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LAND USE IMPACT ON WATER QUALITY IN TWO RIVER SYSTEMS IN SOUTH AFRICA

Monika Ogden

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Department of
Physical Geography and Ecosystem Science
Centre for Geographical Information Systems
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

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Department of Physical Geography and Ecosystems Science, Lund University

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Monika Brigitte Ogden
Master thesis, 30 credits, in Geographical Information Sciences

Dr Martin Berggren
Lund University

Dr Melanie Lück-Vogel
CSIR
South Africa

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ABSTRACT

South Africa is a water-scarce country that is expected to face challenges regarding freshwater resources in the future. The country requires not only a certain quantity of water but also a certain quality. The water quality of the country is not always of an acceptable standard and nutrient pollution is one of the problems faced by water bodies. Nutrient pollution occurs when runoff rich in nutrients from agricultural land, informal settlements, mines, industries, and urban areas with inadequate water treatment systems, flows overland or via shallow groundwater into surface water systems. The water eventually flows into estuaries just before it reaches the sea, carrying its pollutants with it. Estuaries are ecologically and economically important to the country and need to be conserved and managed properly.

This study aims to identify the land cover in two different catchments and to analyse the water quality in relation to land cover data. It shows that temporal and spatial changes in land cover and water quality differed greatly between the temperate, well-developed Duiwenhoks catchment area and the subtropical, rural Mzimkulu catchment area. Land cover was not found to change significantly in the Duiwenhoks catchment between 1984 and 2009, but all land cover classes besides urban areas changed significantly over time in the Mzimkulu catchment, particularly a decrease in grassland and an increase in bare unvegetated ground, plantations and sugar cane.

A relationship was found to exist between land cover and water quality, where concentrations of phosphates, nitrates and ammonium nitrogen increased with increases in land cover classes such as bare ground, cultivated grains, sugar cane, urban and rural areas and plantations. All of these classes are anthropogenic and suggest that with an increase in human activities water quality would worsen. The study shows that GIS and remote sensing can be successfully used as a tool in classifying land cover over time in order to use the results in analyses that aim to answer questions about variables related to changes in land cover. The resulting correlations found between land cover and water quality can be used to infer changes in future scenarios.

SAMMANFATTNING

Sydafrika är ett land med knappa vattentillgångar och dess färskvattenresurser väntas stå inför utmaningar i framtiden. Landet behöver inte bara en viss kvantitet vatten utan även en viss kvalitet. Landets vattenkvalitet är inte alltid av godtagbar standard och övergödning är ett av problemen för vattenförekomsten. Övergödning uppstår när näringsämnesrik avrinning från jordbruksmark, informella bosättningar, gruvor, industrier och tätorter med otillräckliga system för vattenrening flyter landvägen eller via ytligt grundvatten i ytvattensystemen. Vattnet strömmar slutligen in i flodmynningar precis innan den når havet och för med sig föroreningarna. Flodmynningar är ekologiskt och ekonomiskt viktiga för landet och måste bevaras och hanteras på rätt sätt.

Denna studie syftar till att identifiera marktäcket från två olika upptagningsområden samt att analysera vattenkvaliteten i förhållande till uppgifterna om marktäcket. Det visar att temporala och rumsliga förändringar i marktäcket och vattenkvaliteten varierade kraftigt mellan det tempererade och välutvecklade upptagningsområdet i Duiwenhok, och den subtropiska landsbygden i Mzimkulu. Marktäcket konstaterades inte förändras väsentligt i Duiwenhoks avrinningsområde mellan 1984 och 2009, medan alla marktäckesklasser förutom stadsområden förändrades kraftigt under samma tid i upptagningssområde vid Mzimkulu.

En relation konstaterades mellan marktäcket och vattenkvaliteten, där fosfater, nitrater och ammoniumkväve ökade i relation till en ökning av marktäckesklasserna såsom barmark, odlad säd, sockerrör, stads- och landsbygdsområden samt planteringar. Alla dessa klasser är av antropogen natur och indikerar att med en ökning av mänskliga aktiviteter sänks troligtvis vattenkvaliteten. Studien visar att GIS och fjärranalys med framgång kan användas som ett verktyg för att klassificera marktäcket över tid för att kunna använda resultaten i analyser som syftar till att svara på frågor om variabler relaterade till förändringar i marktäcket. De erhållna korrelationer som hittades mellan marktäcke och vattenkvalitet kan användas för att dra slutsatser om förändringar i framtida scenarier.

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LIST OF ABBREVIATIONS AND TERMS

df	Degrees of freedom
DMS	Dissolved major salts
Fynbos	Shrubby vegetation with tough, leathery leaves comparable to Mediterranean vegetation
GIS	Geographical Information Science
NH_4	Ammonium nitrogen
NO_3	Nitrate
PO_4	Phosphate

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

South Africa is a water-scarce country and will potentially face dire water shortages in the near future given the increasing human demand for fresh water, compounded by the effects of climate change. The country's annual average rainfall of 450 mm is much less than the 860 mm global average (CSIR 2010a). Not only is the quantity of water important, but also the quality, as many water systems are polluted to the point where the water is unsafe for human consumption.

Calder *et al.* (1995) stated that human activities such as agricultural development, deforestation, biomass burning and human settlements have shown to affect water runoff and chemistry. Land cover therefore can have strong correlations with water quality.

The aim of this study was to demonstrate the application of GIS (Geographic Information Science) and remote sensing to identify the links between land use and river water quality in two contrasting catchment areas in South Africa, using historical data. The main hypothesis is that a change in land cover representative of increased human activity towards increased urban and rural settlements, along with an increase in cultivated areas over time, had a direct negative effect on the water quality in the catchment. The temporal development of water quality at each catchment was assessed over five different points in time, as was the spatial difference in water quality between the two catchments. The spatial difference within each catchment in water quality and land use was also explored.

Land cover refers to the composition and characteristics of the elements on the surface of the earth (Cihlar 2000), while land use refers to the human activity associated with a piece of land (Lillesand *et al*. 2004 in Richardson S.a.). Many different classifications exist even within the same country as classifications can be subjective or differ according to the needs of the study they are being used in. A widely used classification is the National Land Cover Project 2009 which mapped the land cover of South Africa and grouped the 31 classes into twelve categories based on their impact on runoff (Ellery *et al.* 2010).

Land cover change is one of the largest threats to ecological systems (Foody 2003) and hence warrants a lot of focus. Satellite remote sensing is 'an important tool for monitoring and management of natural resources and the environment' and is widely used in land use/land cover studies (Bahadur 2009). For these reasons satellite remote sensing was used to analyse changes in land cover and relate these to a real-world problem South Africa faces today – water quality.

Changes in land cover and land use affect the timing and amount of runoff in a catchment (Ellery *et al.* 2010), and the runoff and sediment load varies with different land cover and land use types in the catchment. It is therefore helpful to study the effect of land cover on water quality to determine what effect different land uses have.

It was expected that there was little or no significant change in land cover over time in one of the study sites as the area is more established, has been farmed for decades and there is little room for rural settlement, agricultural or urban expansion. In contrast, it was expected that there was a significant change in land cover in the second study site. This was because the area is less developed and has more room for growth. Large areas of natural vegetation still exist which can more easily be converted into rural, urban or cultivated areas. It was expected that this change was likely to happen around the time of the end of Apartheid in 1994 when people moved from homelands and rural areas. These people would also have had more access to land and piped water for cultivation after the end of Apartheid. With the increase in settlements in the area, bare land would also increase as the ground around the houses is traditionally swept bare, and the cattle that would move into the area with the people could be responsible for overgrazing and trampling also causing an increase in bare unvegetated ground.

Estuaries were the starting point for identifying study sites due to their conservation importance, conspicuousness and popularity with humans for a range of activities. The definition of an estuary in South Africa is "a partially enclosed, permanent water body, either continuously or periodically open to the sea on decadal time scales, extending as far as the upper limit of tidal action or salinity penetration. During floods an estuary can become a river mouth with no seawater entering the formerly estuarine area, or, when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become a lagoon or lake which may become fresh or hypersaline.” (Van Niekerk & Turpie 2012).

Estuaries, being the interface between the rivers, land and sea are largely influenced by what the rivers bring in via runoff from upstream in the catchment. Turpie *et al.* (2002) state that the management and the quantity and quality of freshwater inputs will directly affect the future health and productivity of estuaries in South Africa. For this reason the study focused on water quality and land cover further upstream, as this is the water that will ultimately affect the estuaries. Using data from further upstream also reduces the effect of internal processes such as evaporation and internal loading/sequestration (Bowes & House 2001) which could mask the effect of land cover on water quality. If only the estuary were to be considered in terms of water quality, pollution sources near the estuary could be disguised by floodwaters from further upstream that have a diluting effect. In areas with distinct seasonal rainfall and flow peaks the water quality variables measured in streams and rivers could be in direct contrast to those measured in the estuary, depending on the season, amount of flow and discharge pulses. Salts may accumulate upstream in the rivers during drier periods while the estuary remains unaffected, or floods may bring an accumulation of salts to the estuary even if upstream the dynamics and values are quite different. Focusing on the rivers eliminated these variables and made comparisons with land cover easier. Also by studying the effects in sub-catchments as opposed to the catchment as a whole, more direct comparisons and deductions could be made by identifying more localised changes and their direct effect on the water quality measured in the area.

1.2 BACKGROUND

Among South Africa’s main water quality problems are salinisation and in increase in total dissolved salts (CSIR 2010a). Salinisation can be described as an increase in salts, and total dissolved solids refer to dissolved matter. This increase is due to increased export of solutes and the effect of evapotranspiration (CSIR 2010a). This occurs due to municipal and industrial effluent, irrigation return flows, storm-water runoff, pollutants from mining and industry, as well as seepage from waste disposal sites. Many of South Africa's sewerage systems are overloaded or unmaintained, and much of the country's waste water is not treated properly before being discharged into rivers (CSIR 2010a). Pesticides and fertilisers from modern agricultural practices also contaminate rivers and groundwater via runoff (Walmsley 2000). An increase in urban and rural settlements could potentially exacerbate this sewerage problem, and thus the correlation between an increase in these land cover types and water quality was explored.

The two study sites that were selected were the Duiwenhoks catchment area from the Warm Temperate region with all-year rainfall (Figure 1 and 3), and the Mzimkulu catchment area that falls within the Subtropical region with the country's typical summer rainfall (Figure 2 and 3).

According to Whitfield (2000), the Duiwenhoks Estuary is in excellent condition, although the freshwater supply to the estuary is progressively being curtailed. The estuary's inlet is restricted and tidal action keeps the mouth open (Akoto 2009). It is one of the country's most important nursery estuaries in terms of biodiversity and the presence of sub-adult cob species (Van Niekerk & Turpie 2012). Mzimkulu is one of the country's important fish nurseries based on biodiversity, the presence of sub-adult cob species, and the possibility of juvenile Zambezi sharks (Van Niekerk & Turpie 2012). The estuary is reportedly in poor condition due to water pollution and siltation (Whitfield 2000). A sugar mill discharges waste into the river just upstream from the estuary which affects estuarine health (Van Niekerk & Turpie 2012).

A national biodiversity assessment was undertaken and a condition score allocated to each estuary. "The health assessment was based on the Estuarine Health Index developed for South African ecological water requirement studies that has been applied systematically to over 30 estuaries at various levels of data richness and confidence. The individual estuarine health assessment scores were then translated into health categories and aggregated for the various estuarine ecosystem types to reflect the overall ecosystem status of South Africa's estuaries" (Van Niekerk & Turpie 2011). Duiwenhoks estuary's health condition is as follows: hydrodynamics (very good condition[1]); physical habitat, habitat state, microalgae, macrophytes, birds, biological state, and the mean estuary health state (good condition); hydrology, water quality, invertebrates and fish (fair condition). No variables are in poor condition. Its pressures are fishing effort (high pressure – 13 tonnes per year), inflow change (medium pressure), pollution and habitat loss (low pressure) (Van Niekerk & Turpie 2012).

Looking at Mzimkulu Estuary's health condition, none of the aspects are in very good or poor condition and only the number and species of birds are in a good, healthy condition. Hydrology, hydrodynamics, water quality, physical habitat, habitat state, microalgae, macrophytes, invertebrates, fish, biological state and mean estuary health state are only in fair condition. The estuary's pressures are fishing (high pressure – 0.2 tonnes per year), inflow change, pollution and habitat loss (medium pressure), and mining and artificial breaching are present (Van Niekerk & Turpie 2012).
Turpie *et al.* (2002) ranked Duiwenhoks as the 33rd top estuary in South Africa. Estuaries were ranked according to conservation importance, which took weighted size, habitat, zonal type rarity and biodiversity importance into account. Mzimkulu is only ranked 129th according to conservation importance in South Africa (Turpie *et al.* 2002).

From an ecological and economic point of view, estuaries are functionally important as they serve as nurseries for a large number of commercially important fish species and crustaceans. Estuaries have multiple uses ranging from ecological, subsistence (local fisherman relying on fish and shellfish caught in the estuary for food), recreation and tourism to commercial and industrial (CSIR 2010a). The almost 300 estuaries in South Africa have an estimated average fish nursery value of R100 000 – R10 million (US$11 500 - US$1.1 million), and a tourism value of R10 000 – R1 million (US$1150 - US$115 000) per annum (CSIR 2010a), which gives an idea of their economic importance. Reduced water flow is one of the problems many estuaries face. It is reduced due to an increase in abstractions for urban and agricultural water requirements, as well as forestry and alien vegetation which consumes a lot of water (Hosking *et al.* 2004). Furthermore a large number of estuaries is considered to be in

[1] Condition scores are ranked from very good through good, fair to poor. Very good indicates an undisturbed state, good indicates that it is close to natural, fair corresponds with somewhat disturbed and poor indicates an unhealthy or poorly functional state.

poor (disturbed) or fair condition (somewhat disturbed) in South Africa; some of the threats being pollution, habitat destruction within the estuarine functional zone, and climate change (Van Niekerk & Turpie 2012). Only a small number is considered to be in good (undisturbed) condition.

For purposes of this study the main focus was not on the condition of the estuaries but rather to look at the water quality upstream in the rivers which will ultimately flow into the estuaries, bringing with them any pollutants they may carry. Water quality is a term which can have multiple meanings. In this study water quality refers to variables within the water whose measurements allow us to make assumptions about anthropogenic effects on water. As an overall indicator dissolved major salts (DMS) and electrical conductivity provide an idea of how many salts are suspended in the water. The higher the concentrations the poorer the water quality as it can lead to changes in turbidity and salinisation with a resulting effect on aquatic ecosystem productivity (DEADP, S.a). It should be noted that high concentrations of dissolved major salts and electrical conductivity do not necessarily come from sources of runoff from anthropogenic pollution, but could also be introduced into the system from groundwater. The pH is an important variable as organisms are adapted to survive in a certain optimal pH range (Farrel-Poe 2005), and water is only safe for human use and consumption within a range of about 6.5-8.5 (SDWF S.a). Finally, in order to make more direct assumptions based on anthropogenic effects on water quality, three nutrients were selected which typically have an anthropogenic source and which increase through pollution, application of fertilisers, and untreated human waste - Phosphate (PO_4), Nitrate Nitrogen (NO_3) and Ammonium Nitrogen (NH_4). It has been shown that nitrogen and phosphorus contribute to eutrophication (Bootsma and Hecky 1993 in Kingdon *et al.* 1999) and are thus important variables to measure. Phosphate is linked to effluent, nitrates to fertilisers and ammonium nitrogen to sewerage and fertilisers (Showalter *et al.* 2000).

It was expected that there would be differences in the water quality variables discharged between the two catchments based on differences in rainfall patterns, hydrology and pollution sources. The Duiwenhoks catchment, with its lower annual rainfall spread more evenly across the year contrasts with the Mzimkulu catchment which has higher rainfall with obvious seasons. In Duiwenhoks nutrients and other water quality variables would be discharged more evenly throughout the year while in

Mzimkulu it would be expected that there would be a distinct 'flushing' of nutrients as the first rains of the season bring large quantities of runoff, water discharge and nutrients that had accumulated over the dry season.

Pollution sources also differ between the two catchments. In Duiwenhoks the majority of anthropogenic use is cultivated land. The type of farming here is both crop and livestock farming and has been established for many decades. The town (Heidelberg that falls in the centre of the catchment is small but well-established and urban. A waste-water treatment plant is located near the town. A large portion of the catchment area is natural fynbos (tough, shrubby vegetation most comparable with Mediterranean vegetation) with no known anthropogenic pollution sources (Figure 1).

Figure 1. Representative photos from the Duiwenhoks catchment area. a) Commercial cultivated crops; b) Established urban areas – Heidelberg; c) Natural fynbos; d) Croplands interspersed with fynbos with an example of a rural homestead. (Photographs taken by author on fieldtrip (2012).)

