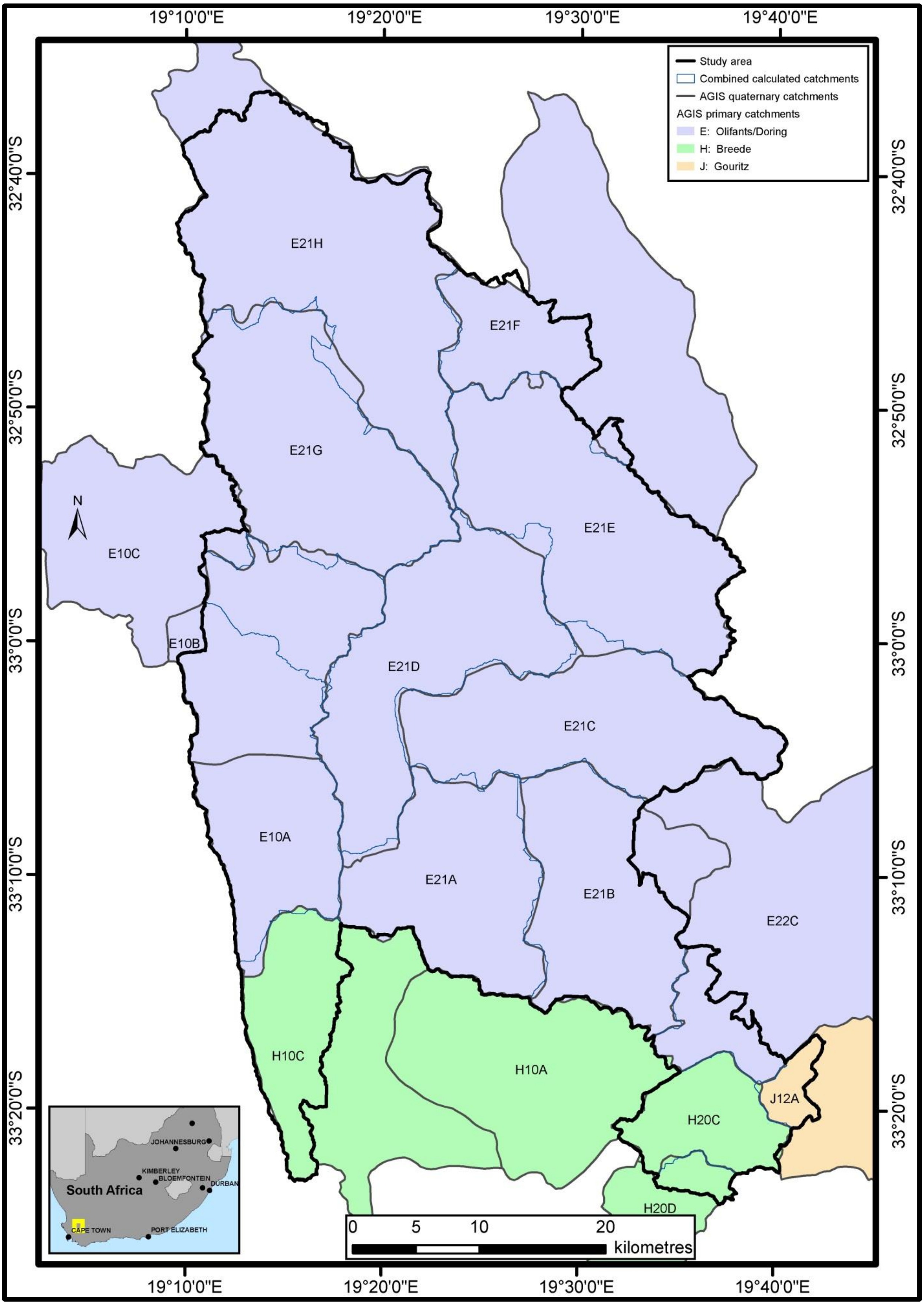


Appendix C 5: Koue Bokkeveld hydrology: DEM-derived streams

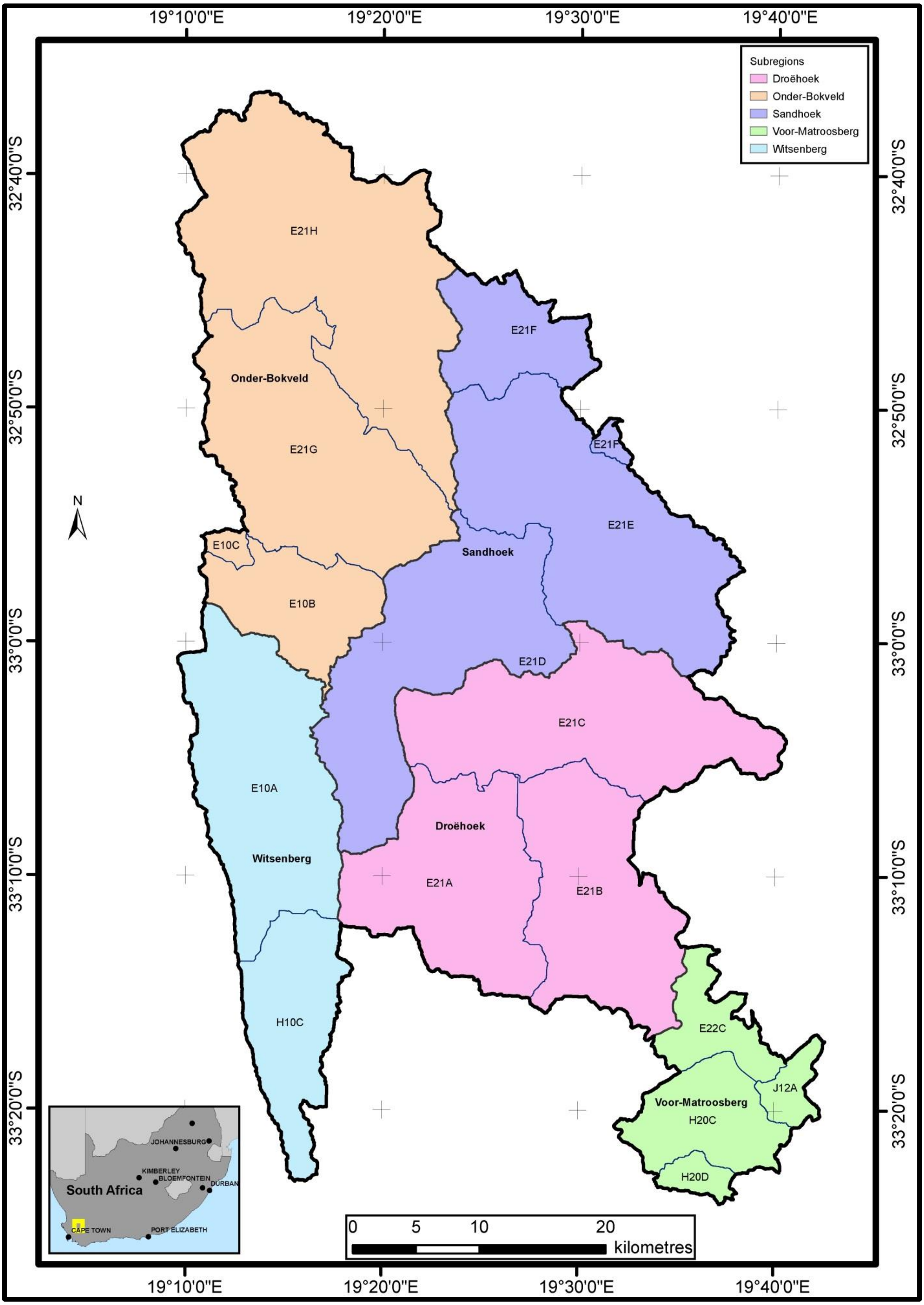


Source: AGIS

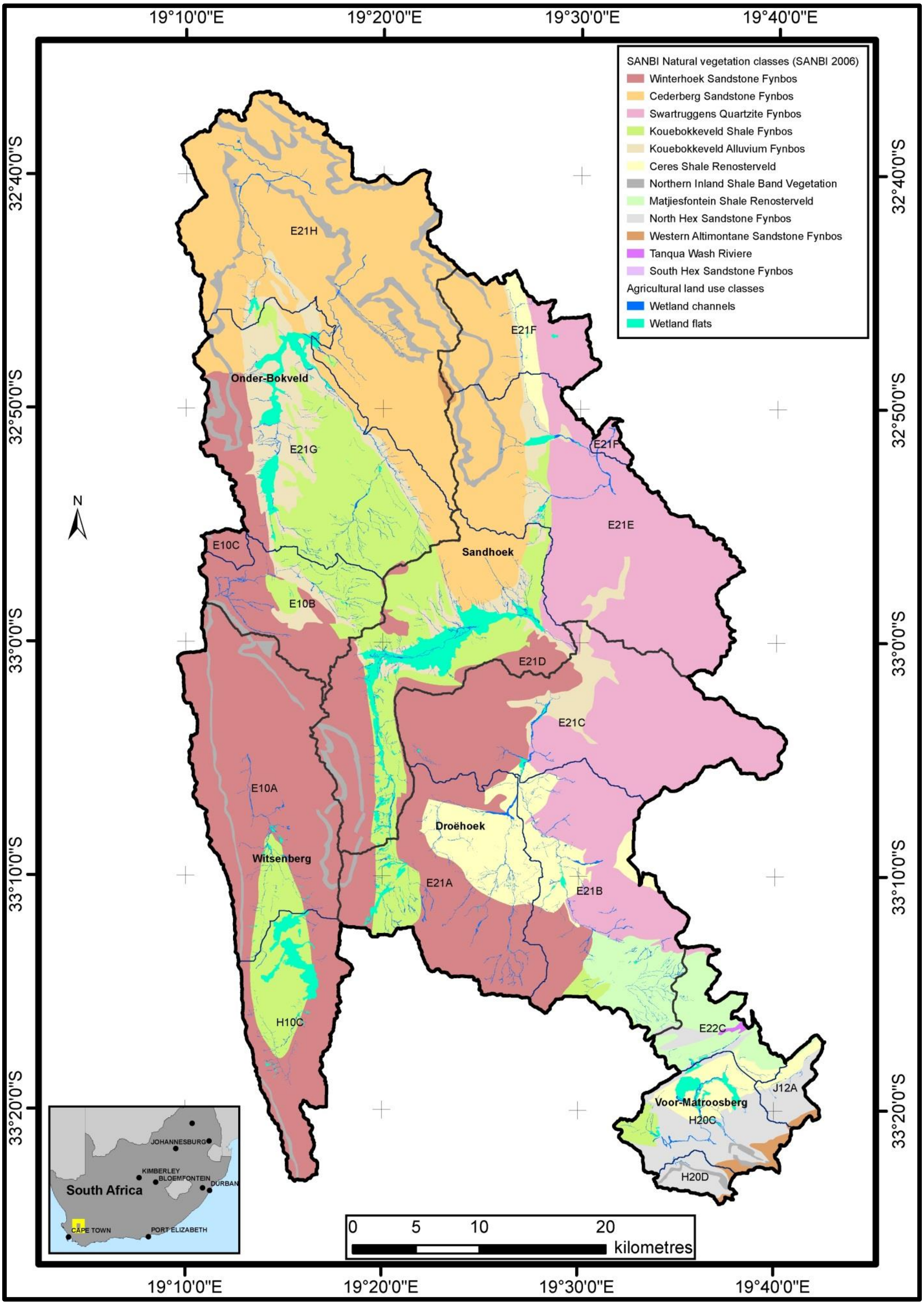
Appendix C 6: Koue Bokkeveld hydrology: Derived and provided catchments compared



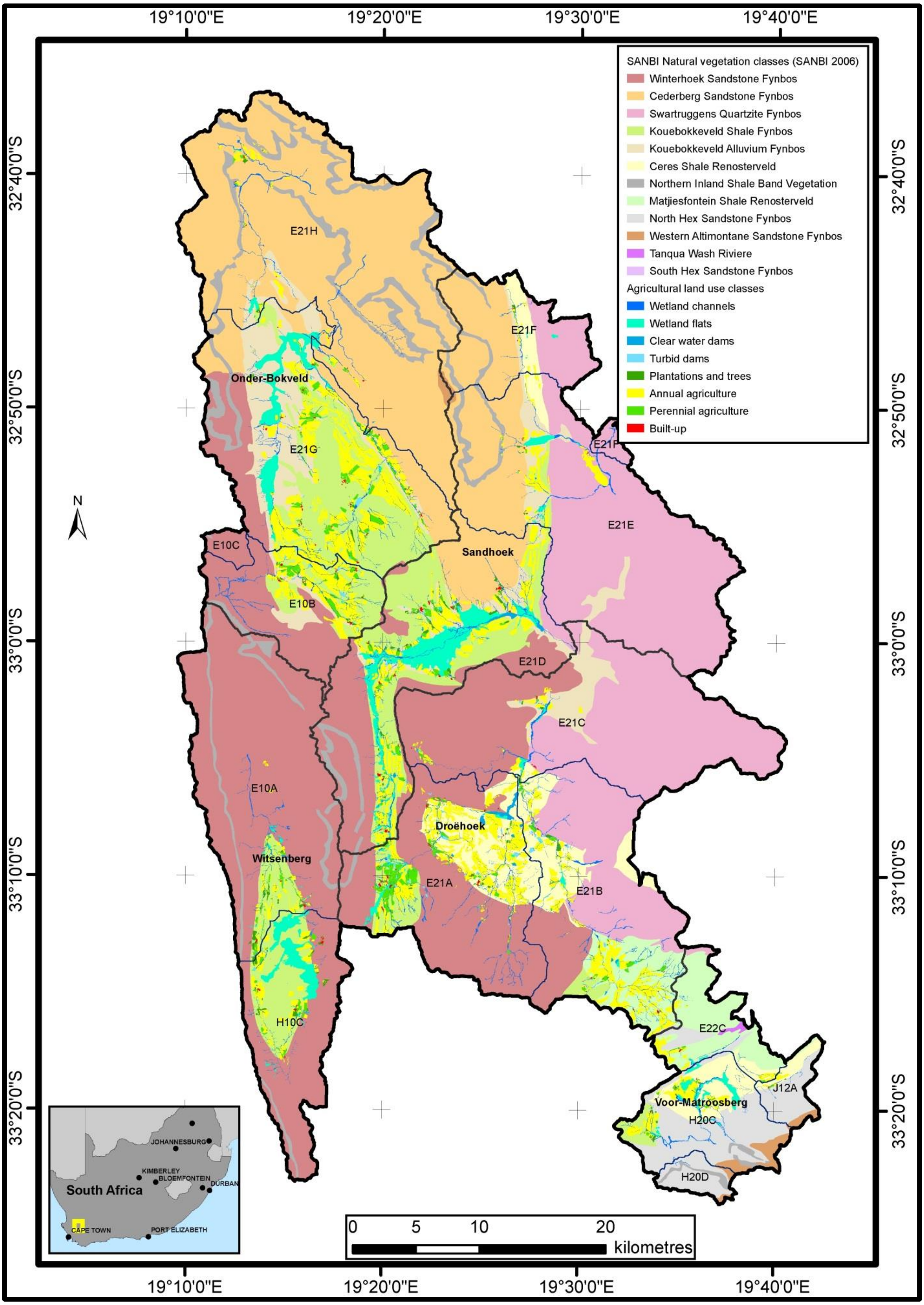
Appendix C 7: Koue Bokkeveld hydrology: Comparative catchment delineation