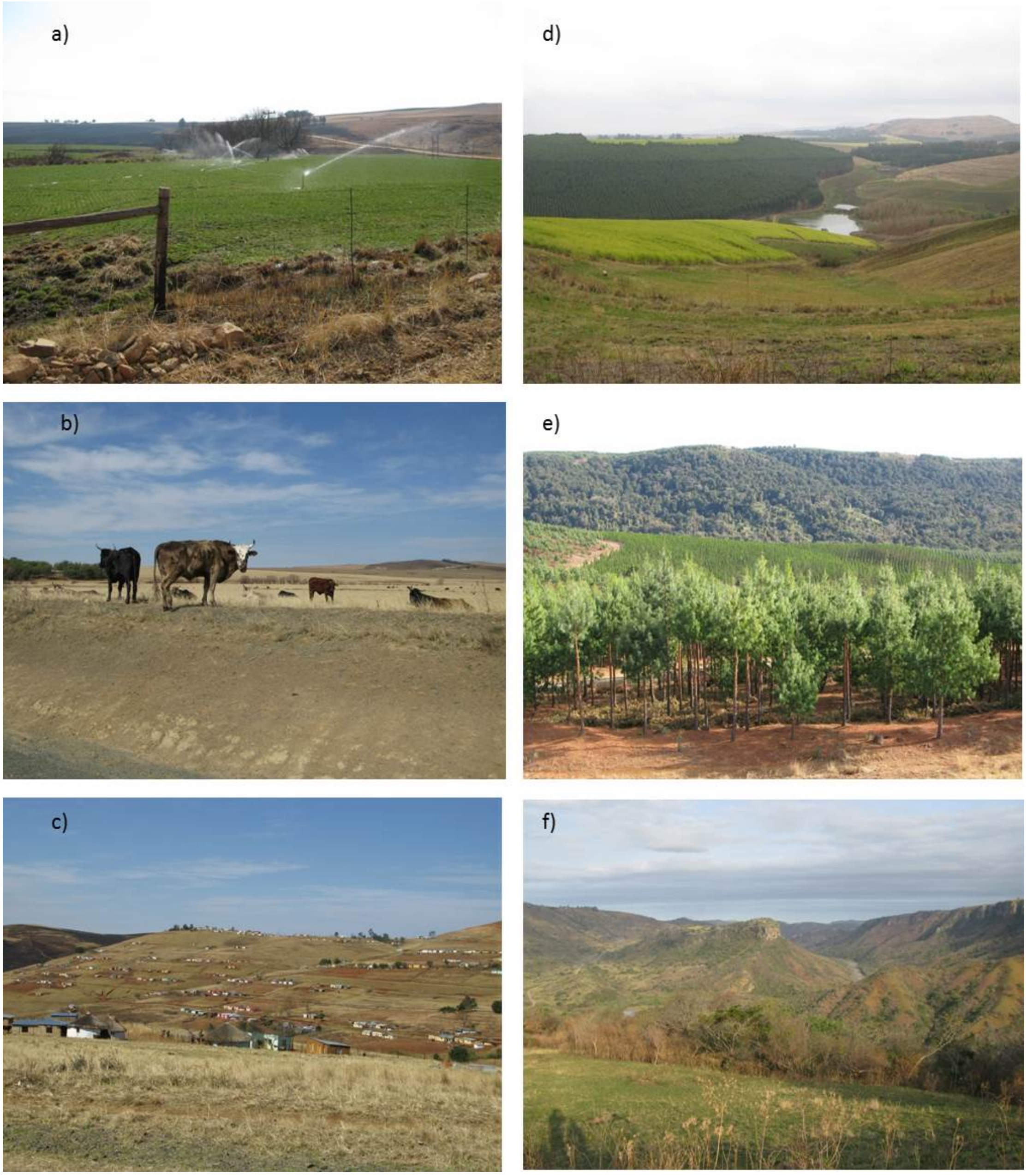


Figure 2. Representative photos from the Mzimkulu catchment area. a) Commercial cultivated crops; b) Rural farmers have free-roaming cattle who feed off the natural vegetation c) Rural settlement interspersed with bare areas (some of which are fields), surrounded by natural grassland; d) Natural grassland, sugar cane field with a plantation in the distance; e) Plantation in the foreground with a natural forest in the background; f) Natural wooded/savannah. (Photographs taken by author on fieldtrip (2012).)

In Mzimkulu the most obvious source of pollution is the sugar mill and a cement mine, but they both lie just upstream of the estuary and unfortunately do not fall within an area that could be analysed in this study. Farming also contributes to pollution in this catchment, although there is both large scale commercial farming (in the upper reaches of the catchment closest to the Drakensberg and sugar cane in the lower reaches of the catchment) and subsistence and small scale commercial farming (in the more rural, drier areas in the mid and lower catchment).

The commercial farms (besides sugar cane) have been established for decades, as are those in the Duiwenhoks catchment, and can be expected to use fertilisers and optimised farming practices. The subsistence and smaller-scale commercial farms farmed mainly by the poorer, rural people are less likely to make use of fertilisers, but are more likely to be susceptible to overgrazing and trampling causing an increase in bare areas and erosion. Other sources of anthropogenic pollution are the small urban areas in the upper reaches of the catchment, as well as the many settlements scattered throughout. Plantations are also prevalent in the catchment and although these are not necessarily sources of pollution, they are anthropogenic (Figure 2).

By studying the past and current land use patterns in a catchment and relating them to existing data on water quality and estuarine health, we may be able to estimate what may happen to water quality in the future with varying expected changes in land use associated with predicted climate change.

CHAPTER 2
METHODOLOGY

2.1 STUDY AREA

2.1.1 Site Selection

Although estuaries were used to identify suitable catchment areas, rivers were the focus of the study. This is due to their connectivity between land in the upper reaches of the catchment and the estuary, as well as the proximity of the monitoring stations to the headwaters. By utilising water measurements from further upstream internal processes such as evaporation and internal loading are minimised, providing a more direct comparison between the water quality variable and land cover. Water quality is affected more by internal surface water processes as one moves downstream, and estuaries and rivers themselves have a cleaning effect on the water (Eyre 1997; Soto & Mena 1999), thus they disguise the water quality changes caused by changes in land use. The sea and its backflow into the estuary can also affect the water quality measurements taken in an estuary (Yamamuro & Kanai 2005), potentially disguising changes caused by land use. Despite the fact that water quality and flow measurements used in the study are focused on upstream river stations, actual catchment selection was based on estuaries due to their conservation and anthropogenic importance, as the relationships between water quality and land use would have an effect on the entire catchment, including the estuary.

There are 258 estuaries in South Africa according to Whitfield (2000) and almost 300 according to the National Biodiversity Assessment (Van Niekerk & Turpie 2012). Estuary selection for the project was done according to the criteria listed in Appendix A. For purposes of this study only permanently open estuaries were considered. Those with large dams in their catchment areas were eliminated from consideration because the system should be unimpeded to accurately measure change caused by changes in runoff and a dam would mask these. Large catchments with large estuaries were selected to ensure that changes picked up by remote sensing and ancillary data were due to changes within the catchment and its land use.

The resulting sites selected for this study were the Duiwenhoks Estuary Catchment in the Warm Temperate region and the Mzimkulu Estuary Catchment in the Subtropical region. The secondary catchments of these two estuaries contain all the rivers that flow into these estuaries and were thus the areas of focus in this study.

2.1.2 Location

Duiwenhoks:

The 1366.72 km^2 Duiwenhoks catchment falls within the Western Cape Province of South Africa in the Warm Temperate Region. The northern boundary lies along the Langeberg mountain range at roughly 33.92^{o}S and extends south to the coastline at the Indian Ocean west of Stilbaai with its southern-most point at 34.44^{o}S. It extends from 20.79^{o}E to 21.42^{o}E (Figure 3). The only main town in the catchment is Heidelberg which lies approximately 40 km from the river mouth. The Cape Floral Region World Heritage Site falls within the north-western corner of the catchment area.

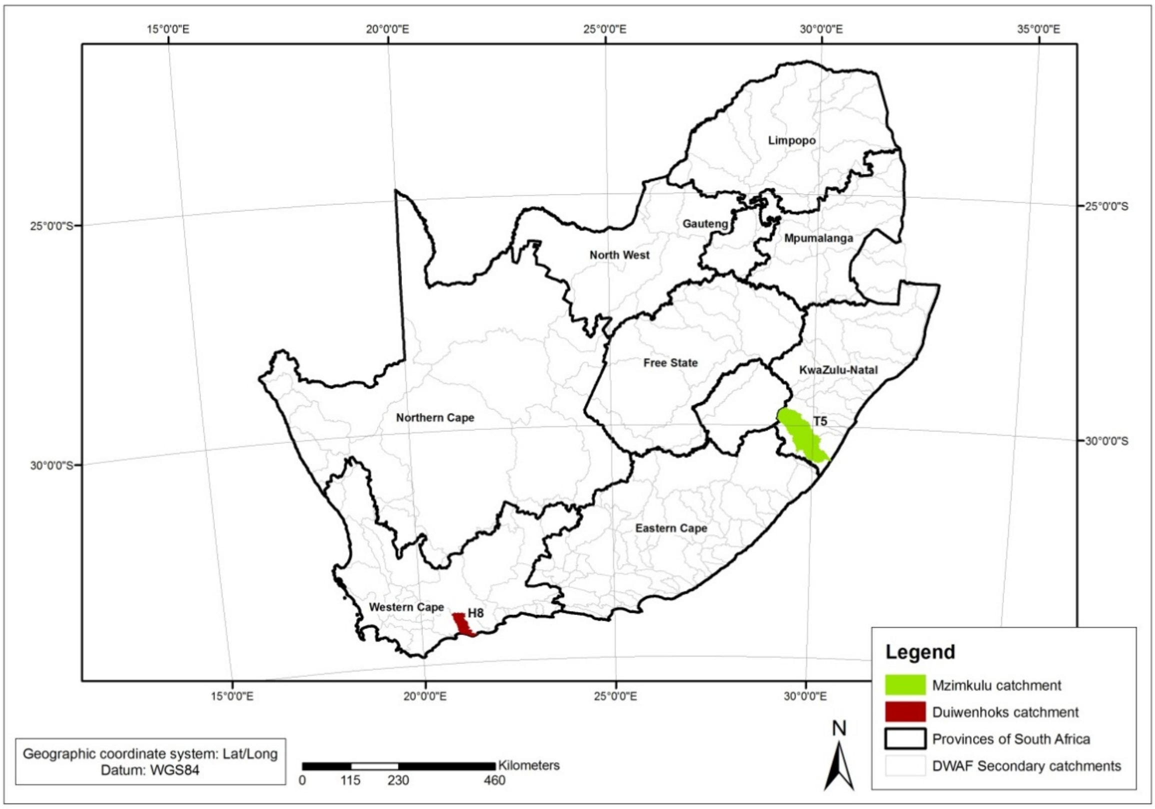


Figure 3. Site location of the Duiwenhoks and Mzimkulu catchment areas. (Data source: CD:NGI South Africa (2012))

Mzimkulu:

The 6670.97 km^2 Mzimkulu catchment falls within the KwaZulu-Natal Province in the Subtropical Region. The catchment area extents from roughly 29.62^{o}S in the Drakensberg near Sani Pass on the border with Lesotho southwards to 30.74^{o}S on the

Indian Ocean coastline near Port Shepstone. The Mzimkulu catchment extends from 29.11°E to 30.46°E (Figure 3). Himeville, Underberg, Umzimkulu and Harding are towns that fall within the catchment. The uKhahlamba Drakensberg Park lies in the northern section of the catchment area, and is both a World Heritage Site and a Ramsar Site.

2.1.3 Topography

In the Duiwenhoks catchment altitude ranges from 1180 m above sea level in the Langeberg and decreases fairly evenly to sea level at the estuary mouth in the south, with the exception of a large relatively flat area in the middle of the catchment (Figure 4).

The lower, flatter Duiwenhoks catchment contrasts with the steeper Mzimkulu catchment. The highest reaches of the Mzimkulu catchment lie 3280 m above sea level in the Drakensberg, and altitude decreases more or less evenly down to sea level at the estuary mouth. All the major rivers in this catchment are perennial (Figure 5). Two rivers flow into the estuary, the Mzimkulu River and the Mzimkhulwana River. The Mzimkulu River is one of the largest and one of very few free-flowing rivers left in the country (CSIR 2010a).

Geology in the Duiwenhoks catchment forms part of the Cape Supergroup while that in Mzimkulu forms part of the Karoo Supergroup (ENPAT – Geology). Vegetation in the Duiwenhoks catchment is part of the Fynbos Biome and that in Mzimkulu falls within the Grassland and Savannah Biomes (Mucina and Rutherford 2006). For a description and maps of geology and natural vegetation at the study sites see Appendix B.

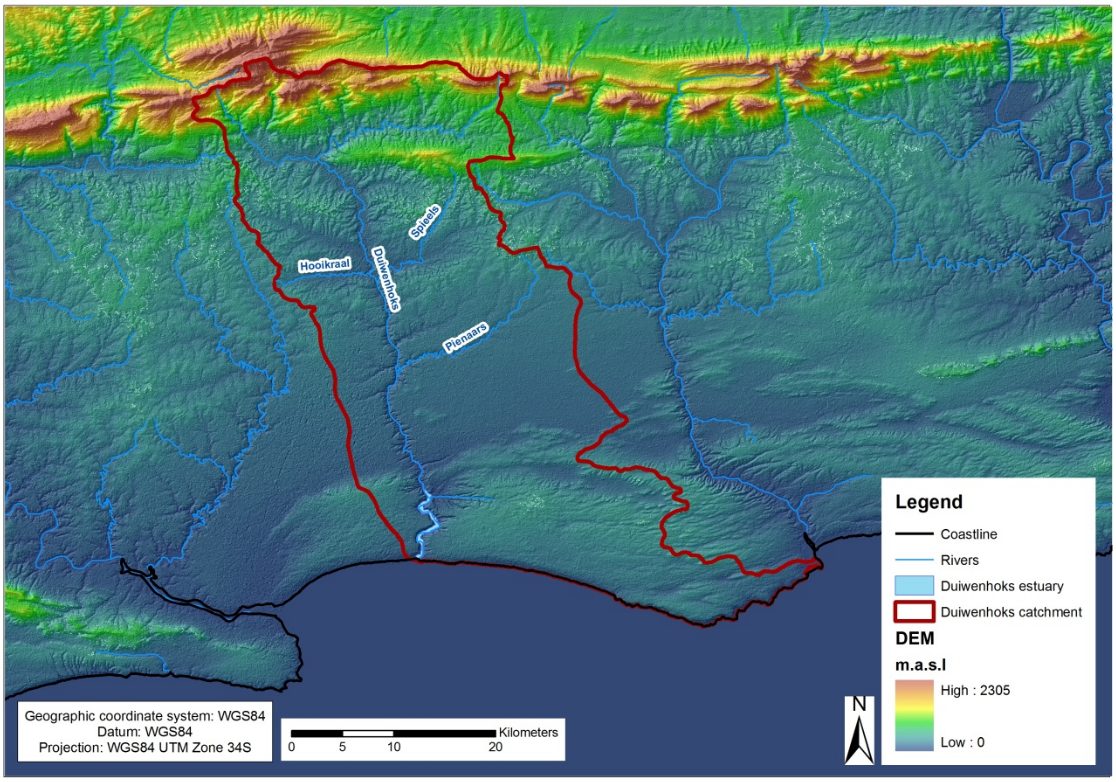


Figure 4. Topographic map of the Duiwenhoks catchment area. (Data source: Rivers – CD:NGI South Africa (2012); ASTER GDEM – a product of METI and NASA)

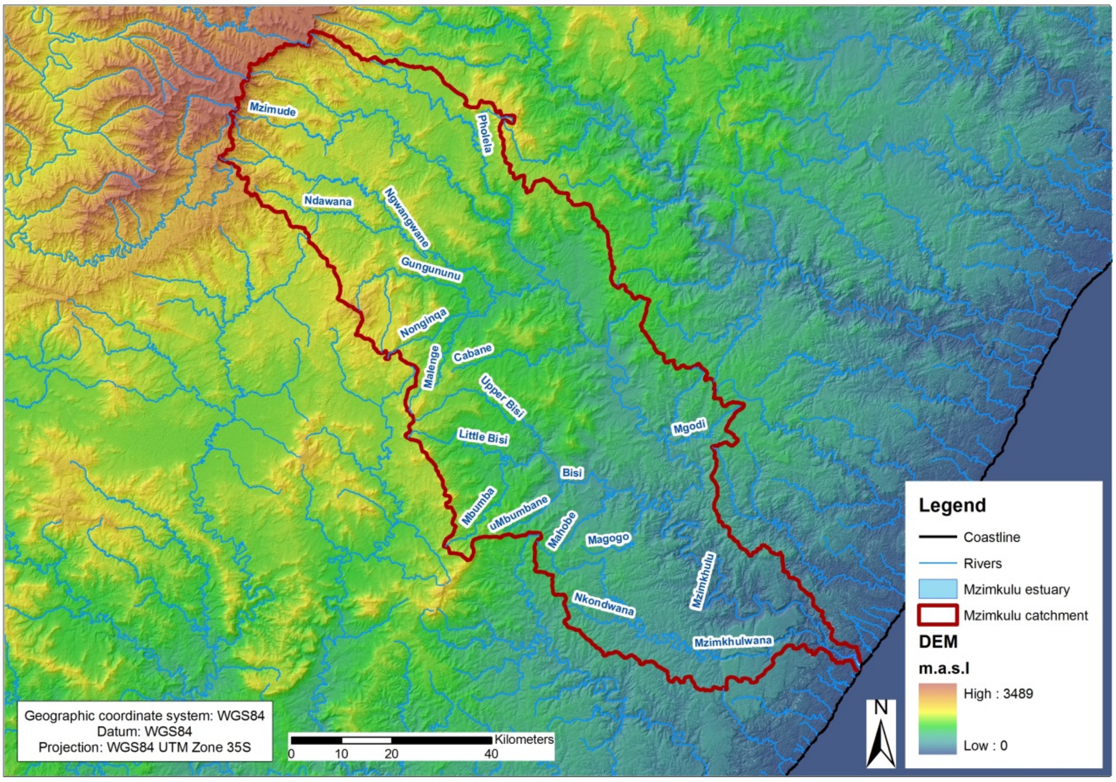


Figure 5. Topographic map of the Mzimkulu catchment area. (Data source: Rivers – CD:NGI South Africa (2012); ASTER GDEM – a product of METI and NASA)

2.1.4 Climate

The climate in the Duiwenhoks region is temperate, while in Mzimkulu it is subtropical. The mean annual temperature in the Duiwenhoks catchment area varies from 15.1^{o}C - 16.4^{o}C, with an average minimum of 5^{o}C and a maximum of 28^{o}C. The mean annual temperature in the Mzimkulu catchment area has a wider range and varies from 10.8^{o}C - 20.0^{o}C, with an average minimum ranging from -2^{o}C to 11^{o}C and a maximum of 28^{o}C.

Mean frost days per annum in Duiwenhoks range from 3 - 13 days and in Mzimkulu range from 0 - 78 days. The mean annual potential for evaporation ranges from 1756 mm - 1948 mm in Duiwenhoks and 1594 mm - 1737 mm in Mzimkulu (Mucina & Rutherford 2006).

The Fynbos Biome has all-year rainfall with slightly less rain in summer and highest rainfall in winter, mainly between March and August. The mean annual rainfall is low with 389 mm in the East Coast Renosterveld, and higher in the Eastern Fynbos-Renosterveld with 615 mm (Mucina & Rutherford 2006). The entire catchment falls within the all-year rainfall region (Schulze & Lynch 2007) ensuring connectivity between rivers, estuaries and the sea in the sense that rainfall and resulting flow of water in all the rivers of the catchment occurs in the same season (Van Niekerk & Turpie 2012).

The Mzimkulu region is more typical of the rainfall pattern in the larger portion of the country with well-defined summer rainfall where most rain falls between November and March. The mean annual rainfall is about 763 mm over most of the catchment, and up to 985 mm in the Indian Ocean Coastal Belt (Mucina & Rutherford 2006). The entire catchment falls within the summer rainfall region, with the majority falling in mid-summer and the area around the estuary receiving rain in late summer (Schulze & Lynch 2007).

2.1.5 Estuary Description

The Duiwenhoks estuary mouth is at 34^{o}22’S; 21^{o}00’E. It is roughly 17 km long (Figure 6). The Mzimkulu estuary mouth is at 30^{o}44’S; 30^{o}27’E and is roughly 10 km long (Figure 7). The average flow rate of the Duiwenhoks river is 211 392 m^3/day

(Anderson *et al.* 2002), or 77.1 million m^3/annum, while the average flow rate of the Mzimkulu River is 1478.2 million m^3/annum (Van Niekerk & Turpie 2012). Mzimkulu is ranked fifth of the major catchments in South Africa, with 3.9 % of the country's runoff. The estuarine habitat in the Duiwenhoks Estuary constitutes 39 % sand/mud banks, 36 % is made up of the channel, and 25 % is intertidal salt marsh (Anderson *et al.* 2002; Van Niekerk & Turpie 2012). The Mzimkulu estuarine habitat consists of 63 % channel, 15 % reeds and sedges, 13 % swamp forest, and 9 % is sand/mud banks (Van Niekerk & Turpie 2012).

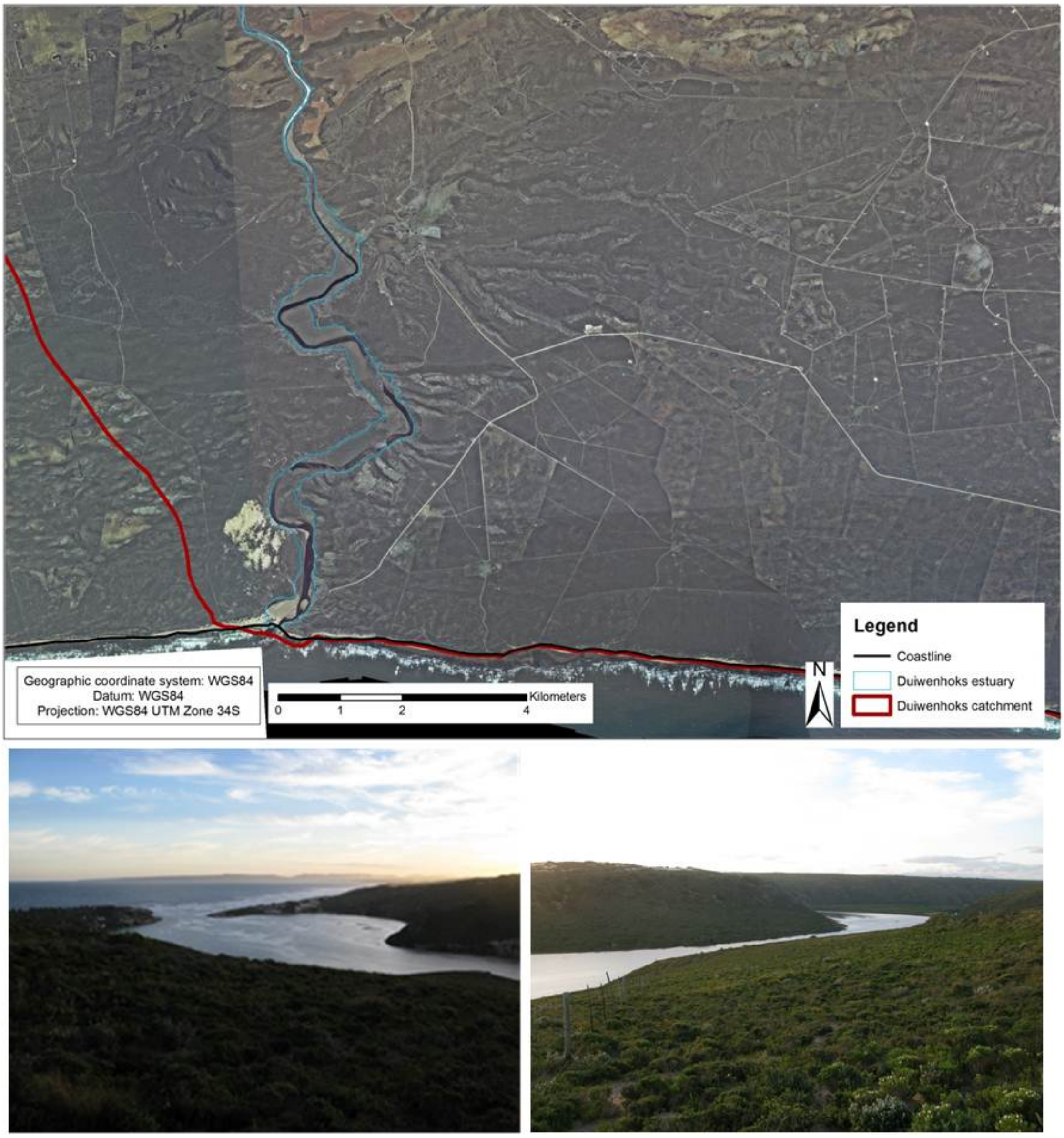


Figure 6. Orthophoto of the Duiwenhoks estuary and photos of the estuary mouth taken in the field. (Data source: Estuary – NFEPA (National Freshwater Ecosystem Priority Areas), CSIR (2011); Orthophotos – CD:NGI South Africa (2011). Photographs taken by the author during fieldwork (2012).

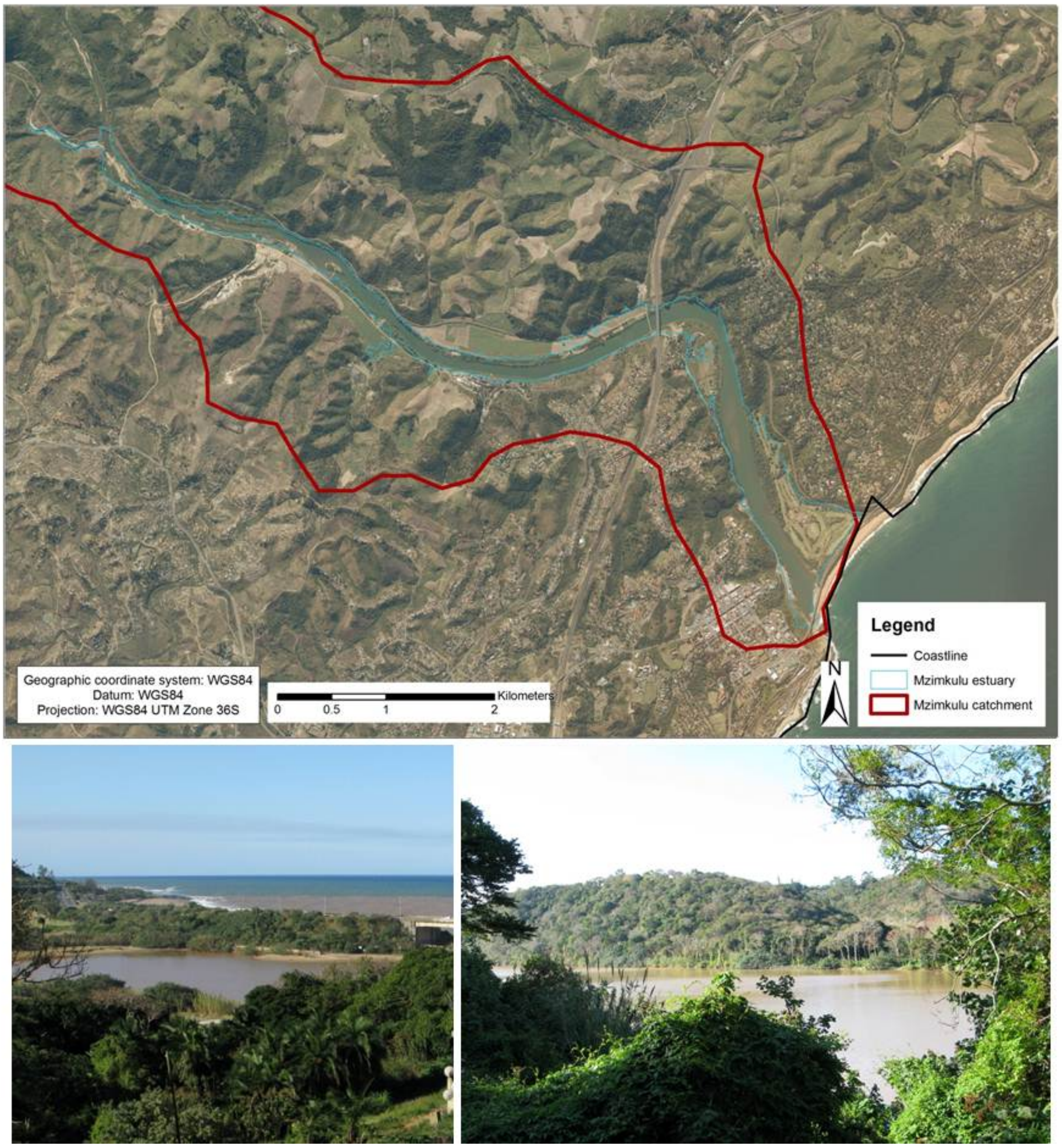


Figure 7. Orthophoto of the Mzimkulu estuary and photos taken in the field. (Data source: Estuary – NFEPA (National Freshwater Ecosystem Priority Areas), CSIR (2011); Orthophotos – CD:NGI South Africa (2011). Photographs taken by the author during fieldwork (2012).)

2.2 SPATIAL DATA

2.2.1 Spatial data selection

Many earth observation satellites currently provide imagery, and the selection of imagery for a particular study depends on the requirements and purpose of the respective application. Multiple spectral datasets such as Landsat Thematic Mapper (TM) and SPOT are useful for detecting land cover change (Hill & Aifadopoulou

1990; Santillan *et al.* 2011). Due to the lower cost, longer timespan and higher frequency Landsat imagery is often used in land cover/land use studies (Manandhar *et al.* 2009). Multispectral data of the Landsat TM series are amongst the most frequently used earth observation data for Land Cover/Land Use change monitoring worldwide. This is due to its unequalled historical data availability since the early 1980s with Landsat 4 and 5, and since 1999 with Landsat 7 ETM+ and is to be continued with Landsat 8 which was launched in February 2013 (www.ldcm.nasa.gov - keyword: Landsat data continuity mission). Although Landsat is considered to be of medium resolution and capable of identifying features only at landscape level, those sensors that have a high and very high resolution (<30 m) with the capability of identifying objects to stand or even tree level have only been around since 1999 (IKONOS), 2001 (QuickBird), or even later (Martinez & Mollicone 2012), making them too new for time series analysis at this stage. Aerial photos can also be used and have been in use prior to satellite imagery. If they are correctly orthorectified they can be of much use due to their much higher resolution. However aerial photos can be more difficult or expensive to source, more photos are required to cover the area, and times and seasons in which the photos were taken may not correspond between sites due to them being taken much less frequently than satellite imagery.

The spatial resolution required for the specific study is to be considered when selecting imagery as it is not always necessary to utilise imagery with the finest resolution (Hengl 2006). The Landsat TM, with a spatial resolution of 30 m is found to be sufficient for this study. Although the number of land use classes that can be defined using imagery classification decreases with spatial resolution, Landsat shows good overall accuracy and results in terms of the amount of and type of land use classes identified (Rozenstein & Karnieli 2011; Martinez & Mollicone 2012). Martinez and Mollicone (2012) also found that it may provide the best balance between spectral, spatial and temporal resolutions and thus Landsat may be the optimal source for land cover classification at a regional scale. Therefore, Landsat TM imagery will be used in this study due to its suitability for detecting land cover change at a landscape level.

There have been several versions of Landsat sensors, with Landsat 7 being the only one currently operational. Landsat 5 was decommissioned in December 2012. While Landsat 7 is the most recent of the satellites, launched in 1999, Landsat 5 has been collecting imagery since 1984 (USGS 2010) and hence the time-series analysis can span a larger time-frame. The sensors of Landsat 5 and 7 are virtually identical (Table 1) and imagery from both is thus interchangeable. Landsat 5 was used for the earlier dates, and Landsat 7 was used between 1999 and 2003. After 2003 the Landsat 7 images have scan line correction errors resulting with gaps in the images and were not deemed useable for the project, so Landsat 5 imagery was again used after 2003.

Table 1. Specifications of Landsat 5 and Landsat 7 sensors.

Band number	**Landsat 5 TM**		**Landsat 7 ETM**	
	µm	Resolution	µm	Resolution
1	0.45 – 0.52	30m	0.45 – 0.515	30m
2	0.52 – 0.60	30m	0.525 – 0.605	30m
3	0.63 – 0.69	30m	0.63 – 0.69	30m
4	0.76 – 0.90	30m	0.75 – 0.90	30m
5	1.55 – 1.75	30m	1.55 – 1.75	30m
6	10.4 – 12.5	120m	10.4 – 12.5	60m
7	2.08 – 2.35	30m	2.09 – 2.35	30m
8	-	-	0.52 – 0.9	15m

Data derived from the USGS http://landsat.gsfc.nasa.gov.

Digital Elevation Models (DEMs) also had to be selected. The two main sources are the SRTM (Shuttle Radar Topography Mission), and the ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer's Global DEM). SRTM uses stereo radar imaging to create an image from electromagnetic scattering coefficients (Wikipedia 2013a), while ASTER GDEM uses multitemporal optical multi-angle imagery of visible light for the DEM derivation (Wikipedia 2013b). Radar imaging allows elevation data to be collected regardless of time or weather conditions and the SRTM dataset's high accuracy and freely accessible imagery makes it a popular choice.

The ASTER GDEM has a horizontal resolution of one arc-second (ca 30m) while SRTM has one of three arc-seconds (ca 90m) in areas outside the USA (Hayakawa *et al.* 2008). SRTM has a vertical accuracy of 16 m and a horizontal accuracy of 20 m (Rodriguez *et al.* 2006), and the ASTER GDEM has a vertical accuracy of about 20 m and a horizontal accuracy better than 50 m according to Fujisada *et al.* (2005) and 30 m according to Sefercik (2012). Hayakawa *et al.* (2008) found that the ASTER GDEM had fewer missing cells and more realistic representations and that ‘overestimation of valleys by SRTM-3 is more common than underestimation of ridges by GDEM’, and that GDEM also reflects actual elevation better than SRTM when compared with topographic maps. The ASTER GDEM is not without fault though, as Sefercik (2012) found it to have distortions in steep, mountainous and forested areas, despite having good accuracy in urban regions. There is also a limitation in the DEM’s accuracy due to the algorithm used for DEM extraction (Watanabe 2005). Sefercik (2012) concluded that its accuracy was sufficient for a scale of 1:25 000 to 1:100 000. ASTER GDEM has been found to “prove suitable for a large range of environmental and geoscientific applications involving the use of 3D data and DEMs” (Toutin 2008).