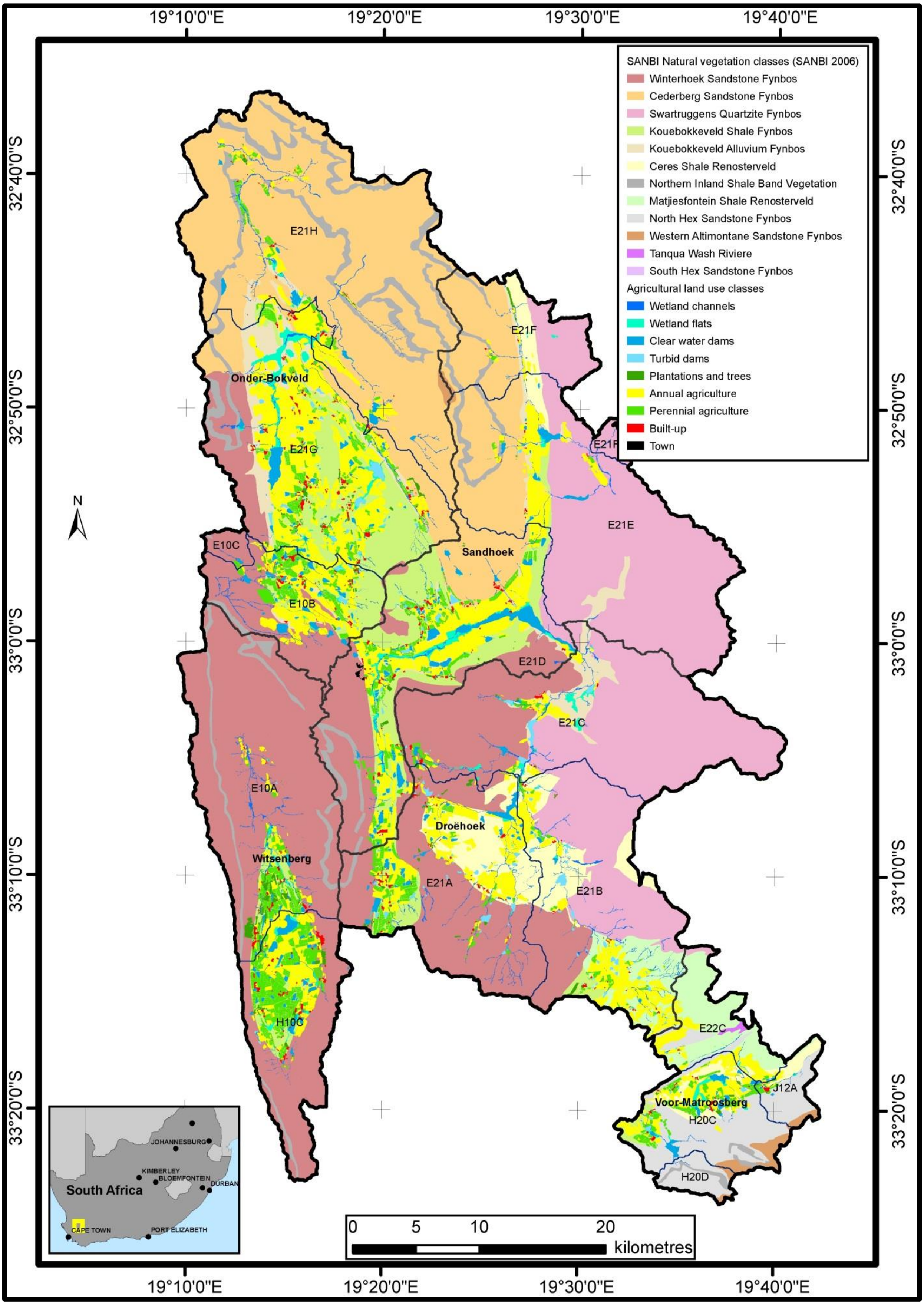
Appendix C 8: Subregional catchment composition



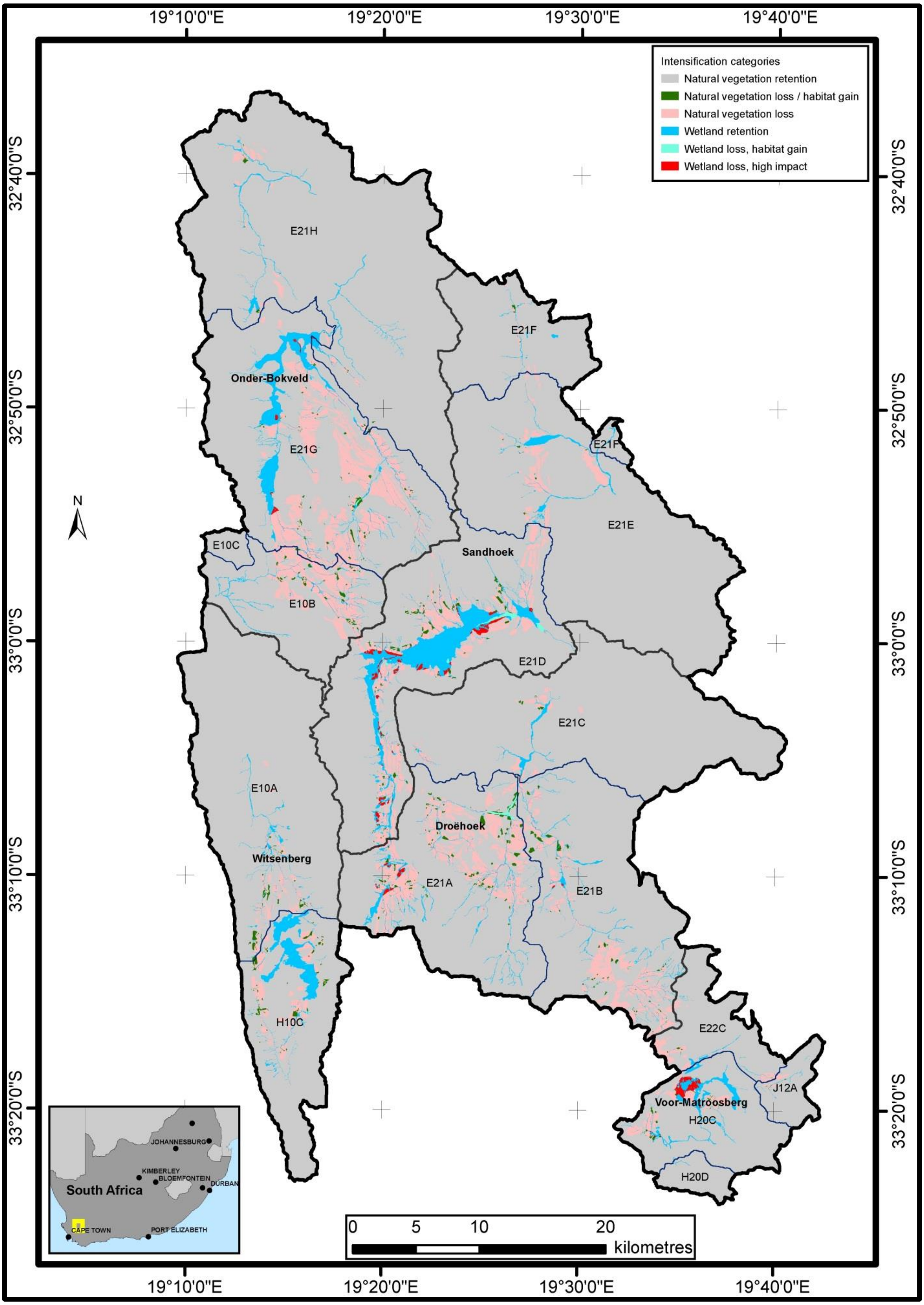
Appendix C 9: Koue Bokkeveld land cover: The reference state



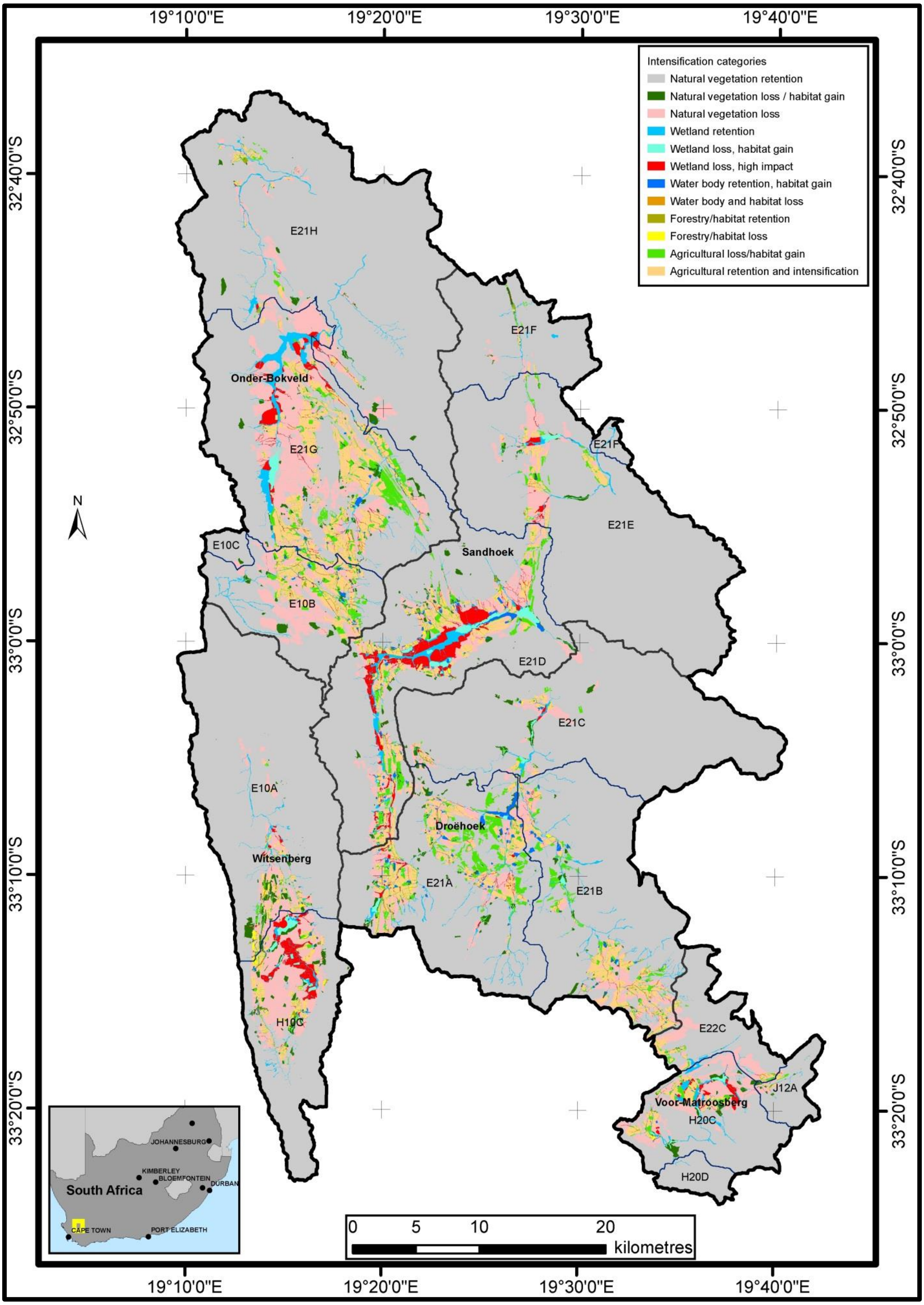
Appendix C 10: Koue Bokkeveld land cover: 1949



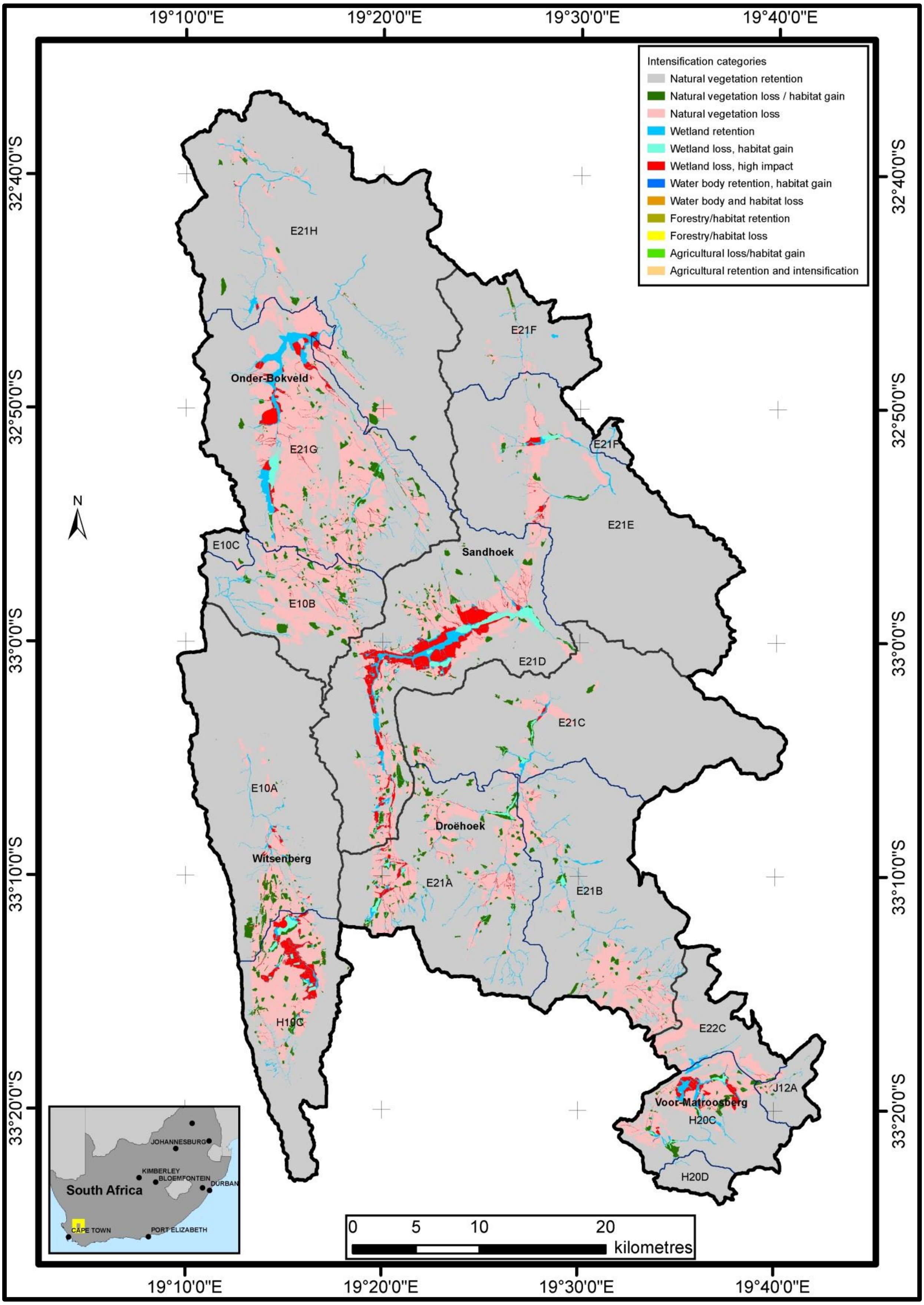
Appendix C 11: Koue Bokkeveld land cover: 2009



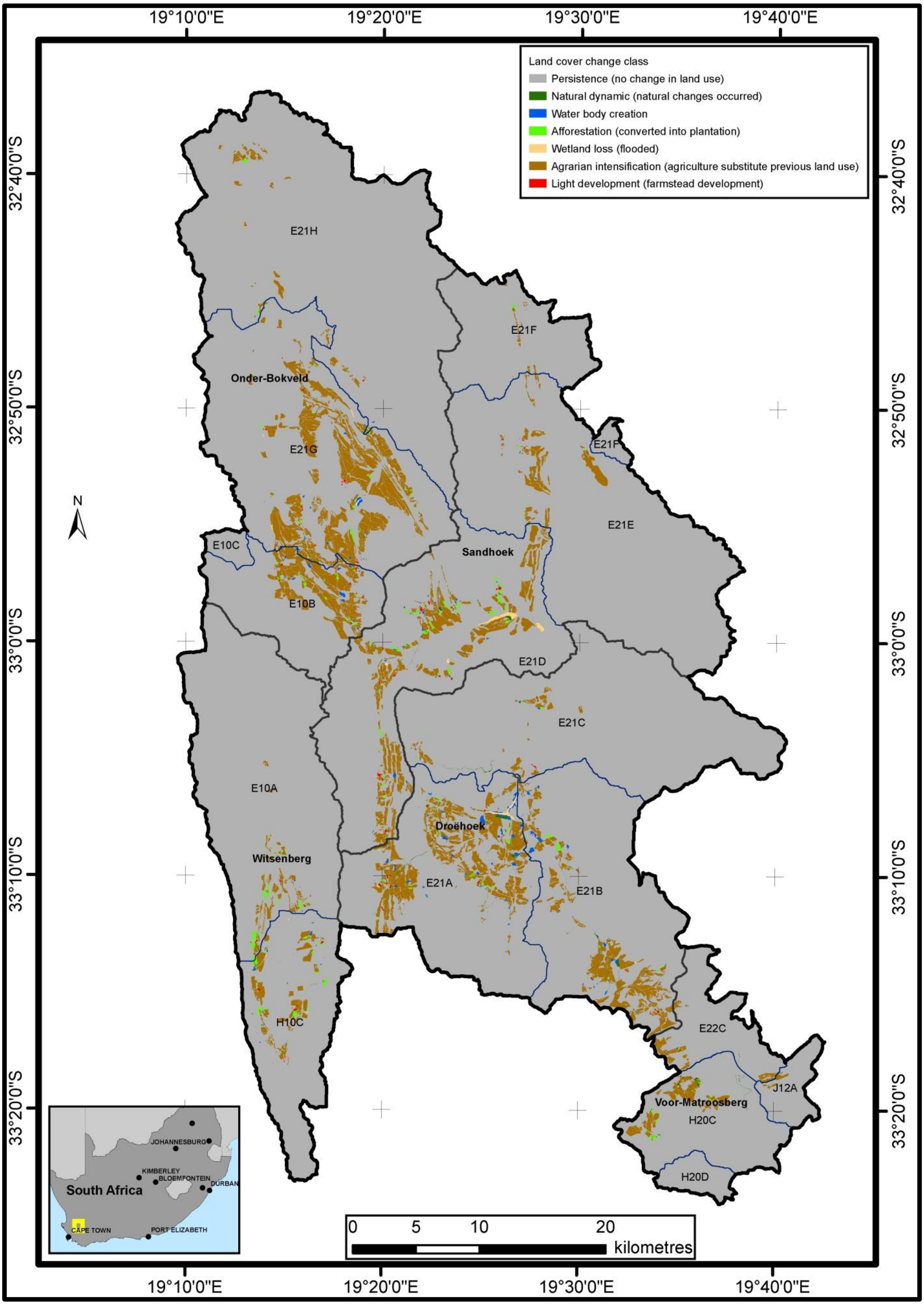
Appendix C 12: Land cover change: Reference state - 1949 (Intensification matrix)



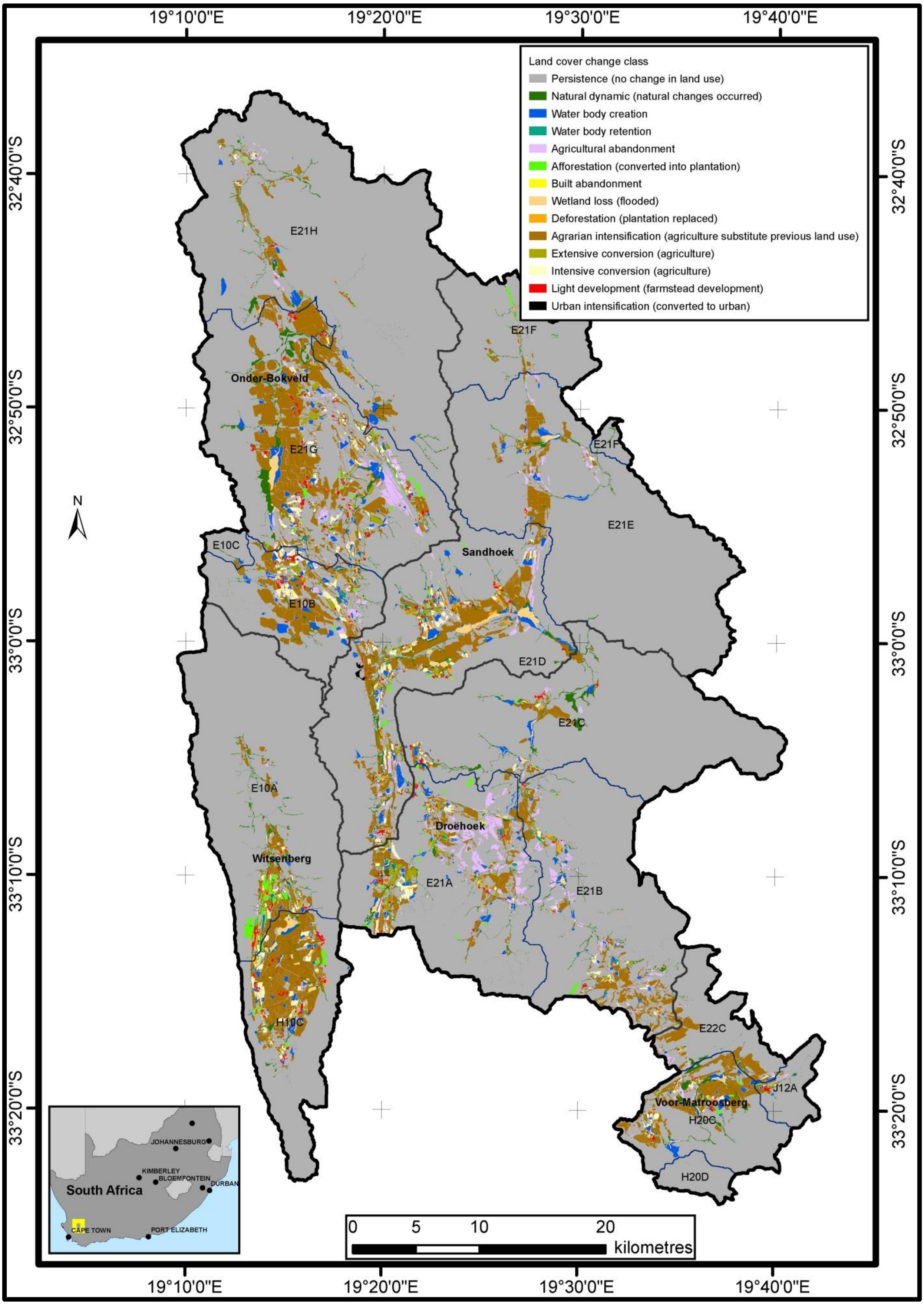
Appendix C 13: Land cover change: 1949 - 2009 (Intensification matrix)



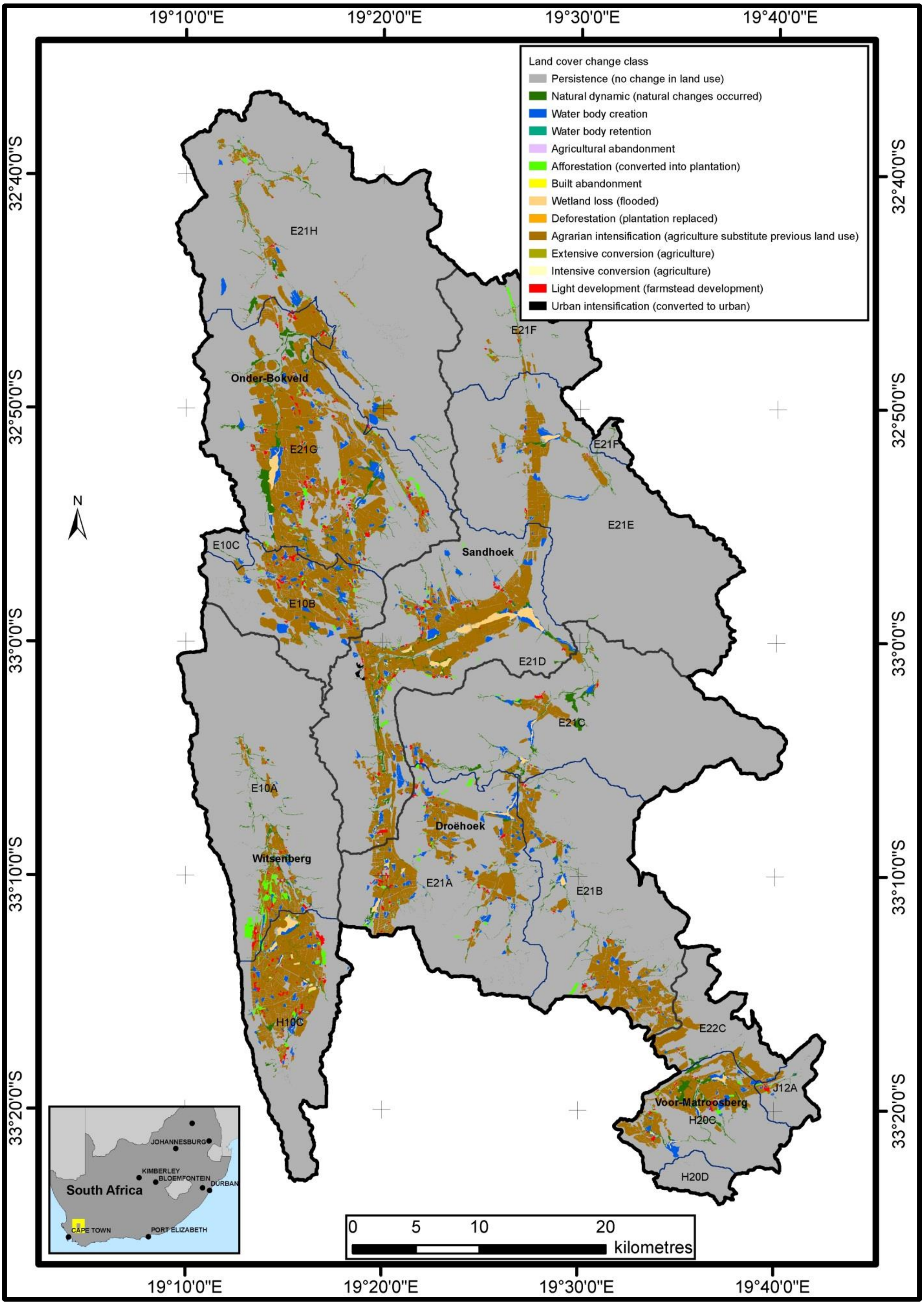
Appendix C 14: Land cover change: Reference state - 2009 (Intensification matrix)



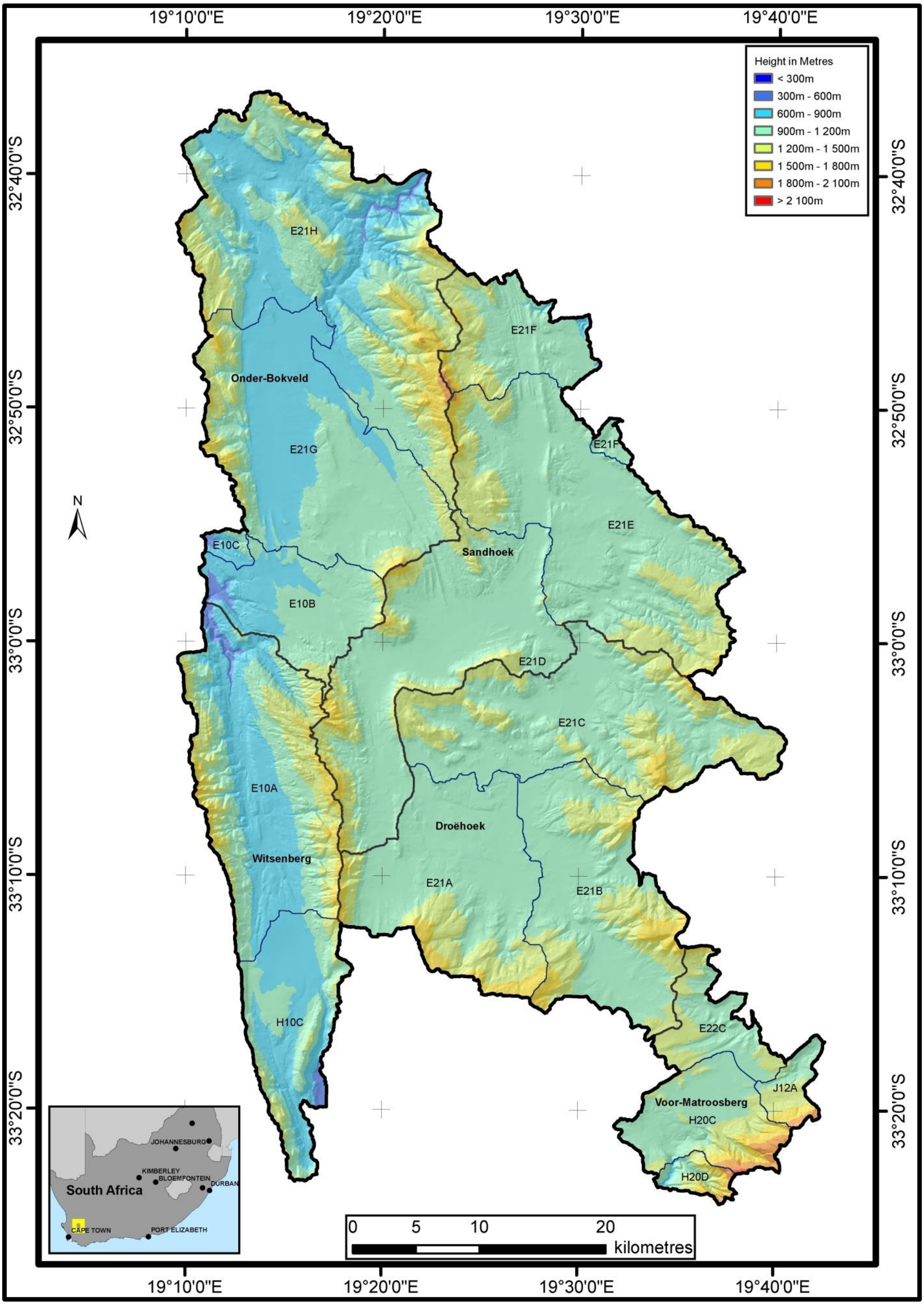
Appendix C 15: Land cover change: Reference state - 1949 (Productivity dynamics)