The repeat cycle of the Terra spacecraft on which the ASTER is mounted is 16 days and the distance between orbits is 172 km, the same as that of Landsat (Iwasaki & Fujisada 2005). This results in a high repetition rate and therefore greater chance to obtain cloud-free images, as well as the possibility to take images at different acquisition angles. The more images available for one area that can be combined the better the DEM quality. The resolution of Landsat and ASTER GDEM are also both in the same range. For these reasons the ASTER GDEM (Version 1) was selected for use in this study.

Additional GIS data included vegetation, geology, existing land cover datasets and topographic and cadastre data from SANBI (South African National Biodiversity Institute), CD:NGI (Chief Directorate: National Geo-spatial Information) of the Department of Rural Development and Land Reform, and from ENPAT of the Department of Environmental Affairs and Tourism.

2.2.2 Imagery selected

Duiwenhoks only required one Landsat image to cover the study area (path 173, row 84) but Mzimkulu required two (paths 168 and 169, row 81). Images were chosen between 1984 and 2009 (later images were unavailable) to make use of as long a timespan as possible. Only cloud-free images were selected. Five time-frames were selected with one as close to the start of Landsat 5’s image acquisition and one as close to the current time as possible. It was decided that another image from the Apartheid era (pre-1994) would be useful and the remaining two from post-Apartheid. This allowed a comparison between pre- and post-Apartheid as there was a major shift in land use and expansion of urban and rural settlements expected after 1994 when the population moved out of the homelands. Ideally the same dates for Duiwenhoks and Mzimkulu should have been chosen but cloud-free imagery from dates that coincided for all three path and row combinations were not always available. It was also attempted but not always possible to select imagery from the same season, which could potentially lead to differences due to seasonality as opposed to 'true' change. Imagery selected is shown in Table 2, and examples of the Landsat imagery is shown in Figures 8 and 9.

Table 2. Imagery selected for the project.

	Year 1	Year 2	Year 3	Year 4	Year 5
Duiwenhoks Path 173 Row 84	1987/01/27 TM	1990/06/12 TM	2000/07/17 ETM	2002/05/04 ETM	2009/04/29 TM
Mzimkulu 1 Path 168 Row 81	1984/06/24 TM	1990/06/25 TM	1997/01/19 TM	2002/08/21 ETM	2009/05/12 TM
Mzimkulu 2 Path 169 Row 81	1984/08/18 TM	1989/03/09 TM	1996/12/25 TM	2002/08/12 ETM	2009/05/19 TM

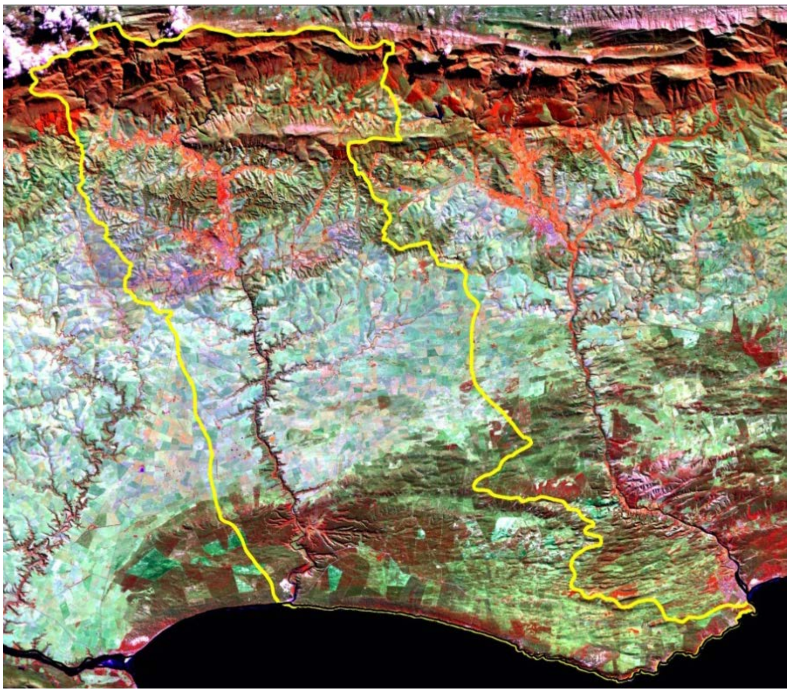


Figure 8. Subset (67 km x 58 km) of Landsat TM image of the Duiwenhoks catchment area (Path 173 row 84. Band combination RGB 453, 29/04/2009).

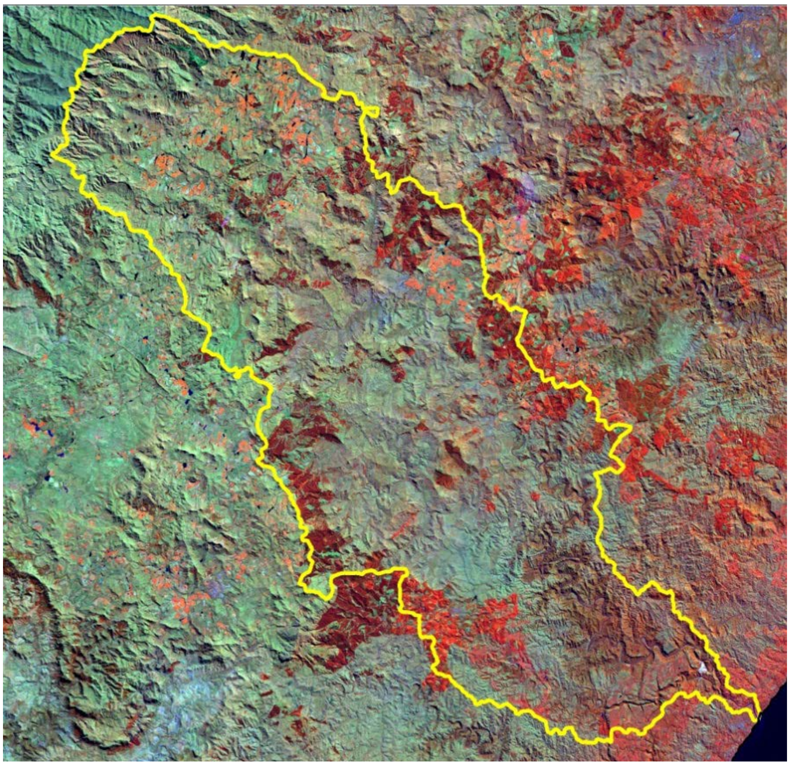


Figure 9. Subset (144 km x 138 km) of Landsat TM image of the Mzimkulu catchment area (Path 168 and 169, row 81. Band combination RGB 453, 12 & 19/05/2009).

2.3 CLASSIFICATION METHODS

2.3.1 Groundtruthing

2.3.1.1 Fieldwork

Fieldwork to collect ground control points took place from 13-16 August 2012 (Mzimkulu catchment), and from 19-21 August 2012 (Duiwenhoks catchment). An iPad loaded with GISRoam (made by Cogent 3D, Inc., Tucson, USA) and TerraPad (made by Fasterre, Quebec, Canada) applications was used in the field. This was both to replace the need for paper maps for navigation and for use as a secondary GPS (Global Positioning System) as it was able to track the route and record points overlaid on either Google Earth satellite imagery, the loaded Landsat image, and any shapefiles of the area that were of use during the fieldwork, such as the National Land Cover map. This provided a real-time look at the current position along the data collection route, an idea of what land cover to expect and how large the area was, to give an idea of when one was in a suitable position to take a recording.

The route selected followed an extensive, representative path through the different land cover types in a logical, time-saving way with minimal back-tracking. Points were collected along the road for large enough (minimum roughly 1 hectare) homogenous areas. Points were collected at least 100m from each other. Ground control points were recorded using a Garmin eTrex Legend GPS once the GPS had reached less than 10m accuracy. All data were also recorded on paper to prevent data loss through technical issues. Georeferenced photos of the land cover were taken at each location. In this way, 162 GCPs (Ground Control Points) were collected in the Mzimkulu catchment and 94 in the Duiwenhoks catchment.
GISRoam on the iPad indicated the route driven, and was used to record points when there wasn't time to collect points using the Garmin GPS. This was possible due to the fact that a shapefile for each class was created, and points could be added to the active class merely by pressing a button, thus eradicating the need to stop and record GPS coordinates or land cover. Instances where this method was used included stretches of highway where it was unsafe to stop and take a recording or along roads where there was nowhere to pull off the road. Actual accuracy readings were not provided, but visual comparisons after loading the points into ArcGIS show that points were located in the correct lane of the road, corresponding to where the readings were taken. This made them sufficiently accurate for use in this study.

Using this method, 203 points were collected for Mzimkulu and 47 points for Duiwenhoks. Due to the fact that some classes were not directly alongside the road, such as waterbodies and wetland, these classes were not attempted in the field.

2.3.1.2 Class selection

Based on the visual observation of land cover types during fieldwork a certain number of classes were decided upon. The distinction was made based on classes that are obviously different (such as bare ground, waterbodies and plantations) and where it was suspected that runoff would be different and hence affect the amount of nutrients and sediment that enter the river system and affect water quality. Examples of this are the distinction between cultivated areas, where it was expected that the irrigation patterns, soil-binding properties of the crops/plants and resultant runoff differed. Elwell and Stocking (1976) found that the percentage of vegetation cover is the major factor determining susceptibility to erosion in crops and grassland. Increased urbanisation also leads to an increase in runoff, while an increase in afforestation leads to a considerable reduction in runoff (Hundecha & Bárdossy 2004).

Cultivated areas were therefore divided into grains and sugar cane, and grains were further subdivided into irrigated and non-irrigated grains. Natural vegetation was also subdivided. Built-up areas differed vastly between urban and rural areas, where urban areas had the typical concrete and brick infrastructure, with tar roads, parking lots, shopping centres and suburban houses, while rural settlements comprised of sparse, smaller houses, with little or no concrete or tar in between, and areas around the houses were bare ground swept clean by the residents. The spectral reflectance of these two built-up areas as well as their characteristics and water runoff qualities therefore differ vastly.

The classes distinguished were as follows:

- Built-up
    - Urban
    - Rural
- Unvegetated bare ground
- Natural Vegetation
    - Forest
    - Wooded/savannah
    - Fynbos
    - Grassland
- Plantations
- Cultivated
    - Sugar cane
    - Grains
        - Irrigated grains
        - Non-irrigated (or rain-fed) grains
- Wetlands
- Water

Not all classes were present in each site.

2.3.1.3 Digitising

Ground control points collected in the field were recorded on the road instead of in the middle of the homogenous patch. (It was not possible to walk off the road into the field or property alongside it as usually there was a fence along the road and it was not practical, nor possible to obtain permission from landowners to enter their property.) These points were manually moved a relevant distance from the road (20-100m) in the direction recorded where the land cover of interest was located. Additional points were digitised using the Landsat imagery supplemented by colour orthophotos taken in 2009-2011, obtained from the Chief Directorate: National Geo-spatial Information. This included points for those classes not recorded in the field, such as waterbodies, as well as to increase the number of points collected in each class.

Table 3. Final number of ground control points for each class.

Land cover class	Mzimkulu	Duiwenhoks
Built-up - Urban	15	32
Built-up - Rural	58	-
Unvegetated bare ground	42	73
Natural - Forest	17	-
Natural - Wooded/savannah	61	56
Natural - Fynbos	-	181
Natural - Grassland	115	-
Plantation	59	29
Cultivated - Irrigated grains	55	54
Cultivated - Non-irrigated grains	-	167
Cultivated - Sugar cane	60	-
Wetland	59	52
Water	69	91
Total	**610**	**735**

The number of points digitised in the Mzimkulu catchment was 242 and brought the total of points for groundtruthing up to 610. In the Duiwenhoks catchment an additional 601 points were digitised, bringing the total of ground control points to 735

(Table 3). The number of GCP's collected in the field was related to the size of the study sites. Duiwenhoks was smaller and had less roads, as well as more homogenous and bigger land use classes. This meant that collecting more points would have made the effort redundant. However, to sample the whole catchment representatively, including areas inaccessible by road, a large proportion of points were later digitised.

2.3.2 Pre-processing

Landsat imagery was checked to be correctly georeferenced using GPS points and vector data such as roads obtained from the Chief Directorate: National Geo-spatial Information.

In both study sites the imagery was imported into ArcGIS ArcMap 9.3 (ESRI). The imagery for Mzimkulu was first mosaicked and for both sites imagery was subset to fit the respective catchment area.

Besides the individual bands from the Landsat image, other data were also derived. These included NDVI (Normalised Difference Vegetation Index) (Gao 1996; Pettorelli *et al.* 2005), NDWI (Normalised Difference Water Index) (Gao 1996), slope and aspect (both derived from the ASTER DEM). NDVI and NDWI are calculated by the following equations:

NDVI = (band 4 – band 3) / (band 4 + band 3)

NDWI = (band 4 – band 5) / (band 4 + band 5)

where band 3 (red band) = 0.63-0.69 µm; band 4 (near infrared band) = 0.76-0.90 µm and band 5 (near infrared band) = 1.55-1.75 µm.

The NDVI is sensitive to vegetation and clearly indicates healthy/dense vegetation versus unvegetated areas or unhealthy/open vegetation due to the reflectance of the chlorophyll in the leaves picked up by bands 3 and 4 (Gao 1996; Pettorelli *et al.* 2005). NDWI works in much the same way but picks up water and wet areas in contrast to drier areas (Gao 1996).

Spectral signatures of all bands for the most recent images were explored to identify those bands that would be best at picking up the most difference between classes.

2.3.3 Unsupervised classification

The classification method selected was unsupervised classification. This method was chosen over digitising due to the labour-intensive and slow nature of digitising, as well as the fact that the Mzimkulu catchment in particular was extremely heterogeneous and it would have been too time-consuming to digitise manually. It was also preferred to supervised Maximum Likelihood classification as this method requires a greater level of experience in selecting training classes in order to derive an accurate land cover map.

The most recent image was classified first in order to perform an accuracy assessment using the ground control points to select the best band combination. In order to perform the unsupervised classification the ISO Cluster function in Spatial Analyst (ArcGIS 9.3) was used, after which the signature file derived from the ISO Cluster was used in the Maximum Likelihood Classification function in Spatial Analyst (ArcGIS 9.3) to delineate 100 classes. The high number of classes was selected to allow for more options to merge files after classification.

2.3.4 Classification improvement

Some classes were not picked up satisfactorily in this classification approach. In Duiwenhoks urban areas, plantations, wetlands and water, and in Mzimkulu bare ground, rural areas, sugar cane, wetlands and water required improvement. The most apparent problem was that water and shadows were picked up as one class. To rectify this, shadows from each year were extracted from the classification, merged together to create one multitemporal shadow mask for the site, and this total shadow area was masked out in each year. This was to avoid incorrect results in area statistics and change analysis through comparing land cover classes with shadow masks of different years. The disadvantage is that it removes all water too. Therefore, water was then added back into the classification by using the merged polygon layer of dams, perennial pans and the perennial river extent, obtained from the Chief Directorate: National Geo-spatial Information. For this reason the area of water was the same each year and was not used in further land cover analyses.

A wetland layer was available from NFEPA (CSIR 2010b) but this was only used in Mzimkulu as the wetland extent for Duiwenhoks was not accurate and included many irrigated areas and areas that did not seem to fall into wetland based on groundtruthing data and visual examination of the orthophotos.

Rural areas in Mzimkulu were extracted from the National Land Cover (2009) map (SANBI 2009). Urban areas in both sites, plantation in Duiwenhoks and sugar cane in Mzimkulu were digitised using the Landsat images as baseline supplemented by colour orthophotos.

Bare areas were mostly picked up by the classification, but parts of fallow fields were also classed as bare. There was no simple way around this problem as bare areas were too difficult to distinguish visually from non-irrigated fields, and were thus not 'improved' after classification.
All of these additional layers were converted to raster and added to the relevant classifications by using the "Over" function in the Spatial Analyst, Math toolbox (ArcGIS 9.3) to create the final land cover classification maps.

2.3.5 Accuracy assessment

Once the most recent image of each site was classified, points were extracted using the ground control points and the raster created in the classification, as the most recent image coincides best with the date of field work. In this way it could be seen what the point was supposed to be (ground control point) versus what it was classified as (raster value). The number of points was entered into an error matrix to calculate Kappa, overall accuracy, as well as producer and user accuracy for each class. The accuracy assessment was computed as in Congalton & Green (1993). Overall accuracy indicates the probability that a randomly selected point on the map is classified correctly, calculated using the map as a whole. User accuracy indicates the probability of a randomly selected point on the map having the same value in the field, while producer accuracy indicates the probability of a randomly selected point in the field having the same value on the map. Kappa is an accuracy estimation that takes into consideration the number of points per class, which can differ vastly. It puts more weight on the well-represented classes and provides an accuracy value for the map as a whole.

Initially accuracy assessments were carried out to identify which band combinations provided the best classification. After the classification was improved, the accuracy assessment was redone using the ground control points for the 2009 images. For previous years without GCP's, Hawth's Tools (created by Spatialecology.com) was used to generate 250 random points within the extent of the study site. Classes were attributed to these points by visually inspecting where the point fell on the unclassified Landsat imagery. These were then used as ground control points for the classifications of years prior to 2009 for accuracy assessments.

2.3.6 Land cover statistics

Land cover area statistics were extracted for each of the two catchments, as well as for each sub-catchment (sub-catchment delineation is explained in section 2.4.1). For statistical purposes some classes were combined. In the Duiwenhoks catchment irrigated and non-irrigated crops were combined into one cultivated crops class. This was due to difficulty distinguishing between these classes in the different seasons, and although the water usage will be different between these two classes both were under cultivation and both were likely to make use of fertilisers.