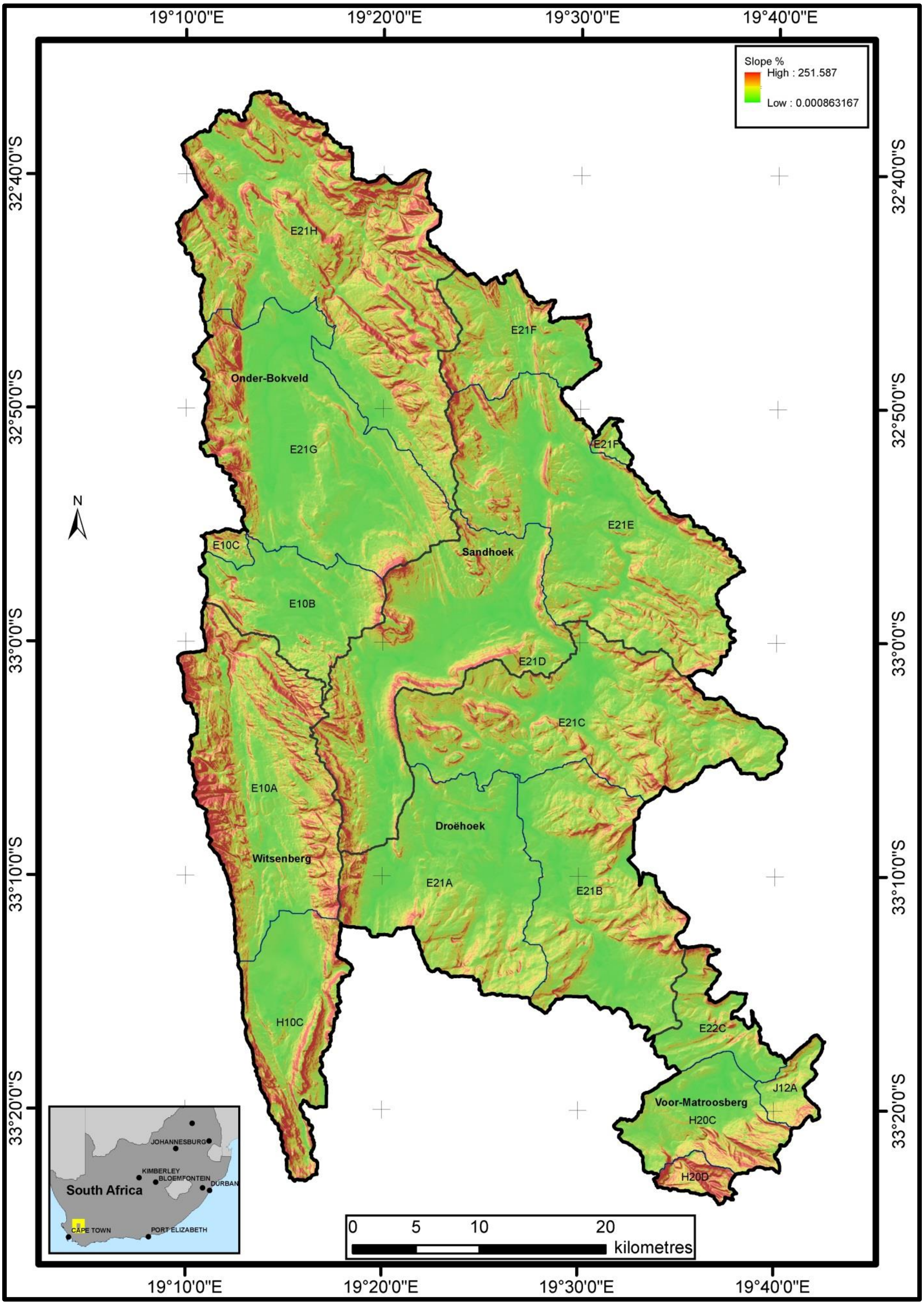
Appendix C 16: Land cover change: 1949 - 2009 (Productivity dynamics)



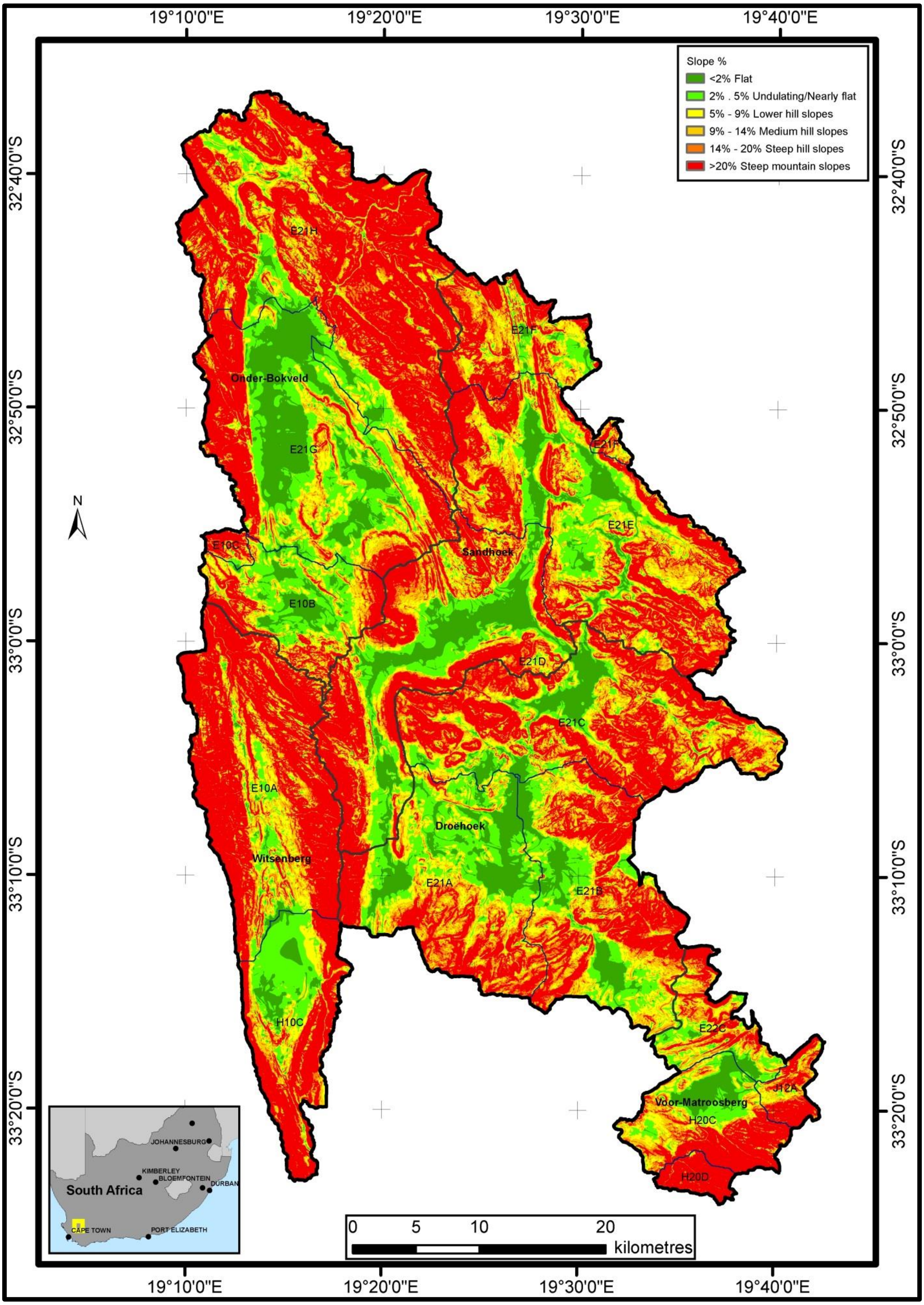
Appendix C 17: Land cover change: Reference state - 2009 (Productivity dynamics)



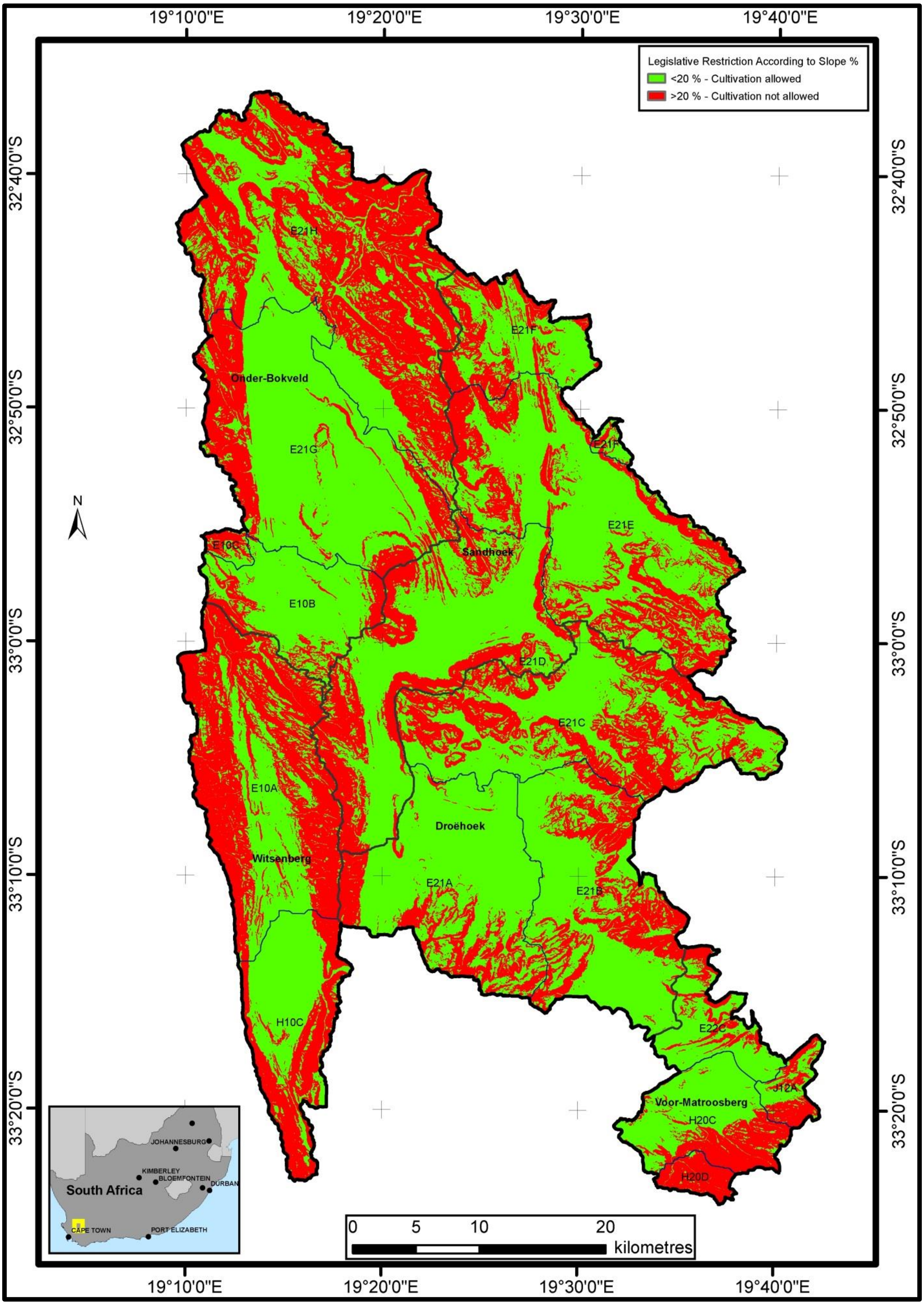
Appendix C 18: Koue Bokkeveld topography: Height above sealevel



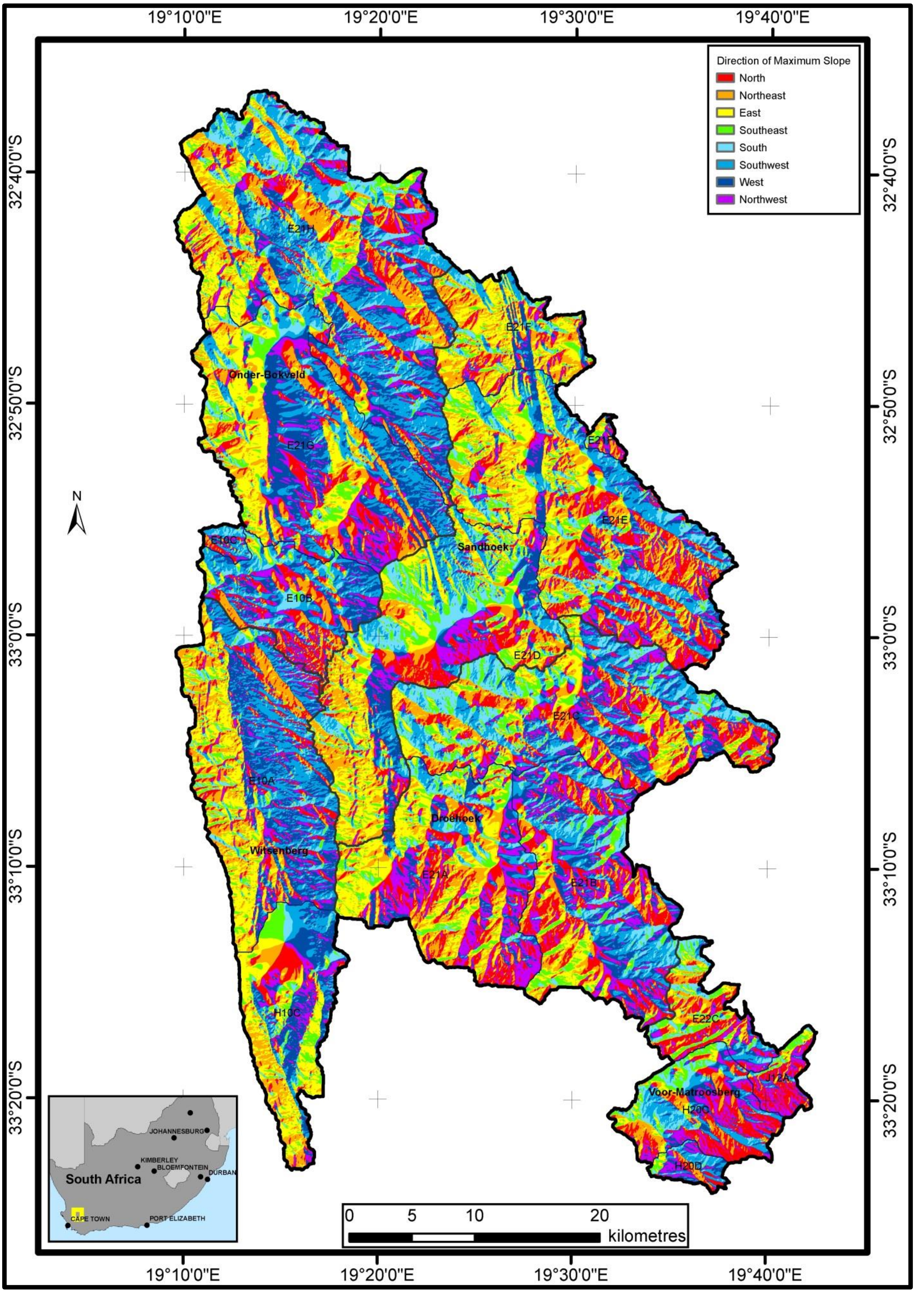
Appendix C 19: Koue Bokkeveld topography: Slope steepness (continuous classes)



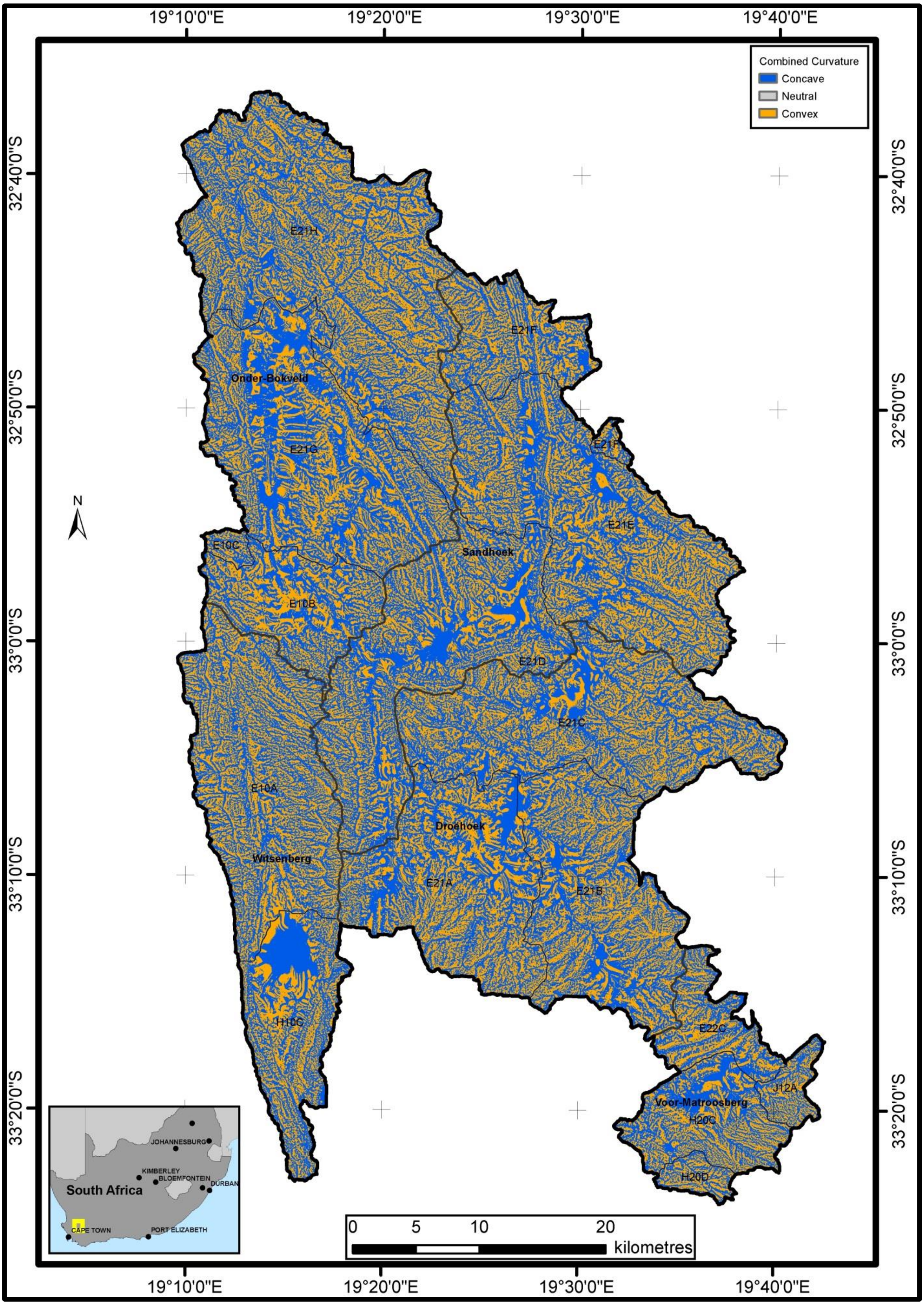
Appendix C 20: Koue Bokkeveld topography: Classified slope steepness



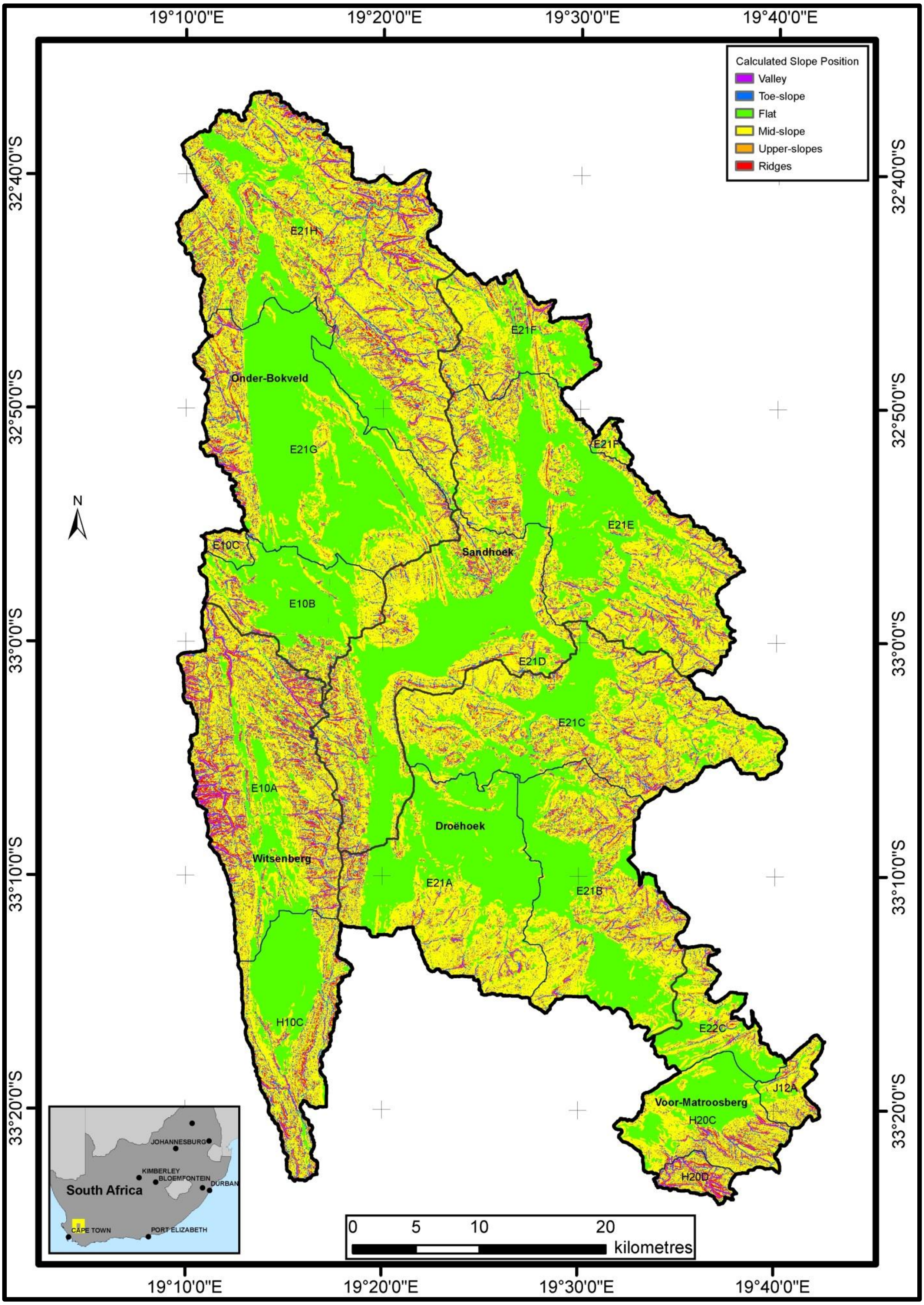
Appendix C 21: Koue Bokkeveld topography: Legal restriction on slope cultivation



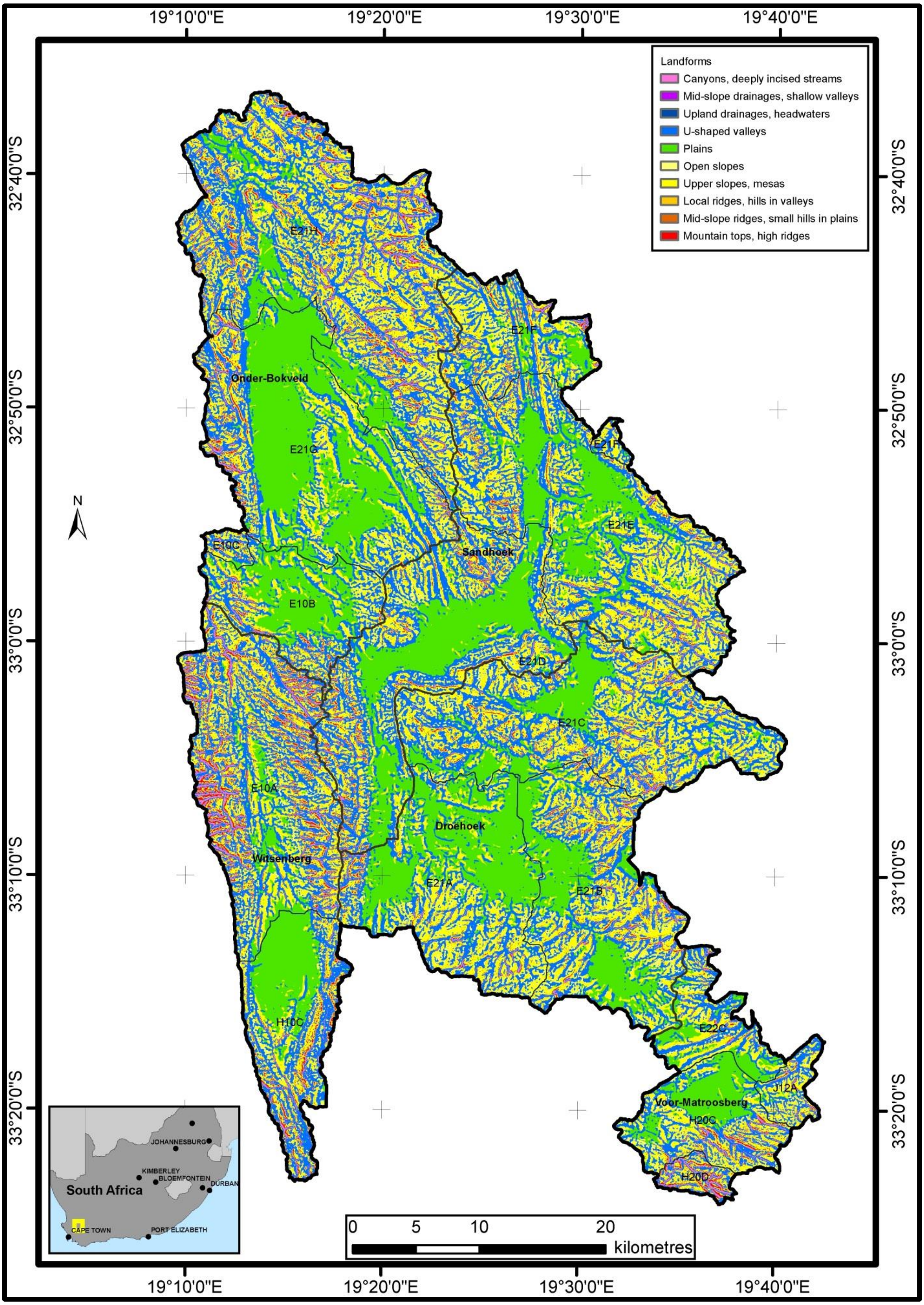
Appendix C 22: Koue Bokkeveld topography: Slope direction (aspect)



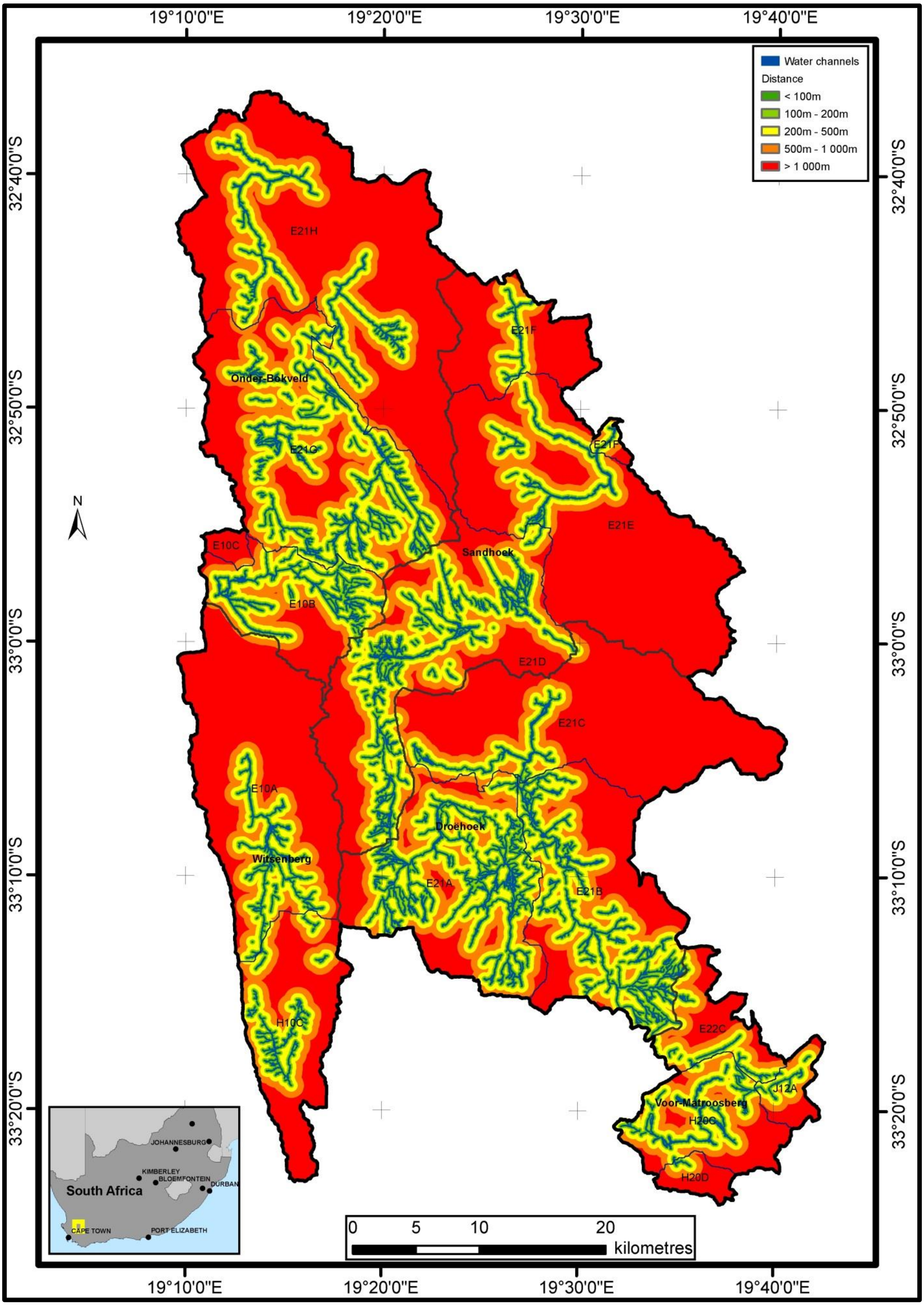
Appendix C 23: Koue Bokkeveld topography: Slope curvature