In the Mzimkulu catchment the forest class was combined with the plantation class in all cases. Although small patches of natural forest do occur in the catchment according to the accepted vegetation map of South Africa (Mucina & Rutherford 2006), many classified forest patches fell outside these areas where the natural vegetation type is grassland and does not consist of a woody layer. Also, despite the fact that the area's vegetation type was naturally classified as forest, this does not mean that the natural type is still present, as human activities such as forestry would occur in such areas but would not be shown as such on a natural vegetation map. The National Land Cover (2009) did not distinguish between forest and other natural areas and therefore did not assist in identifying where the problem in classification lay. In some areas the forest, wooded and plantation classes were just not possible to distinguish using the unsupervised classification. As many forest pixels fell in and around plantations, it was assumed that the differences that caused the classes to be classified differently could be due to plantations consisting of different tree species, or different stages of growth. Forest was therefore combined with plantation for all analyses. This was possible due to the fact that natural forest in this region has a dense canopy, much like plantations do, and both classes do not have a grassy component like wooded/savannah areas. In all but one sub-catchment (water station 102608) the wooded/savannah class was also dealt with in the same manner and combined with plantation for the same reason, although in this case it was probably mistakenly classified as savannah instead of younger, sparser plantations. In the catchment that feeds station 102608 (and the area downstream) a large area is naturally occurring wooded/savannah. Although some plantation was misclassified as wooded/savannah in this sub-catchment and the Mzimkulu catchment as a whole, the correctly classified pixels outweighed the incorrect ones making it impractical and inaccurate to group wooded/savannah with plantation in this case.

For each of these areas the change in area of land cover classes was tabulated and observed versus expected areas were used in Pearson's chi-square test calculations to determine if the change was significant or not for each class.

2.4 WATER QUALITY DATA

2.4.1 Study design

Sub-catchments were delineated within each of the catchment areas. This was to enable the direct analysis of water quality and flow as measured at the water monitoring stations, compared with only the area of land that fell within each station's watershed. In other words, only the area of land that contributed to the station's water quality values and flow measurements was considered in the calculations for each water monitoring station, as opposed to one value for the whole catchment. This spatial delineation of watersheds within the main catchment area also allowed for the comparison of spatial variability within the catchments.

In order to delineate the watersheds for each of the monitoring stations both scientifically and objectively, ArcHydro Tools (ESRI) was used. Methodology involved using the DEM of the catchment to obtain water flow characteristics for the catchment by calculating flow direction and accumulation, followed by determining stream definition, stream segmentation, delineating sub-catchments and finally watersheds. The result was a polygon depicting the watershed/sub-catchment for each of the DWA water monitoring stations.

These sub-catchments were used for all further analyses. Water quality and flow data already corresponded to these watersheds, and to make the land cover area statistics comparable the area for each land cover type was calculated for each sub-catchment.

2.4.2 Data availability and sampling sites

Although no water quality measurements exist for estuaries, the Department of Water Affairs collects water quality data on most major rivers and dams in South Africa. Data for the study was downloaded from the Resource Quality Services in July 2012 from http://www.dwaf.gov.za/iwqs/wms/data/WMS_pri_txt.asp.

Data are collected from rivers, dams, waste water treatment plants, and boreholes. Duiwenhoks had 12 boreholes with data and Mzimkulu had 99 boreholes, but all of these also only had one data entry each and were discounted from this study.

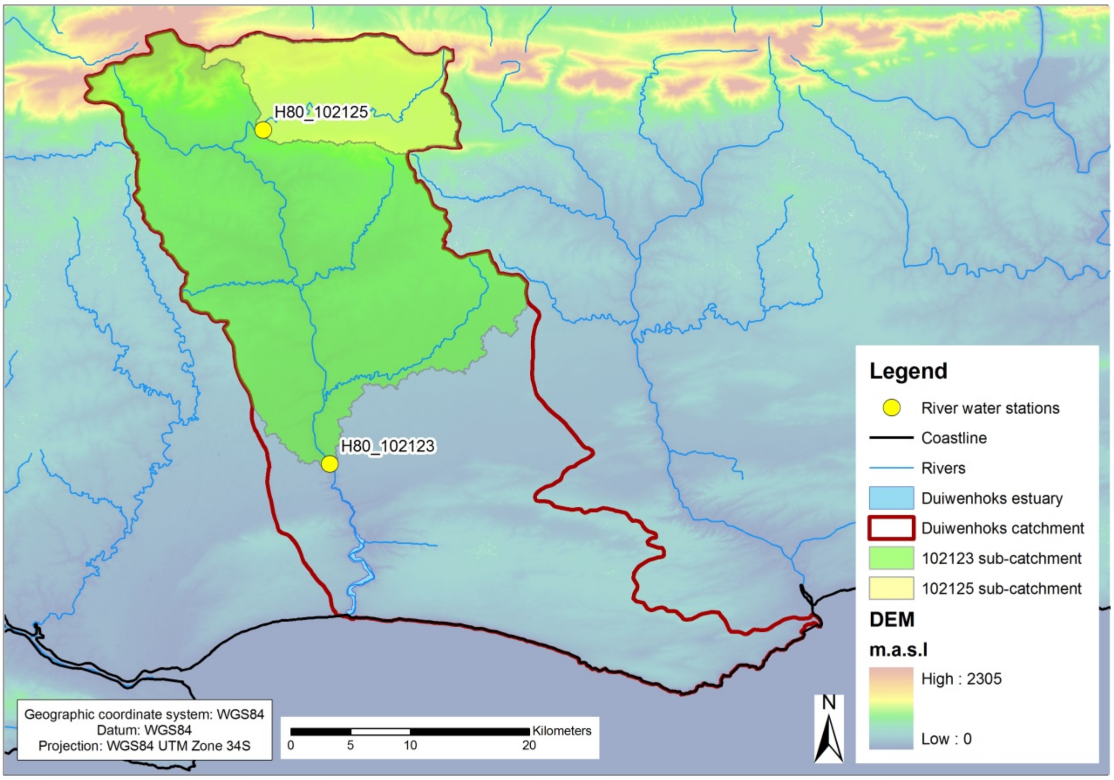


Figure 10. Location of water quality measurement stations in the Duiwenhoks catchment area used in this study. Station numbers are the original identifiers used by the DWAF. (Data source: Rivers – CD:NGI South Africa (2012); Water stations – DWAF (Department of Water Affairs), South Africa; ASTER GDEM – a product of METI and NASA. Sub-catchments created using DEM and ArcHydro Tools, ESRI)

Duiwenhoks has one monitoring site at a dam, with data collected from 1968-1999 (n = 108). There are two waste water treatment sites with data from 2005-2011 (n = 33) and 2004-2011 (n = 36). The four river monitoring sites extend over the following dates: a) 1967-2011 (n = 893), b) 1972-1984 (n = 336), c) 1976-2011 (n = 306) and d) 2008-2011 (n = 62). Only those two that span the whole time frame of the study (a and c above) were of value (Figure 10).

Mzimkulu has one site at a dam with measurements from 1971-1986 (n = 27). As this does not span the period of the study the data were not used. Ten river monitoring sites have data from: a) 1971-2008 (n = 124), b) 1971-2008 (n = 121), c) 1971-2011 (n = 576), d) 1971-2011 (n = 354), e) 1976-2010 (n = 553), f) 1979-1996 (n = 346), g) 1979-1997 (n = 2), h) 1980-1982 (n = 5), i) 2005 (n = 4), and j) 2005 (n = 1). Only those six with data that spans most of the study period (a, b, c, d, e and g) were of use in the study (Figure 11).

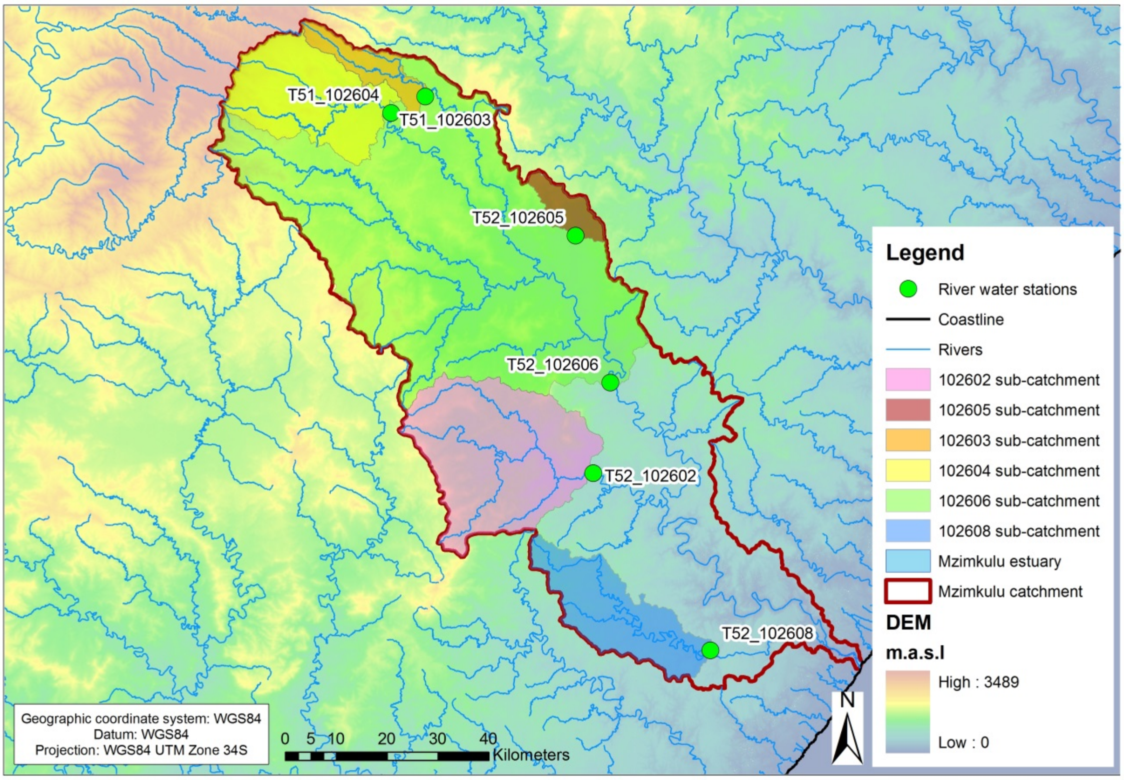


Figure 11. Location of water quality measurement stations in the Mzimkulu catchment area used in this study. Station numbers are the original identifiers used by the DWAF. (Data source: Rivers – CD:NGI South Africa (2012); Water stations – DWAF (Department of Water Affairs), South Africa; ASTER GDEM – a product of METI and NASA. Sub-catchments created using DEM and ArcHydro Tools, ESRI)

Variables measured are shown in Table 4. There is no long-term data on sedimentation or turbidity on any systems in South Africa so these variables cannot be a focus in this study. The variables that have been selected as a focus in the study are dissolved major salts, electrical conductivity, pH and major nutrients, namely phosphate (PO_4), nitrate nitrogen (NO_3) and ammonium nitrogen (NH_4). These ions were selected based on the Environmental Data Analysis (S.a.) which indicates that PO_4 and NO_3 are from sources such as burning vegetation and fertilisers, and high levels of NH_4 can be caused by fertilisers and human and animal waste decomposition.

Table 4. Water quality variables measured by DWA (Department of Water Affairs) (www.dwaf.gov.co.za keyword: Monvar).

Variable name	**Variable type**	**Unit**
Dissolved major salts	Total water	mg/l
Electrical conductivity	Physical measurements	mS/m
pH	Dissolved	pH units
Sodium	Dissolved	mg/l
Potassium	Dissolved	mg/l
Calcium	Dissolved	mg/l
Magnesium	Dissolved	mg/l
Chloride	Dissolved	mg/l
Sulphate	Dissolved	mg/l
Total alkalinity as Calcium carbonate	Dissolved	mg/l
Fluoride	Dissolved	mg/l
Phosphate as Phosphorus	Dissolved	mg/l
Nitrate Nitrogen	Dissolved	mg/l
Ammonium Nitrogen	Dissolved	mg/l
Silicon	Dissolved	mg/l
Sodium adsorption ratio	Dissolved	null

Ancillary data included flow data from the DWA (Department of Water Affairs) (http://www.dwa.gov.za/hydrology), as well as monthly rainfall data for stations closest to each catchment which was obtained from the South African Weather Service (http://www.weathersa.co.za/web/content.asp?contentID=4). Rainfall data was obtained from 1980-2009 where possible, but the weather stations near Duiwenhoks catchment only recorded rainfall data after 1994. Three stations (Shaleburn, Ixopo and Paddock) were used for the Mzimkulu catchment due to its large size and rainfall variability. One rainfall station (Stillbaai) was used in the region of the Duiwenhoks catchment as it was the only one in the proximity of the catchment with enough data.

2.4.3 Data selected

Water quality (chemical) data was downloaded in Microsoft Excel (made by Microsoft, Redmond, USA) format from the DWA website. Data from the selected dates of interest corresponding to the dates of the land cover maps were extracted. For Duiwenhoks the years used in the water quality analysis were 1987, 1990, 2000, 2002 and 2009 for river data. For the Mzimkulu catchment the years used in the analysis were 1984, 1990, 1997, 2002 and 2009.

2.4.4 Data analysis

2.4.4.1 Water quality data

The river monitoring stations had roughly one value taken per month of most or all of the variables shown in the methods (Table 4) as well as a monthly flow value (although some years did have gaps with no data).

Long-term average flow values per month were used in the analysis. These were calculated as the mean for all flow values for each month over the period from July 1967 – June 2012 for Duiwenhoks and November 1956 – June 2012 for Mzimkulu (although there was missing data in some years).

Flow data was compared with rainfall data by comparing the averages over the long term from 1980 – 2009.

To analyse flow data compared with the water quality variables and rainfall, it was necessary to use data from a year where all twelve months had at least flow data and water quality data. The years with data did not correspond across all sub-catchments and did not always correspond with the years used for land cover classification in this study. However dates as close to the classification dates and as close to each other across sub-catchments were selected. Direct comparisons between catchments and even sub-catchments for nutrient export are therefore not possible across the same year.

Areal discharge was calculated using the flow rate per unit catchment area (m^2).

Water quality data was extracted for the years that correspond with the land cover classifications (or in cases where there were no data in those years those as close as possible were selected). For each variable, values were calculated using discharge weighted means, and plotted in graphs along with rainfall to illustrate the relationship between the variables discharged and rainfall.

2.4.4.2 Water quality data related to land cover data

Land cover area values, annual rainfall values and the annual average water quality variable values were used in a simple regression analysis to derive correlation statistics between the land cover type and the water quality variable, as well as between the annual rainfall and the water quality variables. The r-statistic and p-value was derived from the regression analysis for each variable to determine the goodness of fit between the variable and the land cover, or between the variable and rainfall.

Due to the multivariate nature of the data, a multiple linear regression was also used to try to determine the significance of the relationship between the variables in a situation where they are all in play together (where the water quality variable was the dependent variable and the land cover area statistics the independent variables) (Zampella *et al.* 2002; The Cadmus Group Inc. 2010). The method used the Least Squares method to fit a line through the set of observations to best explain the regression.

CHAPTER 3
RESULTS

3.1 CLASSIFICATION AND ACCURACY ASSESSMENTS

3.1.1 Classification

The resulting classification for 2009 for the two study sites is shown in Figures 12 and 13. These are the maps that were compared with the ground control points from the fieldwork to determine map accuracy.

Duiwenhoks was covered by a majority of fynbos and non-irrigated grains, with small patches of the remaining land cover types. The white areas on the maps are where the shadow mask was removed from the classification.

Mzimkulu had a more heterogeneous land cover, with a majority of grassland and large patches of plantation, forest and wooded/savannah. Sugar cane covered a large area near the coast. Again, white areas (shadow) were removed from the classification.