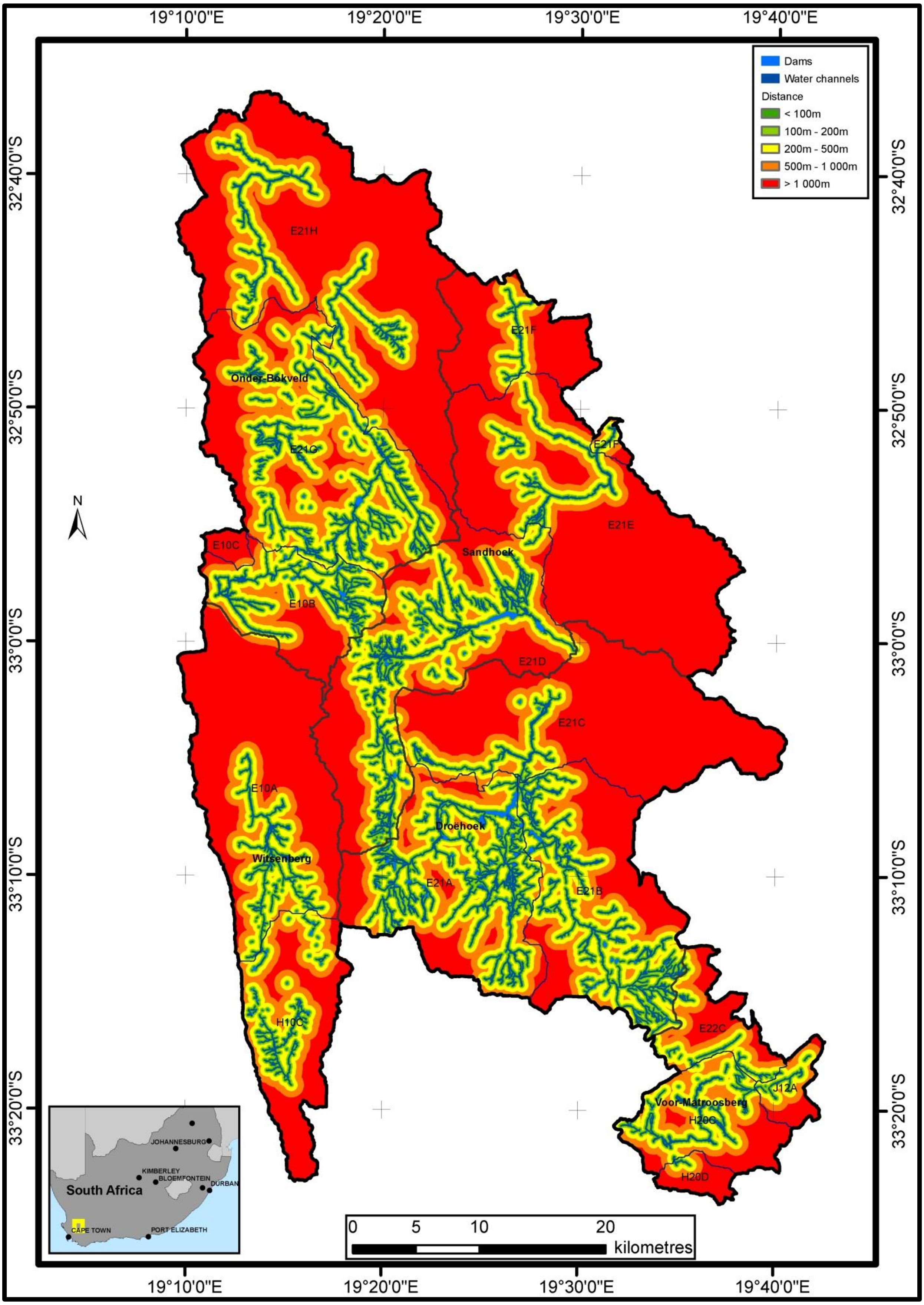
Appendix C 24: Koue Bokkeveld topography: Slope position index



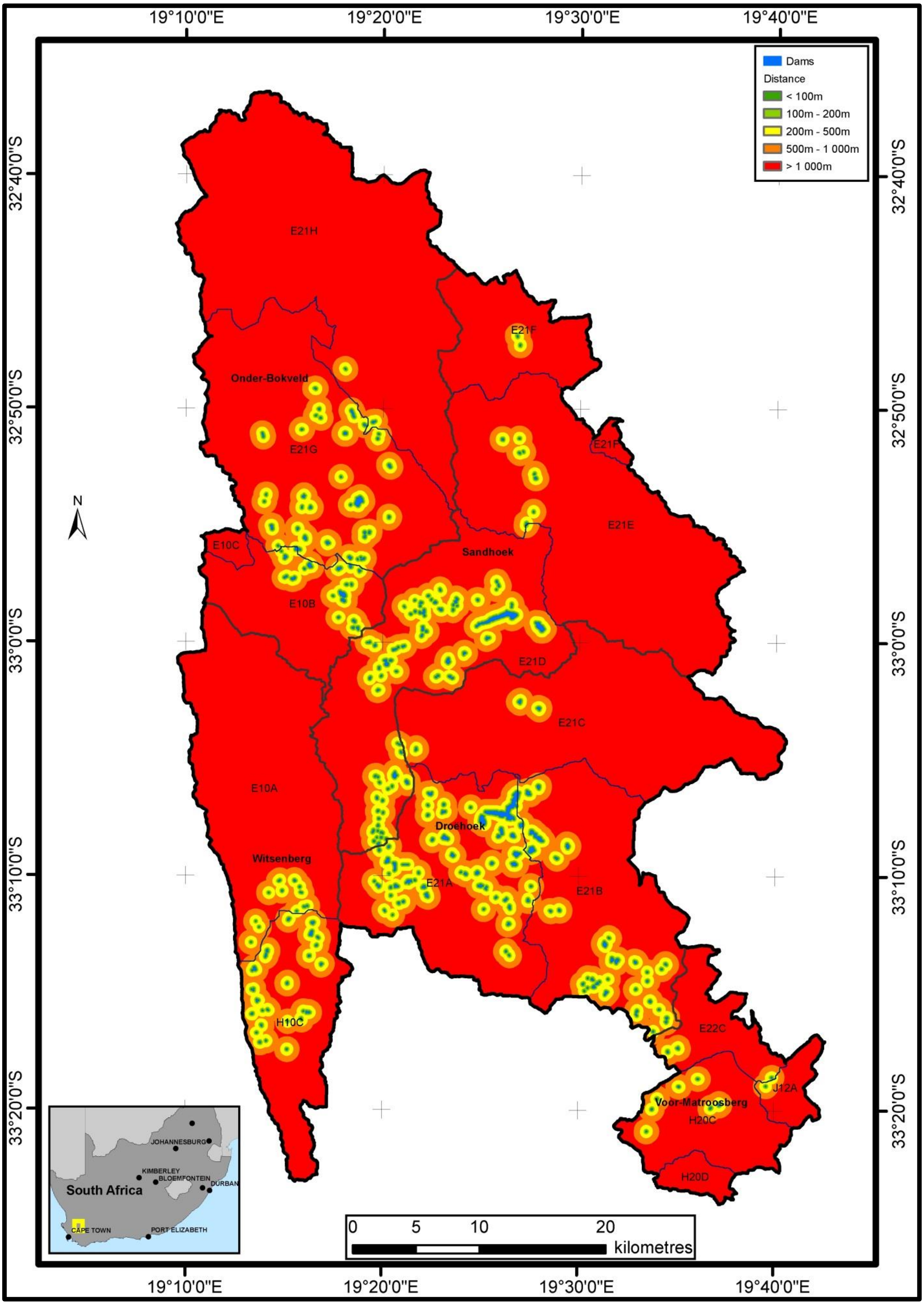
Appendix C 25: Koue Bokkeveld topography: Landform



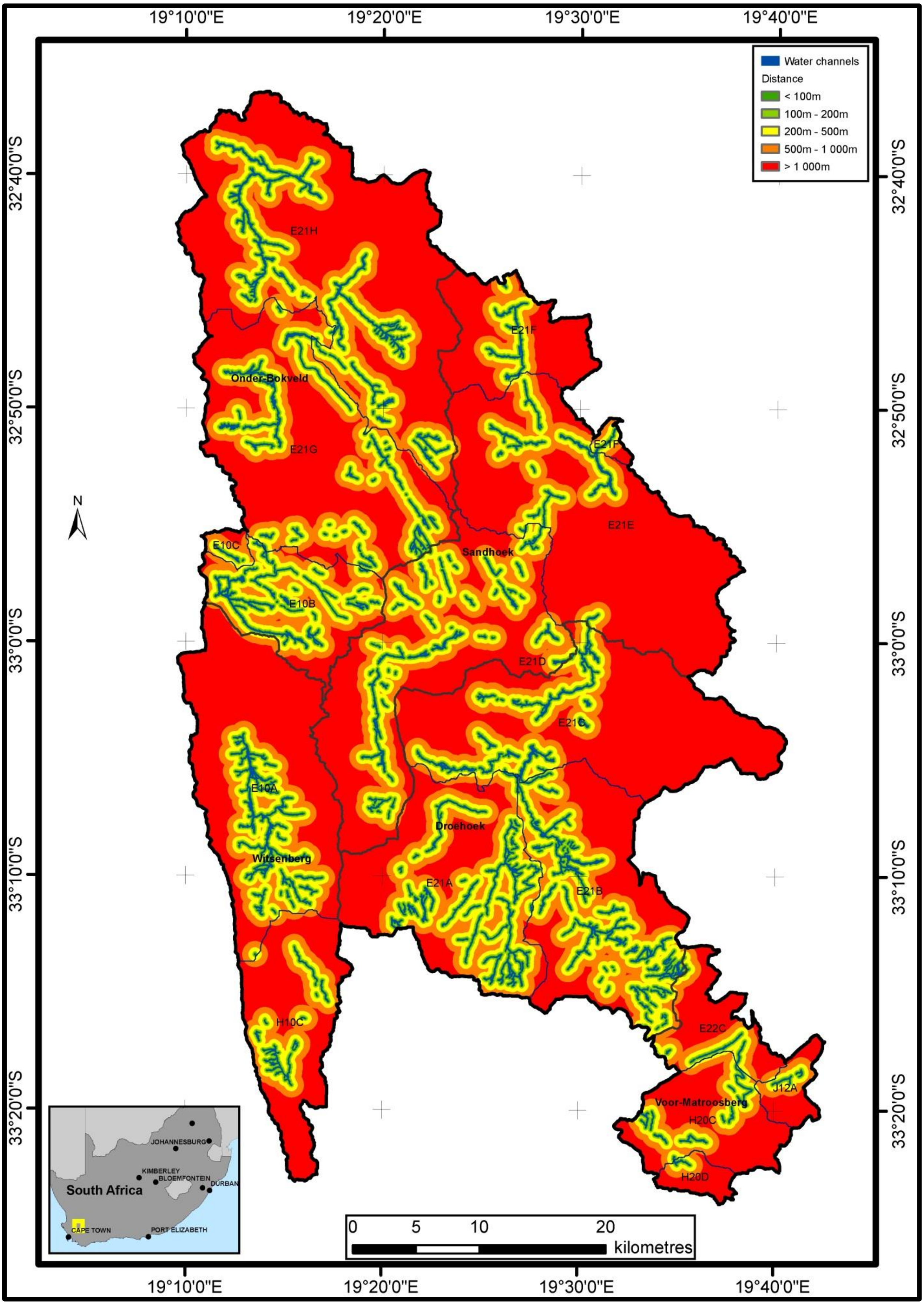
Appendix C 26: Koue Bokkeveld landscape structure: Agriculture-wetland channel distance (1949)



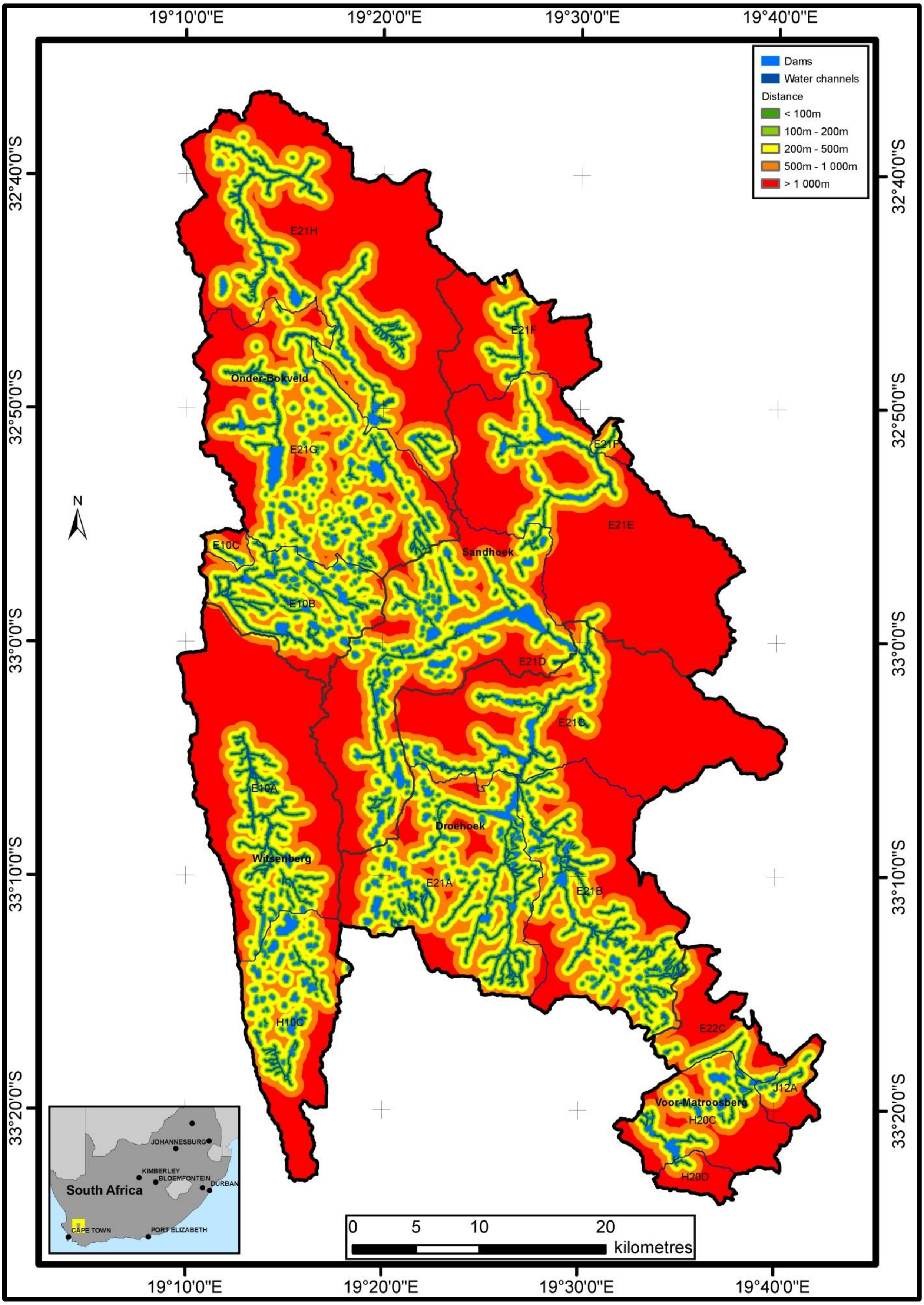
Appendix C 27: Koue Bokkeveld landscape structure: Agriculture-water source distance (1949)



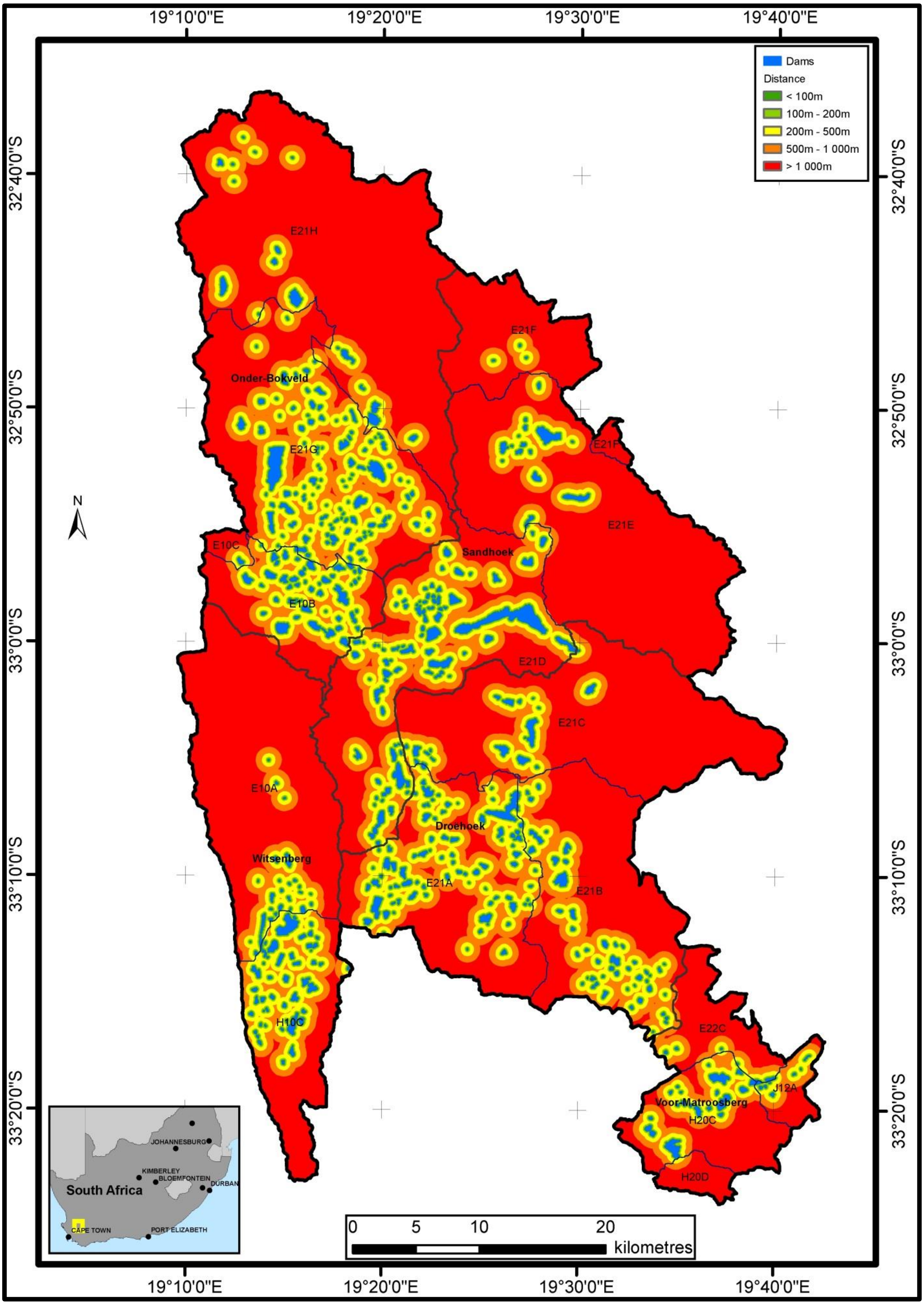
Appendix C 28: Koue Bokkeveld landscape structure: Agriculture-reservoir distance (1949)



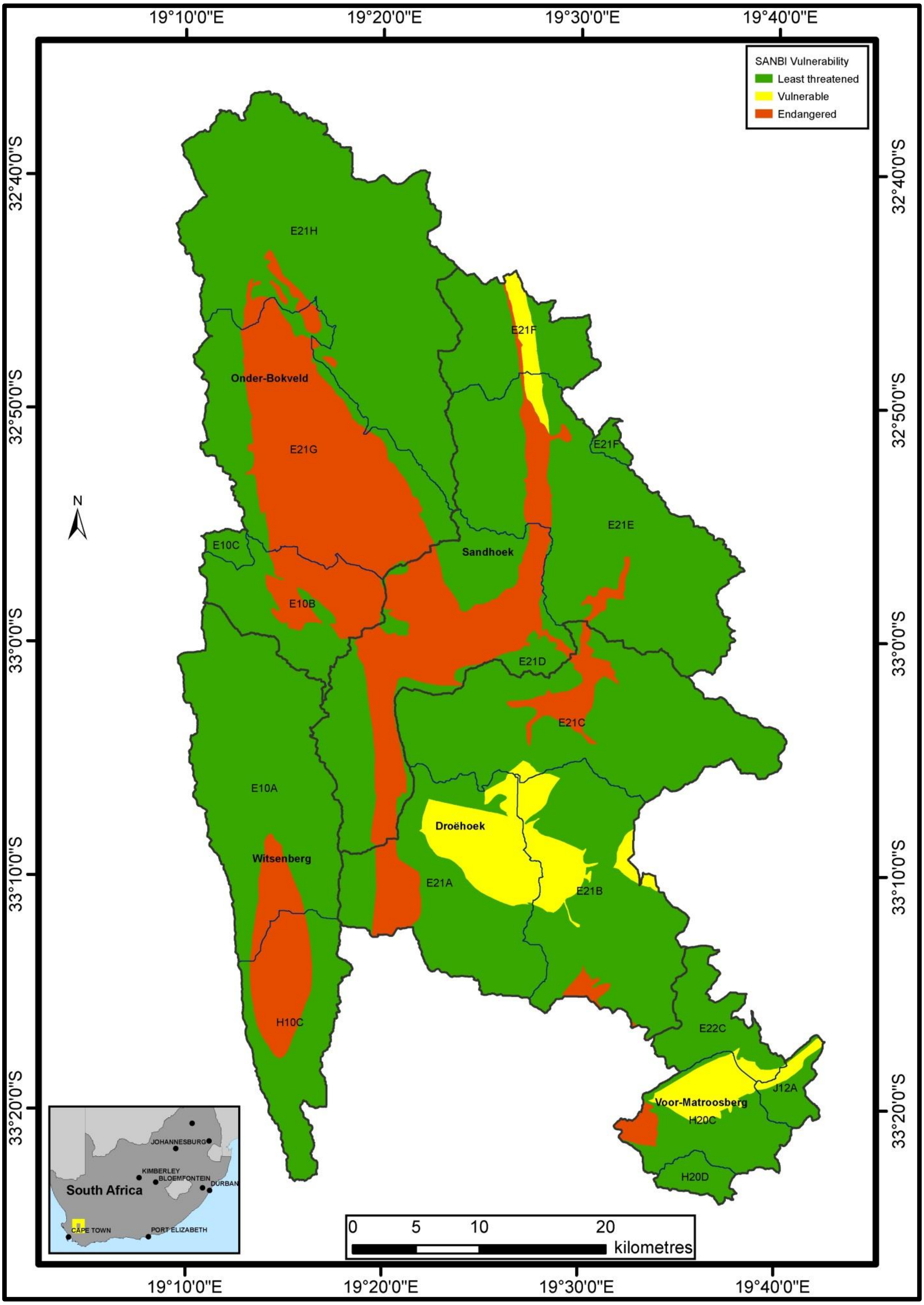
Appendix C 29: Koue Bokkeveld landscape structure: Agriculture-wetland channel distance (2009)



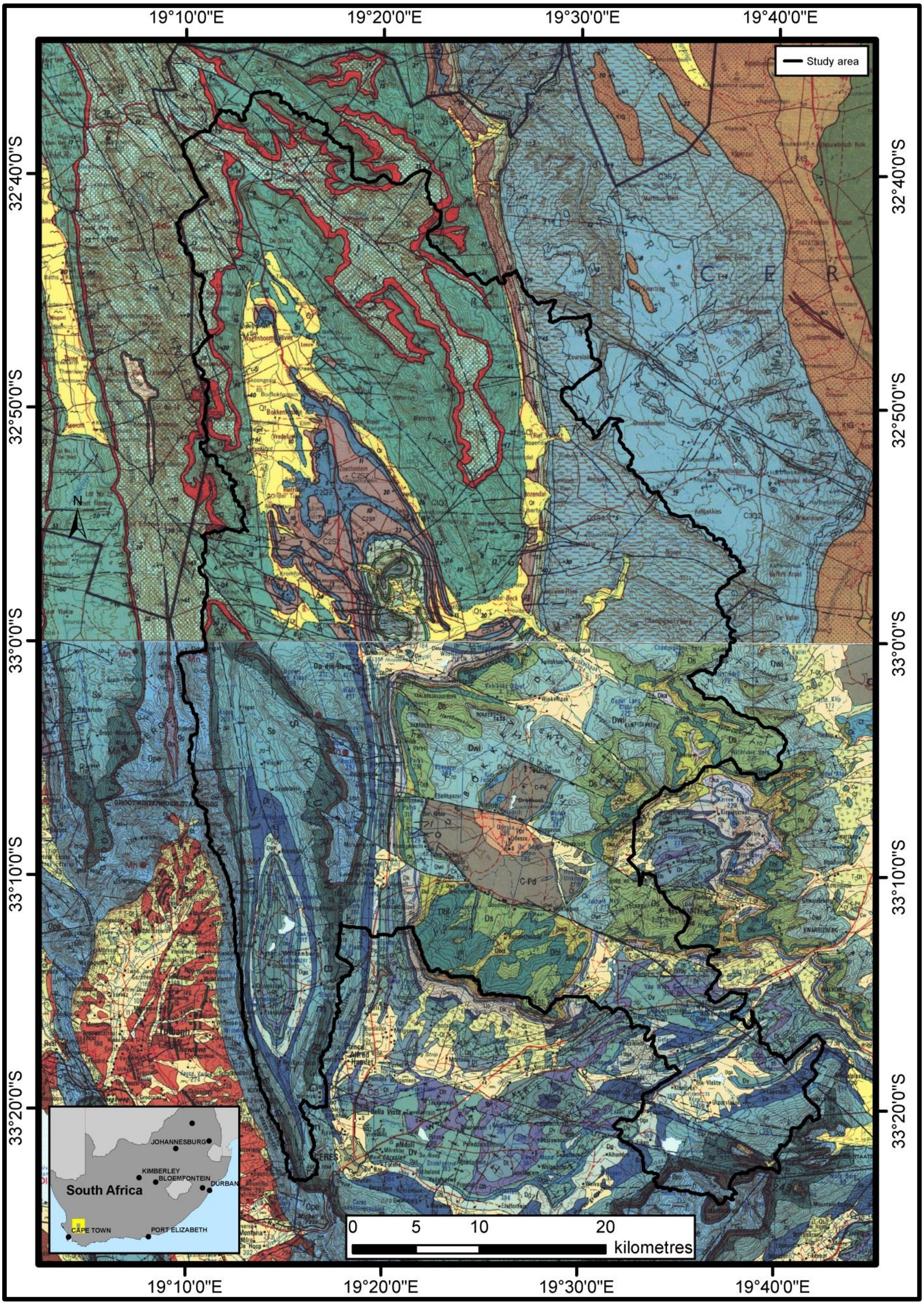
Appendix C 30: Koue Bokkeveld landscape structure: Agriculture-water source distance (2009)



Appendix C 31: Koue Bokkeveld landscape structure: Agriculture-reservoir distance (2009)