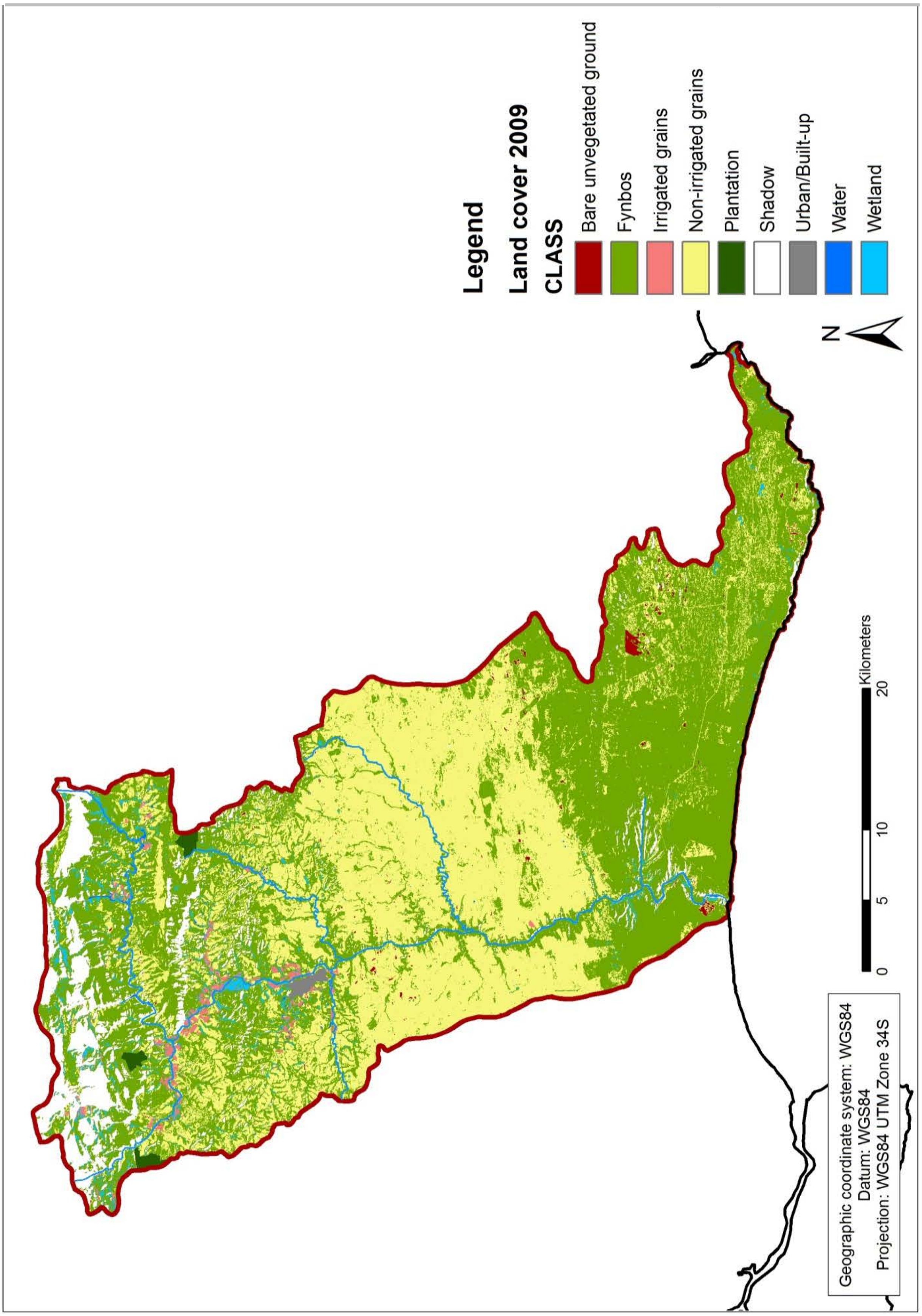


Figure 12. Result from the unsupervised land cover classification for the Duiwenhoks catchment area (2009).

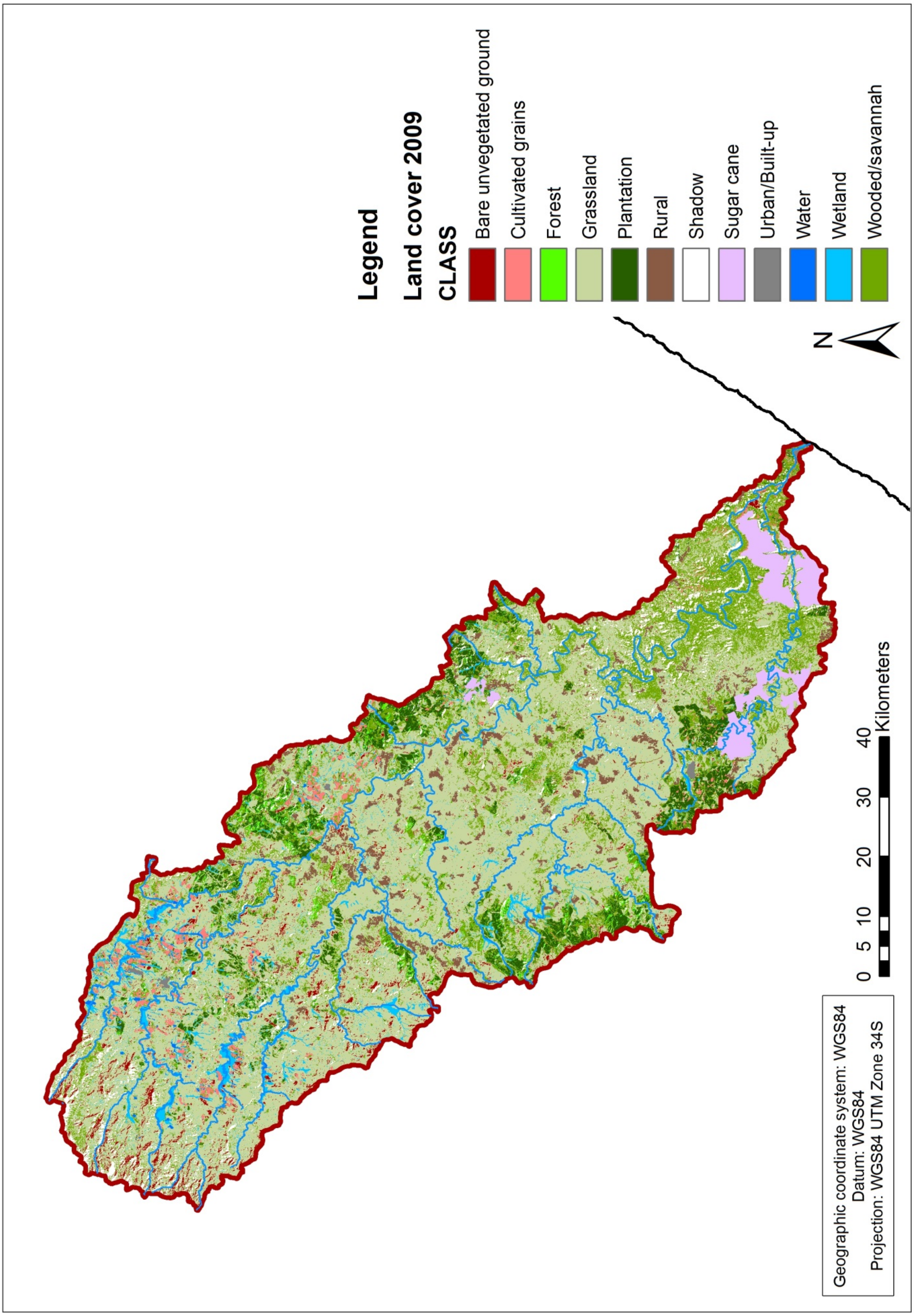


Figure 13. Result from the unsupervised land cover classification for the Mzimkulu catchment area (2009).

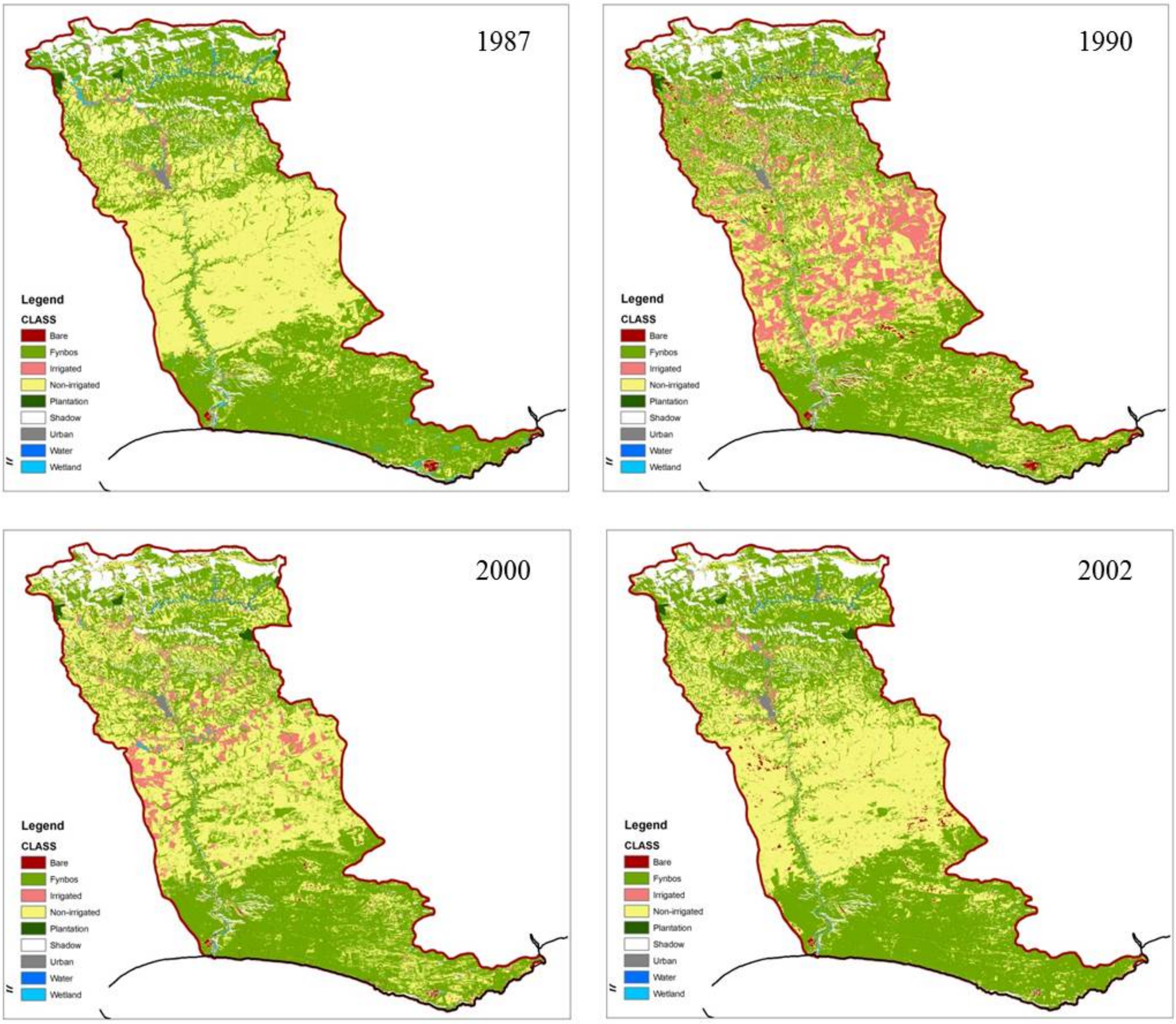


Figure 14. Result from the unsupervised land cover classification for the Duiwenhoks catchment area showing change over time from a) 1987, b) 1990, c) 2000 and d) 2002.

Land cover change over time shows the most visible change between 1987, 1990 and 2000 where the irrigated crops cover a very large area (Figure 14). This is due to the fact that those images were taken in a different season when more of the non-irrigated fields had crops in the growing phase and therefore had the same spectral signature as an irrigated field. This is in contrast to 1987 and 2002 where the non-irrigated fields were not vegetated as the image was taken outside of the growing season. What appears to be a large area of irrigated fields is therefore not a true picture of reality, as those are merely rain-fed grains when they are in the growing phase, making them look spectrally like irrigated grains. This means that the actual area of irrigated grains along the river in the north did not change much in area at all, and thus the amount of water flowing into the system from irrigated grains is firstly minimal, and secondly did not change much over time. Due to the incorrect classification of irrigated fields because of seasonal changes in the imagery, the irrigated and non-irrigated crops were combined for all further analyses.

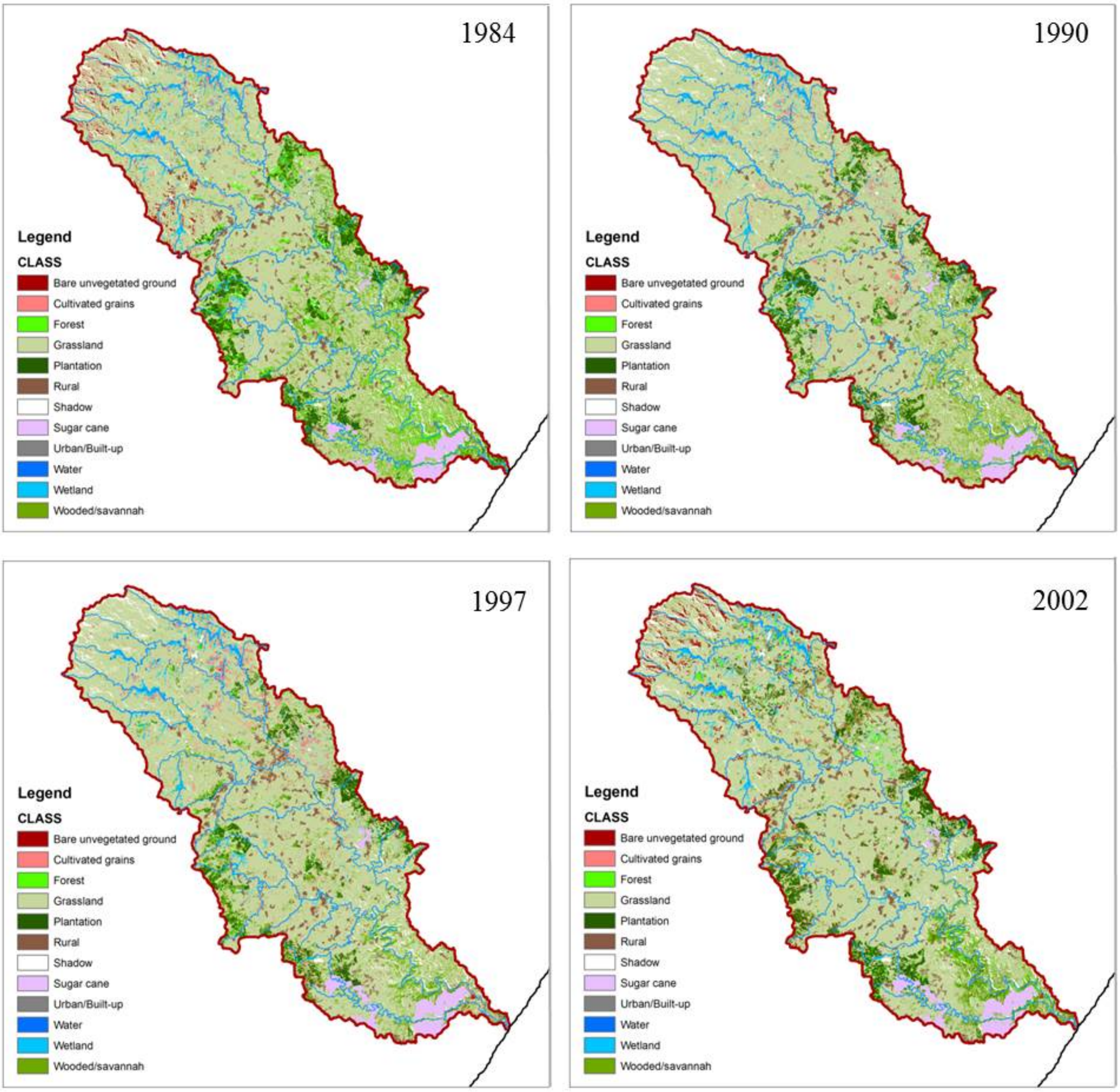


Figure 15. Result from the unsupervised land cover classification for the Mzimkulu catchment area showing change over time from a) 1984, b) 1990, c) 1997 and d) 2002.

The most visible change in Mzimkulu is the change in ‘wooded’ areas – plantation, forest and savannah while most of the other classes remained more or less the same (Figure 15).

3.1.2 Accuracy assessments

Visually, the 2009 classification was good and it picked up small areas of different land cover classes in valleys and other such areas (Figure 16).