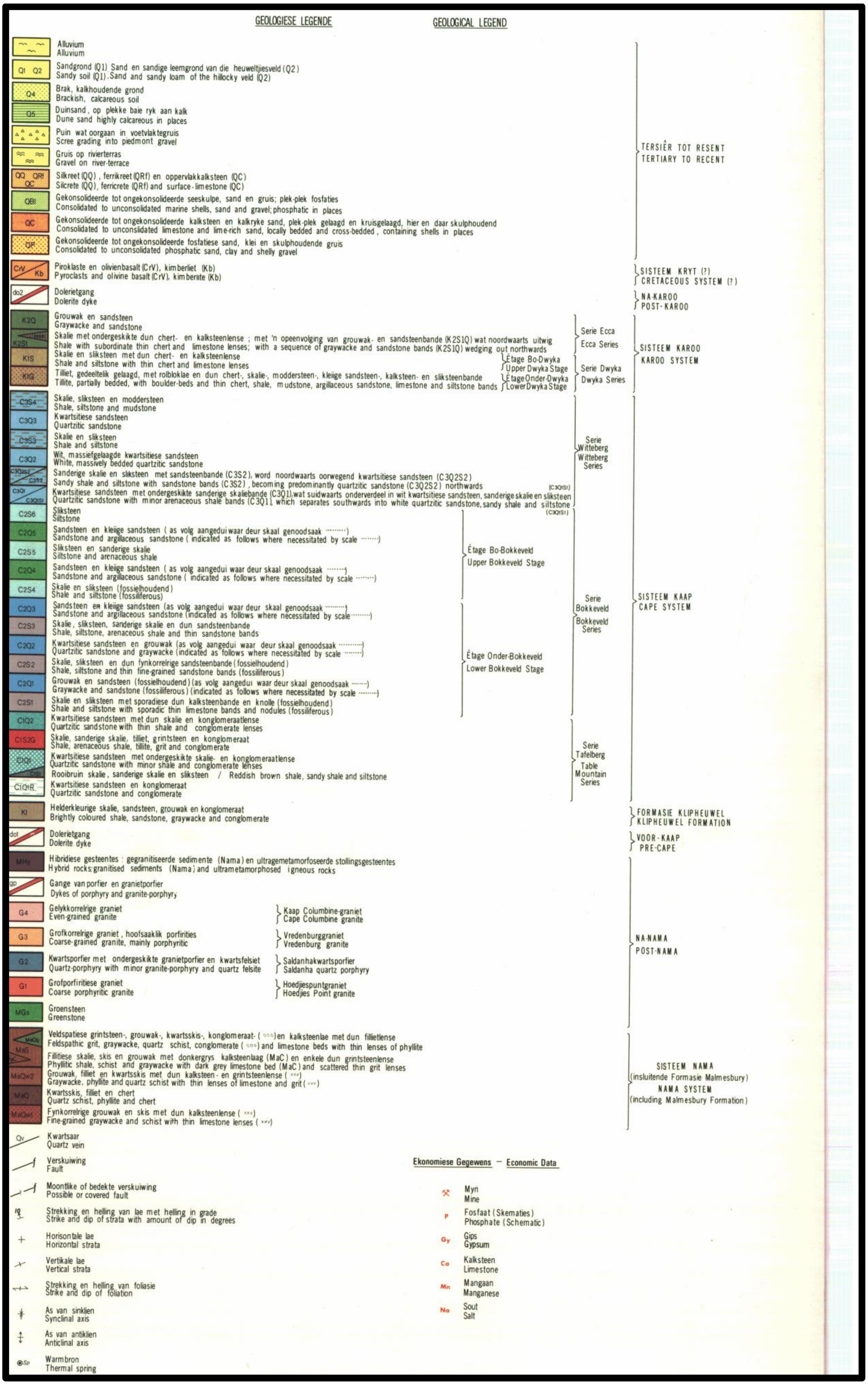


Appendix C 32: Koue Bokkeveld natural vegetation vulnerability



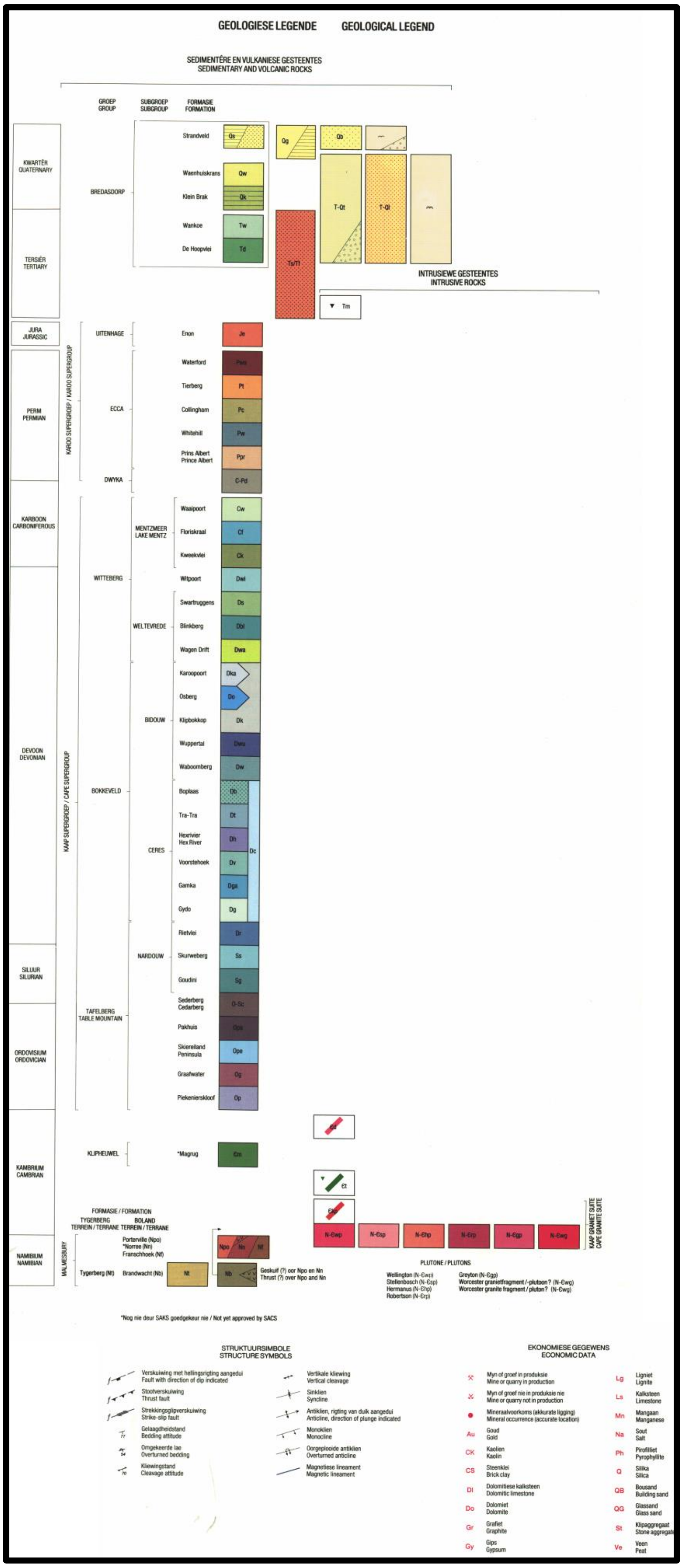
Source: Council for Geosciences, SA geology 1:250 000, Sheets 3218 and 3319.

Appendix C 33: Koue Bokkeveld geology



Source: Council for Geosciences, SA geology 1:250 000, Sheets 3218.

Appendix C 34: Geological legend to Figure C33: Part A



Source: Council for Geosciences, SA geology 1:250 000, Sheets 3319.

Appendix C 35: Geological legend to Figure C33: Part B

APPENDIX D ADDITIONAL DATA TABLES

Table D.1 Complete change matrix for the period reference state to 1949 in present of area cover

Area %		1949																				
		WS	**CF**	**SQ**	**KS**	**KA**	**CR**	**NI**	**MS**	**NH**	**WA**	**TW**	**SH**	**WC**	**WF**	**CD**	**TD**	**PT**	**AA**	**PA**	**Bu**	
Reference State	**WS**	25.57	---	---	---	---	---	---	---	---	---	---	---	0.01	0.00	0.01	0.01	0.02	0.16	0.03	0.01	25.81
	CF	---	19.42	---	---	---	---	---	---	---	---	---	---	---	---	0.00	0.00	0.02	0.14	0.02	0.01	19.61
	SQ	---	---	17.78	---	---	---	---	---	---	---	---	---	0.00	---	---	---	0.00	0.10	0.00	0.00	17.88
	KS	---	---	---	8.47	---	---	---	---	---	---	---	---	0.00	0.00	0.01	0.05	0.13	2.82	0.42	0.05	11.96
	KA	---	---	---	---	4.62	---	---	---	---	---	---	---	---	0.00	0.00	0.01	0.05	0.94	0.15	0.01	5.78
	CR	---	---	---	---	---	3.97	---	---	---	---	---	---	0.02	0.01	0.03	0.04	0.04	1.07	0.08	0.01	5.27
	NI	---	---	---	---	---	---	3.41	---	---	---	---	---	---	---	0.00	---	0.00	0.01	0.00	0.00	3.42
	MS	---	---	---	---	---	---	---	2.62	---	---	---	---	0.01	0.00	0.00	0.01	0.01	0.56	0.03	0.00	3.24
	NH	---	---	---	---	---	---	---	---	2.86	---	---	---	0.00	---	---	0.00	0.00	0.02	0.00	0.00	2.88
	WA	---	---	---	---	---	---	---	---	---	0.45	---	---	---	---	---	---	---	---	---	---	0.45
	TW	---	---	---	---	---	---	---	---	---	---	0.04	---	---	---	---	---	---	---	---	---	0.04
	SH	---	---	---	---	---	---	---	---	---	---	---	0.00	---	---	---	---	---	---	---	---	0.00
	WC	---	---	---	---	---	---	---	---	---	---	---	---	1.19	0.00	0.03	0.01	---	---	---	---	1.22
	WF	0.00	0.00	---	0.00	0.01	0.01	---	---	0.00	---	---	---	0.00	2.15	0.04	0.01	0.01	0.17	0.03	0.00	2.42
		25.57	19.42	17.78	8.47	4.63	3.98	3.41	2.62	2.86	0.45	0.04	0.00	1.23	2.17	0.13	0.12	0.28	5.99	0.77	0.10	100.00

Table D.2 Complete change matrix of the period 1949 to 2009 in present of area cover

Area %		2009																					
		WS	CF	SQ	KS	KA	CR	NI	MS	NH	WA	TW	SH	WC	WF	CD	TD	PT	AA	PA	Bu	T	
1949	WS	24.24	---	---	---	---	---	---	---	---	---	---	---	0.13	0.04	0.14	0.06	0.10	0.56	0.25	0.05	0.01	25.57
	CF	---	18.53	---	---	---	---	---	---	---	---	---	---	0.09	0.01	0.10	0.01	0.03	0.45	0.16	0.04	---	19.42
	SQ	---	---	17.67	---	---	---	---	---	---	---	---	---	0.02	0.01	0.03	0.01	0.00	0.03	0.00	0.00	---	17.78
	KS	---	---	---	5.07	---	---	---	---	---	---	---	---	0.05	0.08	0.18	0.07	0.17	1.69	1.02	0.15	0.00	8.47
	KA	---	---	---	---	2.13	---	---	---	---	---	---	---	0.06	0.15	0.17	0.04	0.01	1.85	0.16	0.05	0.00	4.63
	CR	---	---	---	---	---	2.80	---	---	---	---	---	---	0.03	0.03	0.07	0.03	0.02	0.81	0.15	0.03	---	3.98
	NI	---	---	---	---	---	---	3.35	---	---	---	---	---	0.01	0.00	0.01	0.00	0.00	0.02	0.01	0.00	---	3.41
	MS	---	---	---	---	---	---	---	2.14	---	---	---	---	0.01	0.00	0.00	0.02	0.00	0.43	0.01	0.01	---	2.62
	NH	---	---	---	---	---	---	---	---	2.69	---	---	---	0.00	0.01	0.03	0.00	0.00	0.08	0.04	0.00	---	2.86
	WA	---	---	---	---	---	---	---	---	---	0.45	---	---	---	---	---	---	---	---	---	---	---	0.45
	TW	---	---	---	---	---	---	---	---	---	---	0.04	---	---	---	---	---	---	---	---	---	---	0.04
	SH	---	---	---	---	---	---	---	---	---	---	---	0.00	---	---	---	---	---	---	---	---	---	0.00
	WC	0.05	0.05	0.03	0.08	0.04	0.05	0.00	0.02	0.02	---	---	---	0.44	0.06	0.08	0.03	0.01	0.21	0.04	0.01	0.00	1.23
	WF	0.02	0.01	0.00	0.07	0.17	0.03	0.00	0.01	0.02	---	---	---	0.06	0.34	0.30	0.03	0.01	0.94	0.14	0.01	0.00	2.17
	CD	0.00	0.00	---	0.00	0.00	0.00	---	0.00	---	---	---	---	0.00	0.00	0.10	0.01	0.00	0.00	0.00	0.00	---	0.13
	TD	0.00	0.00	---	0.01	0.00	0.00	---	0.00	0.00	---	---	---	0.00	0.00	0.05	0.04	0.00	0.01	0.00	0.00	---	0.12
	PT	0.01	0.01	0.00	0.02	0.01	0.01	0.00	0.00	0.00	---	---	---	0.00	0.00	0.01	0.00	0.03	0.08	0.06	0.03	---	0.28
	AA	0.05	0.06	0.03	0.62	0.14	0.50	0.01	0.09	0.00	---	---	---	0.03	0.05	0.26	0.12	0.02	3.08	0.87	0.05	---	5.99
	PA	0.01	0.00	0.00	0.05	0.01	0.02	0.00	0.01	0.00	---	---	---	0.00	0.00	0.02	0.00	0.01	0.36	0.25	0.01	---	0.77
	Bu	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	---	---	---	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.05	---	0.10
		24.38	18.66	17.74	5.94	2.50	3.42	3.36	2.26	2.74	0.45	0.04	0.00	0.95	0.78	1.57	0.48	0.43	10.61	3.18	0.50	0.01	100.00

Table D.3 Percentage of the land cover classes on aspect in reference state

Area in Percentage									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
WS	11.99	17.34	19.86	9.67	8.34	12.35	11.34	9.11	100.00
CF	9.13	16.15	16.56	8.84	10.49	19.47	12.16	7.20	100.00
SQ	17.73	14.40	8.98	6.23	10.88	14.82	12.65	14.31	100.00
KS	13.77	12.48	12.95	8.38	6.10	11.95	19.37	15.00	100.00
KA	9.59	12.21	16.40	9.56	7.77	13.73	20.78	9.96	100.00
CR	14.50	13.67	11.37	8.28	8.49	12.68	15.19	15.82	100.00
NI	11.79	19.81	15.20	7.96	10.36	18.78	7.82	8.28	100.00
MS	18.40	10.83	8.32	10.00	11.23	14.03	13.20	13.99	100.00
NH	26.41	8.90	3.57	6.51	7.86	13.14	8.98	24.61	100.00
WA	37.50	7.30	3.09	1.46	4.18	16.87	10.92	18.68	100.00
TW	44.59	18.94	11.58	7.25	4.40	0.95	1.41	10.88	100.00
SH	0.36	---	---	---	---	8.35	65.46	25.83	100.00
WC	10.00	6.95	7.43	5.94	9.70	20.20	22.28	17.48	100.00
WF	11.78	9.68	10.29	11.70	9.69	10.06	19.74	17.07	100.00

Table D.4 Percentage of the land cover classes on aspect in 1949

Area in Percentage									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
WS	11.99	17.42	19.99	9.70	8.31	12.29	11.24	9.06	100.00
CF	9.16	16.17	16.64	8.86	10.50	19.32	12.14	7.21	100.00
SQ	17.79	14.34	8.91	6.23	10.90	14.82	12.66	14.35	100.00
KS	14.82	13.09	13.19	8.83	6.19	10.67	18.25	14.96	100.00
KA	9.44	13.02	18.36	9.71	6.84	12.71	19.91	10.01	100.00
CR	14.77	13.38	11.50	8.76	8.49	12.89	15.03	15.18	100.00
NI	11.72	19.86	15.28	7.95	10.34	18.78	7.82	8.25	100.00
MS	17.98	11.36	9.57	11.79	13.06	13.22	10.65	12.37	100.00
NH	26.45	8.97	3.58	6.52	7.83	13.10	9.01	24.54	100.00
WA	37.50	7.30	3.09	1.46	4.18	16.87	10.92	18.68	100.00
TW	44.59	18.94	11.58	7.25	4.40	0.95	1.41	10.88	100.00
SH	0.36	---	---	---	---	8.35	65.46	25.83	100.00
WC	10.41	7.23	7.08	5.23	9.50	20.08	22.41	18.06	100.00
WF	11.23	9.01	10.68	11.65	9.06	10.31	20.85	17.21	100.00
CD	10.61	12.06	7.98	12.25	10.26	22.06	14.49	10.29	100.00
TD	14.64	9.15	13.77	6.84	10.54	18.34	13.13	13.59	100.00
PT	8.19	13.26	13.29	8.09	12.77	14.99	19.95	9.46	100.00
AA	12.39	11.84	10.04	7.13	7.55	15.33	20.57	15.15	100.00
PA	12.43	7.53	10.55	6.97	6.24	16.73	23.65	15.90	100.00
Bu	13.39	12.08	17.69	9.20	6.75	11.72	16.31	12.86	100.00

Table D.5 Percentage of the land cover classes on aspect in 2009

	Area in Percentage								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
WS	12.10	17.75	20.28	9.89	8.33	12.02	10.78	8.85	100.00
CF	9.13	16.46	17.00	8.95	10.46	19.16	11.75	7.08	100.00
SQ	17.79	14.36	8.92	6.23	10.92	14.78	12.67	14.34	100.00
KS	13.87	12.36	12.80	8.42	5.89	11.47	19.81	15.36	100.00
KA	9.72	15.35	21.57	11.17	6.20	11.05	15.14	9.80	100.00
CR	12.84	13.12	13.02	9.70	8.84	13.02	14.91	14.55	100.00
NI	11.65	19.86	15.33	7.95	10.47	18.78	7.73	8.23	100.00
MS	17.60	11.60	9.65	12.64	14.62	14.04	9.22	10.63	100.00
NH	27.01	8.85	3.33	6.50	7.58	12.96	8.92	24.85	100.00
WA	37.50	7.30	3.09	1.46	4.18	16.87	10.92	18.68	100.00
TW	44.59	18.94	11.58	7.25	4.40	0.95	1.41	10.88	100.00
SH	0.36	---	---	---	---	8.35	65.46	25.83	100.00
WC	9.84	7.01	6.31	4.81	9.55	22.08	22.97	17.43	100.00
WF	9.07	9.92	8.06	7.12	8.56	13.97	26.90	16.40	100.00
CD	10.61	8.46	8.17	7.83	8.99	17.84	22.25	15.85	100.00
TD	11.08	7.33	9.09	6.49	9.92	18.46	23.83	13.80	100.00
PT	8.99	10.79	19.23	8.79	5.65	14.67	20.78	11.10	100.00
AA	13.46	11.97	10.88	7.77	7.53	13.95	19.92	14.52	100.00
PA	13.62	11.38	13.08	8.94	8.11	12.33	18.21	14.33	100.00
Bu	12.00	13.31	18.39	8.37	7.00	11.40	15.88	13.65	100.00
T	20.38	12.49	11.71	26.81	5.11	8.54	2.49	12.47	100.00