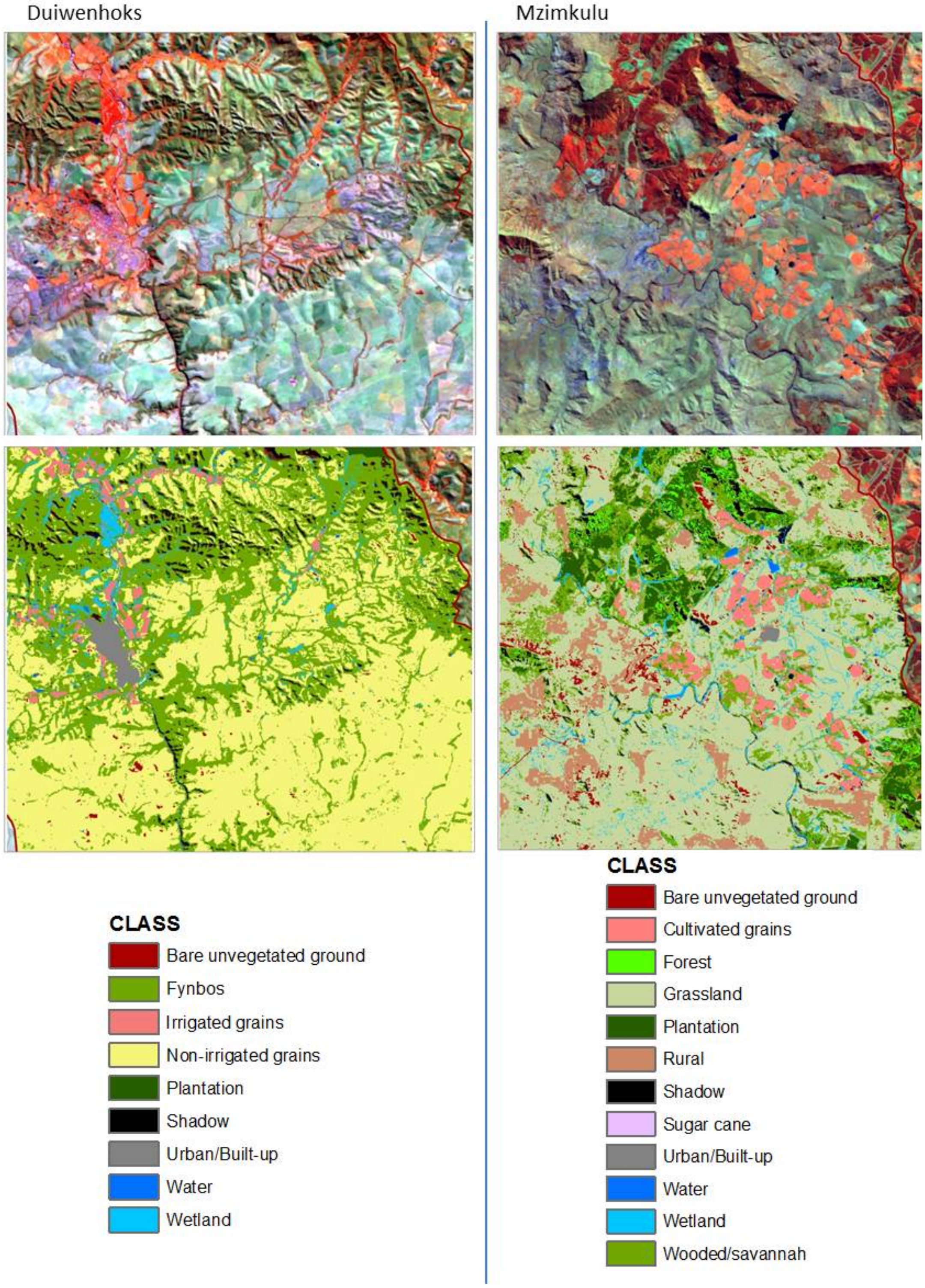


Figure 16. The Landsat image above and the land cover classification below, of a subset of the Duiwenhoks catchment area on the left (29/04/2009), and Mzimkulu catchment area on the right (12-19/05/2009).

Here the classification is shown for Mzimkulu with forest, plantation and wooded/savannah classes separate, although as described in Chapter 2 for statistical purposes the forest and plantation classes were always combined, and in all but one sub-catchment where savannah is prevalent, the wooded/savannah class was normally also combined with plantation. The reason can be observed in Figure 16, where it is evident that plantation has been misclassified as forest or wooded/savannah. Red tones in the Landsat images indicate healthy, growing vegetation, blue-white tones indicate bare soil or fallow fields, green tones indicate natural vegetation which reflects less chlorophyll – in this case evergreen fynbos. Black tones indicate water or shadow.

Map accuracy is assessed in an error matrix such as the one below for Mzimkulu (Table 5). The error matrix indicates the number of points in each class from the ISO cluster relative to the actual class found at the point in the field to determine how accurate the classification is. User accuracy indicates the probability of a randomly selected point having the same value in the field, and producer accuracy indicates the probability of a randomly selected point in the field having the same value on the map (Congalton 1991).

Table 5. Map accuracy error matrix for Mzimkulu.

		Ground truth reference points												
ISO cluster classes at ground reference points	Class	Bare	Forest	Grains	Grassland	Plantation	Sugar cane	Urban	Rural	Wooded	Water	Wetland	**TOTAL**	User's accuracy (%)
	Bare ground	14		4	6				1				**25**	56.0
	Forest		5			5				5			**15**	33.3
	Grains			27						5			**32**	84.4
	Grassland	19		20	102			1	12	3	1	2	**160**	63.8
	Plantation		2			42	1			5			**50**	84.0
	Sugar cane						59				2		**61**	96.7
	Urban							14					**14**	100
	Rural	5			1	1			44			1	**52**	84.6
	Wooded	3	6	3	2	10				35	15	1	**75**	46.7
	Water										33	7	**40**	82.5
	Wetland			1	4						1	48	**54**	88.9
	TOTAL	**41**	**13**	**55**	**115**	**58**	**60**	**15**	**57**	**53**	**52**	**59**	**578**	
	Producer's accuracy (%)	34.1	35.8	49.1	88.7	72.4	98.3	93.3	77.2	66.0	63.5	81.4		**73.18**

Overall accuracy takes all the points into account as a whole, instead of calculating the accuracy per class. It therefore indicates the accuracy of the classified map as a whole. Ideally the Overall accuracy (in this case 73.18%) should be as high as possible. Table 6 shows the overall accuracy and Kappa values for all classifications. Kappa is also a measure of accuracy for the whole map, but it takes the number of points per class into consideration, giving more weight to the well-represented classes.

The accuracy for Duiwenhoks is lower than that of Mzimkulu, but the accuracy for Mzimkulu is good with all but one value above 82%. The Kappa values were also satisfactory and the classification was considered good enough to continue as changes made to attempt to increase the accuracy had a negligible effect (Table 6).

Table 6. Map accuracy for all classifications used in the study.

Duiwenhoks			**Mzimkulu**		
	Overall accuracy (%)	Kappa	Year	Overall accuracy (%)	Kappa
1987	78.4	0.5883	**1984**	84.7	0.6941
1990	67.4	0.4962	**1990**	84.0	0.7022
2000	74.7	0.5607	**1997**	82.9	0.6081
2002	82.6	0.6627	**2002**	84.5	0.7282
2009	73.4	0.6646	**2009**	73.2	0.6950

The Kappa values are noticeably lower than the overall accuracy, which is unusual as they are normally in the same range. This is due to the fact that the Kappa takes the individual classes into account, and the classifications had one or two classes that consistently had very low accuracy values, such as the bare, forest, cultivated grains and wooded/savannah classes in Mzimkulu (Table 5) which brought the total value down.

3.2 AREA STATISTICS

The area each land cover class occupied in each year was calculated to identify trends in land cover change for Duiwenhoks (Table 7) and Mzimkulu (Table 8).

Table 7. Area statistics for Duiwenhoks (in %). Pearson's chi-square p-value and its related level of significance (* = p < 0.05 (significant), ** = p < 0.01 (highly significant), and *** = p < 0.001 (very highly significant)).

	1987	**1990**	**2000**	**2002**	**2009**	**Chi-square significance**	
Sub-catchment 102125 (Upstream							
Bare ground	0.00	1.07	0.64	0.05	0.07	0.469	
Fynbos	60.35	54.10	48.02	57.84	55.58	0.641	
Combined crops	12.66	18.75	25.42	16.51	14.78	0.108	
Plantation	0.32	0.21	0.44	0.14	0.14	0.985	
Sub-catchment 102123 (Downstream)							
Bare ground	0.02	0.91	0.56	0.65	0.15	0.060	
Fynbos	38.59	41.10	35.72	38.50	38.74	0.571	
Combined crops	46.98	43.78	49.67	47.16	45.23	0.527	
Plantation	0.55	0.45	0.66	0.60	0.74	0.961	
Urban	0.32	0.32	0.35	0.35	0.35	1.000	
Whole catchment							
Bare ground	0.36	1.31	0.68	0.83	0.41	0.036	*
Fynbos	51.17	50.55	47.98	52.64	53.36	0.845	
Combined crops	46.92	46.92	47.26	45.75	43.85	0.707	
Plantation	0.34	0.27	0.40	0.36	0.45	0.962	
Urban	0.19	0.19	0.21	0.21	0.21	1.000	

Duiwenhoks:

One significant change in land cover was found in the Duiwenhoks catchment. In the catchment as a whole bare ground was found to change significantly (X^2_4 = 10.292, $p < 0.05$), and it was marginally significant in the downstream sub-catchment. It was at its highest in 1990 and 2002. None of the other land cover classes showed a significant change between observed and expected.

Mzimkulu:

The catchment as a whole shows significant changes in all land cover types except urban, despite urban having increased steadily, although only slightly, over time. Rural areas increased highly significantly (X^2_4 = 14.154, $p < 0.01$) with a steady increase from 1984 to 2009, with the highest increase occurring between 1990 and 1997. The remainder of the classes showed a very highly significant change ($p < 0.001$) (Table 8).

Table 8. Area statistics for Mzimkulu (in %). Pearson's chi-square p-value and its related level of significance (* = p < 0.05 (significant), ** = p < 0.01 (highly significant), and *** = p < 0.001 (very highly significant)).

	1984	1990	1997	2002	2009	Chi-square significance	
Sub-catchment 102604 (Upstream)							
Bare ground	4.96	0.03	0.36	7.95	6.81	5.19×10^{-14}	***
Cultivated grains	3.32	0.89	1.23	1.36	2.49	0.023	*
Grassland	73.59	82.09	80.99	70.37	63.28	0.002	**
Plantation	2.35	1.27	1.67	3.96	10.32	5.28×10^{-15}	***
Rural	10.61	10.55	10.52	10.62	10.76	1.000	
Sugar cane	0.00	0.00	0.00	0.55	0.00	0.023	*
Sub-catchment 102603 (Upstream)							
Bare ground	3.29	0.05	0.52	9.43	4.97	0.0002	***
Cultivated grains	3.85	1.72	2.70	2.43	4.20	0.739	
Grassland	66.37	73.10	70.75	57.83	51.92	0.141	
Plantation	3.86	2.03	2.74	6.51	14.33	0.0001	***
Rural	0.54	0.12	0.12	0.11	0.11	0.909	
Sugar cane	0.00	0.00	0.00	0.49	0.00	0.598	
Urban	0.00	0.97	0.97	1.14	1.14	0.823	
Sub-catchment 102605 (Midstream)							
Bare ground	0.09	0.12	0.66	0.31	1.52	0.628	
Cultivated grains	1.47	2.86	3.18	0.79	1.56	0.725	
Grassland	49.79	55.31	62.56	46.22	32.89	0.042	*
Plantation	36.44	25.49	16.98	35.76	48.63	0.002	**
Rural	2.48	5.98	5.93	5.92	5.95	0.768	
Sugar cane	0.00	0.00	0.00	1.26	0.00	0.282	
Sub-catchment 102606 (Midstream)							
Bare ground	2.47	0.18	0.85	3.29	3.71	1.79×10^{-33}	***
Cultivated grains	1.67	3.11	3.33	1.52	2.63	4.94×10^{-8}	***
Grassland	74.93	80.00	77.02	72.65	63.44	1.03×10^{-15}	***
Plantation	9.62	5.27	7.29	10.51	17.58	3.73×10^{-66}	***
Rural	2.45	2.53	2.54	2.54	2.55	0.999	
Sugar cane	0.00	0.00	0.00	0.53	0.00	1.18×10^{-15}	***
Urban	0.04	0.11	0.11	0.12	0.13	0.810	
Sub-catchment 102602 (Midstream)							
Bare ground	0.28	0.06	0.80	0.53	1.22	0.016	*
Cultivated grains	0.40	2.17	0.99	0.21	0.45	3.23×10^{-5}	***
Grassland	62.08	71.85	70.41	68.55	61.24	0.016	*
Plantation	71.86	76.65	80.29	75.99	79.72	1.04×10^{-7}	***
Rural	2.81	2.83	2.85	2.85	2.86	1.000	
Sugar cane	0.00	0.00	0.00	0.86	0.00	5.58×10^{-6}	***

Sub-catchment 102608 (Downstream)							
Bare ground	0.00	0.13	0.41	0.18	0.44	0.636	
Cultivated grains	0.19	1.39	2.32	2.20	1.97	0.096	
Grassland	44.39	53.78	54.45	47.14	34.73	0.0001	***
Plantation	22.85	14.77	11.68	17.97	15.30	0.001	***
Rural	2.96	3.03	3.57	3.59	3.57	0.973	
Sugar cane	8.89	8.89	13.18	14.97	16.89	0.002	**
Urban	0.43	0.62	0.62	0.62	0.75	0.985	
Wooded/savannah	16.72	13.87	10.33	9.96	22.71	2.55×10^{-6}	***
Whole catchment							
Bare ground	1.46	0.16	0.76	1.99	2.53	1.71×10^{-27}	***
Cultivated grains	1.16	2.38	2.59	1.72	2.03	2.38×10^{-11}	***
Grassland	67.50	74.57	74.73	68.88	59.72	2.46×10^{-116}	***
Plantation	11.04	6.46	6.01	8.71	6.83	3.92×10^{-51}	***
Rural	2.88	2.96	3.24	3.28	3.28	0.007	**
Sugar cane	2.36	2.40	2.71	3.83	2.93	1.89×10^{-7}	***
Urban	0.09	0.14	0.14	0.16	0.17	0.730	
Wooded/savannah	10.76	8.22	7.04	8.68	18.91	1.58×10^{-77}	***

The sub-catchments are likely to provide a better view of changing land use as they are smaller areas and are not as affected by the possible misclassification of the wooded/savannah class. Both upstream sub-catchments showed a very highly significant change in bare ground and plantation ($p < 0.001$, df = 4), both of which increased over time. Grassland also changed highly significantly in sub-catchment 102604 ($X^2_4 = 16.88$, $p < 0.01$) which showed an increase from 1984 to 1990 and then a sharp decrease to 2009. Cultivated grains and sugar cane showed a significant change ($p < 0.05$, df = 4) in this sub-catchment with a decrease in cultivated grains in 1990 followed by a steady increase. 2002 was the only year in which sugar cane featured in the upper sub-catchments.

The mid sub-catchments showed a shared significant change in grassland and plantation. If sub-catchment 102605 is excluded due it its small size and relatively small area, shared classes that showed significant change in the remaining mid-catchments include bare ground, cultivated grains and sugar cane (Table 8).

The lower sub-catchment indicated a highly significant steady increase in sugar cane ($X^2_4 = 29.718$, $p < 0.01$), and very highly significant changes in grassland, plantations and wooded/savannah (Table 8).

3.3 RAINFALL

The annual rainfall for each year from the start to end of the study period (where available) was plotted on a graph along with the region's annual average rainfall over the same time period (Figures 17 and 18).

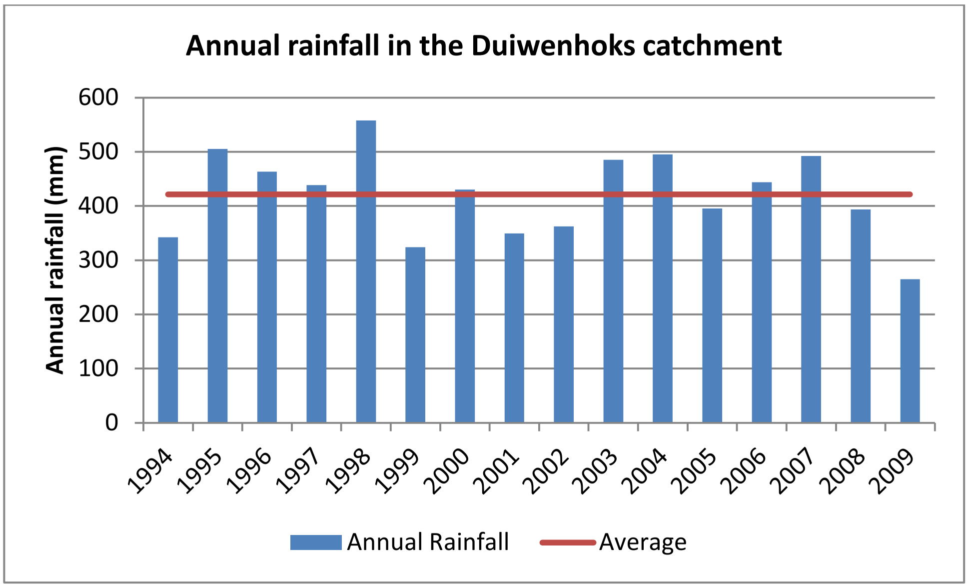


Figure 17. The annual rainfall in the Duiwenhoks catchment over the study period. Data were not available prior to 1994.

Mzimkulu was divided into three rainfall regions corresponding with the upper, mid and lower catchment (Figure 18). The average annual rainfall in the upper catchment was 1054.8 mm, in the mid catchment 770.1 mm and in the lower catchment 1165.1 mm.

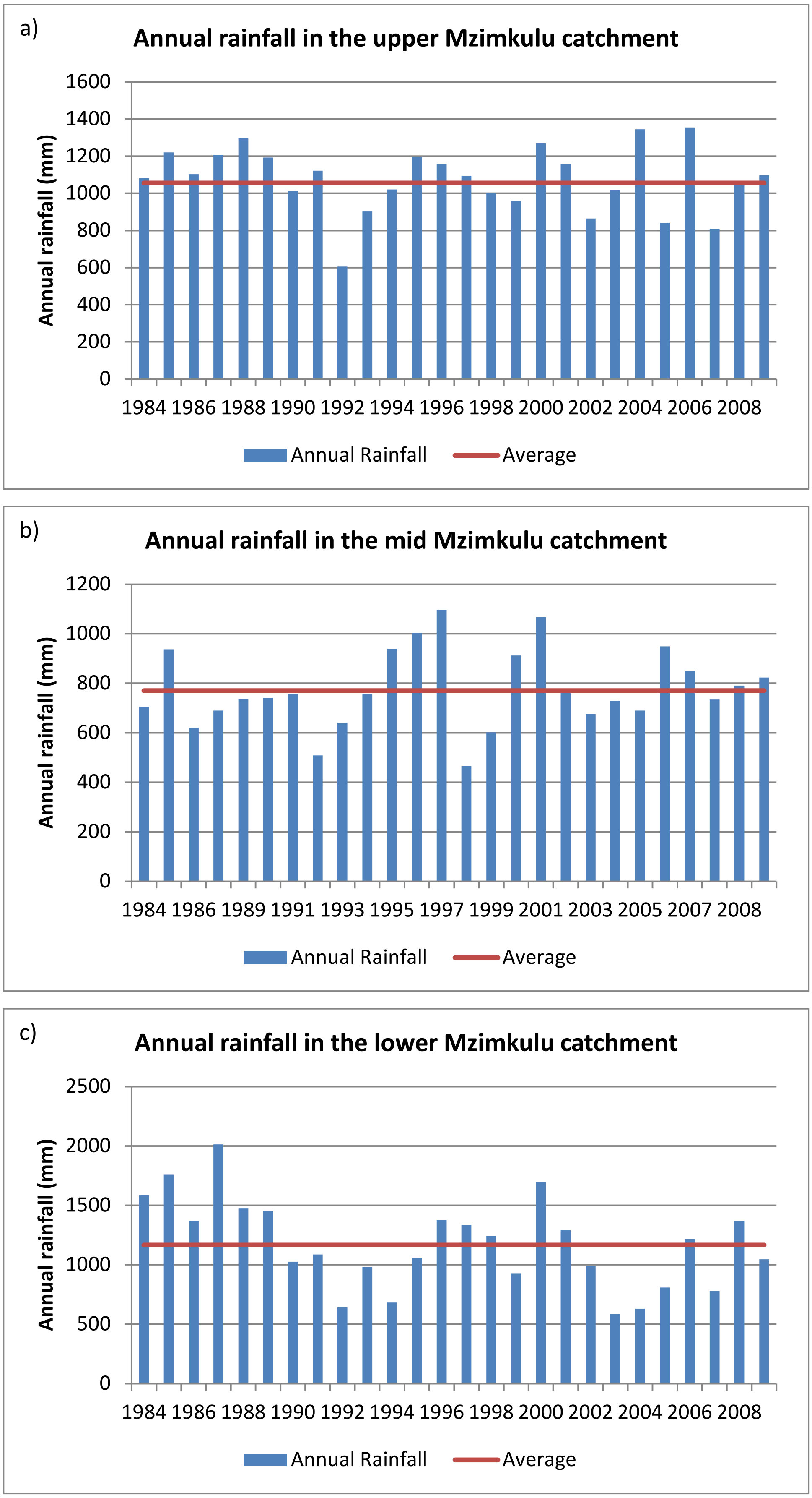


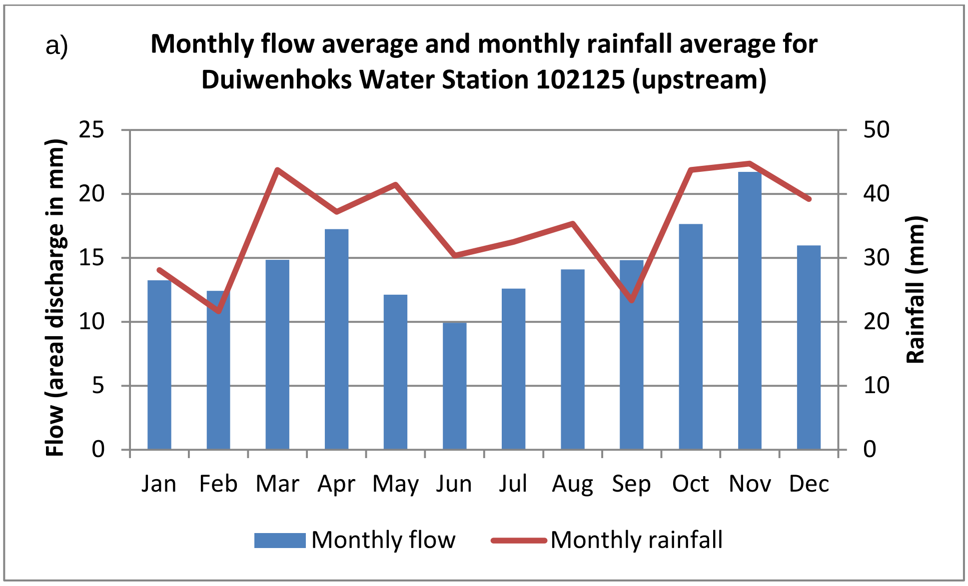
Figure 18. The annual rainfall in the Mzimkulu catchment over the study period a) upper, b) mid and c) lower catchment.

3.4 WATER QUALITY

The long-term monthly average flow data for the catchments indicate that the Duiwenhoks catchment illustrates a peak around March and April and another between October and December (Figure 19) and Mzimkulu has a definite peak in the summer months (Figure 20). These flow rates are comparable with the rainfall patterns in these catchment areas.

The flow rate between the two sub-catchments in Duiwenhoks differs with a higher flow rate recorded in the steeper, smaller upper sub-catchment (102125). Although the values differ, the pattern is almost identical from one month to the next.

In the Mzimkulu catchment a similar trend is evident. Flow rates have an almost identical pattern across the months, although the downstream station indicated a relatively higher flow in winter (June – November) than the other stations higher upstream. The flow rate values decrease as one moves from upstream to downstream. The rainfall pattern in the three areas is similar, although in the lower catchment the dip in winter is not as low.



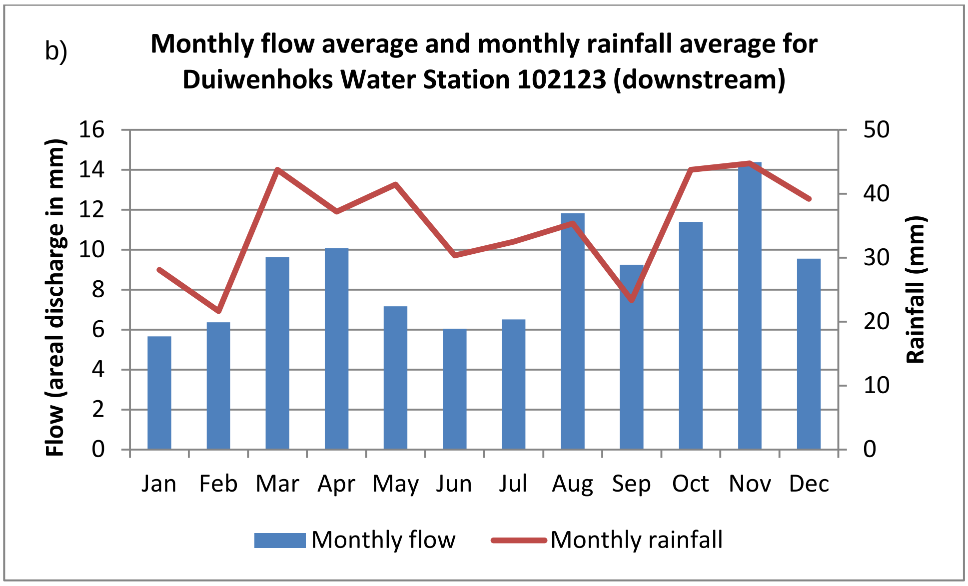


Figure 19. The areal discharge monthly flow rate (in cubic meters/km^2) for Duiwenhoks in the two sub-catchments a) upstream and b) downstream. Flow average was calculated from n = 41-43 values per month, depending on the year in a), and n = 44 - 45 values per month for b).

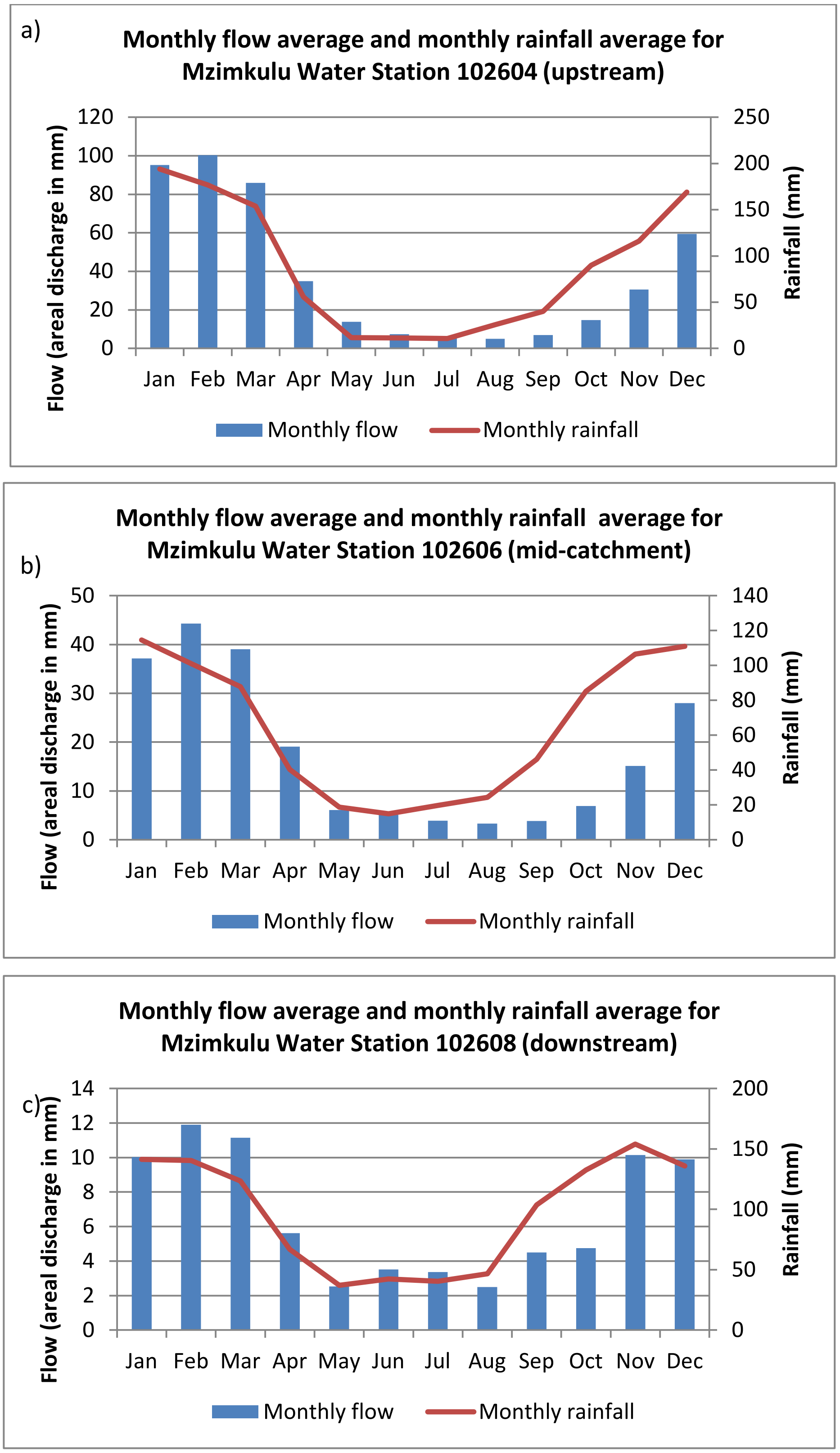


Figure 20. The areal discharge monthly flow rate (in cubic meters/km^2) for Mzimkulu in a sub-catchment that is representative of a) upstream, b) mid-catchment and c) downstream. Flow average was calculated from n = 62 - 63 values per month, depending on the year in a), and n = 33 values per month for b), and n = 41 - 42 values per month for c).

The relationship between dissolved major salts and flow rate in the form of areal discharge was explored for the sub-catchments. All other nutrients in all sub-catchments were analysed in the same way and it was found that all followed the same trend and closely corresponded with flow rates.

3.4.1 Temporal and spatial water quality results

The averaged values of the selected variables were compared over time for each sub-catchment (Figures 21 - 22). In Duiwenhoks' upper sub-catchment (102125) the electrical conductivity decreased with reducing rainfall but showed a spike in 2009 in the driest year. The pH value also increased in 2009. In the lower sub-catchment (102123) electrical conductivity values are a lot higher and also increased drastically between 2001 and 2009. The pH showed the same trend although the values were a bit higher in this sub-catchment. Phosphorus and ammonium nitrogen remained fairly level throughout the study period in both sub-catchments (although phosphorus did increase in 2001 right after the year where crops and plantations were highest, and ammonium nitrogen was highest in 1990 when bare ground was at its highest). Nitrates showed a sharp increase between 2001 and 2009 in the upper sub-catchment but a peak in 2000 and 2001 in the lower sub-catchment. (Figure 21).

In Mzimkulu's upper catchment, the sub-catchments showed a general increase in electrical conductivity with a light dip in 2002 and a peak in 2009. The pH values increased over time from 1982 to 2009. Phosphates and ammonium nitrogen remained fairly level throughout in both sub-catchments, while nitrates varied greatly with highs in 1982 and 1999, and dips in 1993, 2002 and 2009 (Figure 22). These peaks and dips could not be attributed to a change in land cover.

The mid and lower sub-catchments of Mzimkulu unfortunately have less available data and it was deemed that there was not enough for comparative purposes across years.

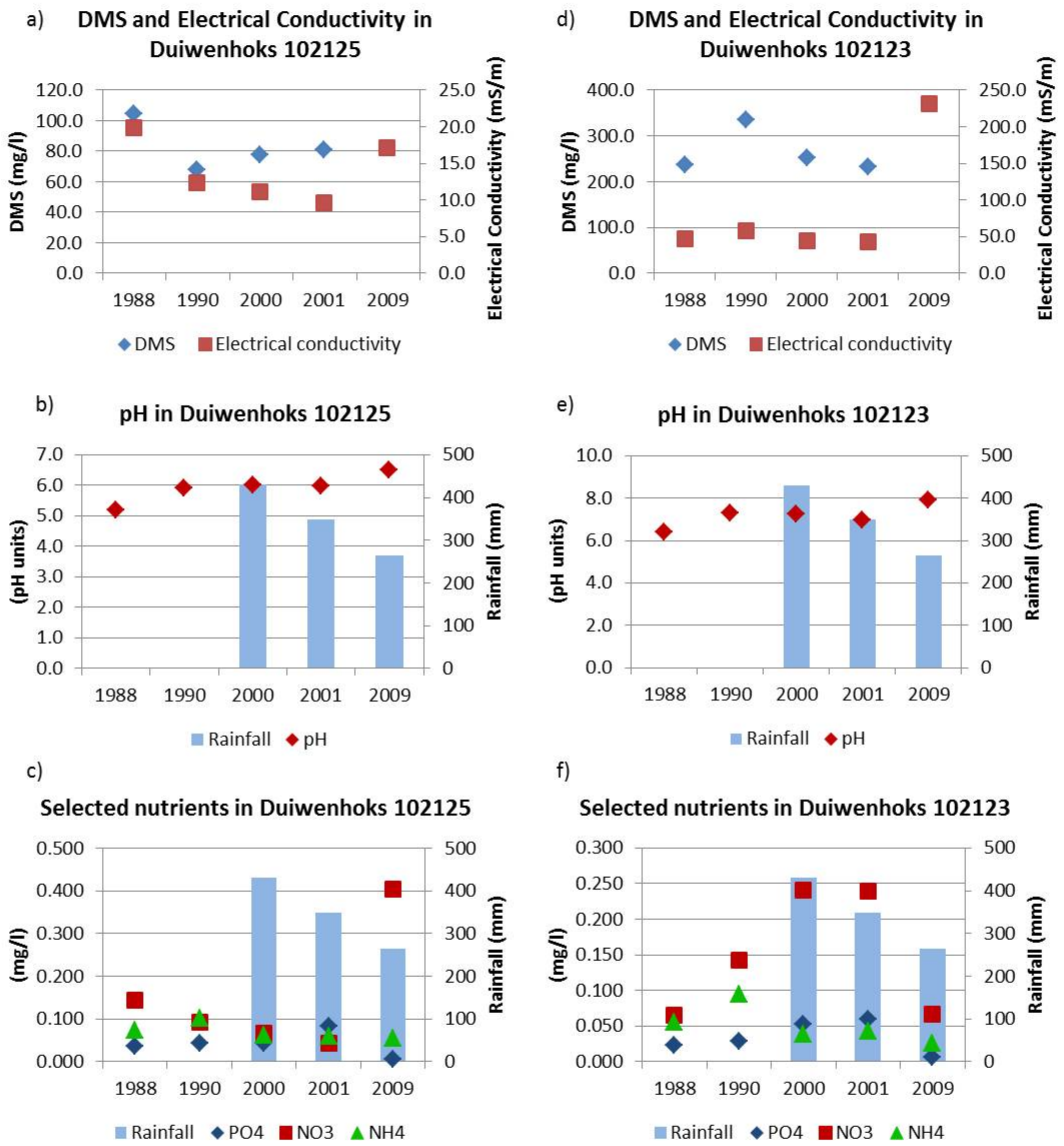


Figure 21. The two sub-catchments of Duiwenhoks showing selected water quality variables compared over time. DMS = Dissolved Major Salts. a) to c) show values for sub-catchment 102125 (upper sub-catchment) and d) to f) show values for sub-catchment 102123 (lower sub-catchment).

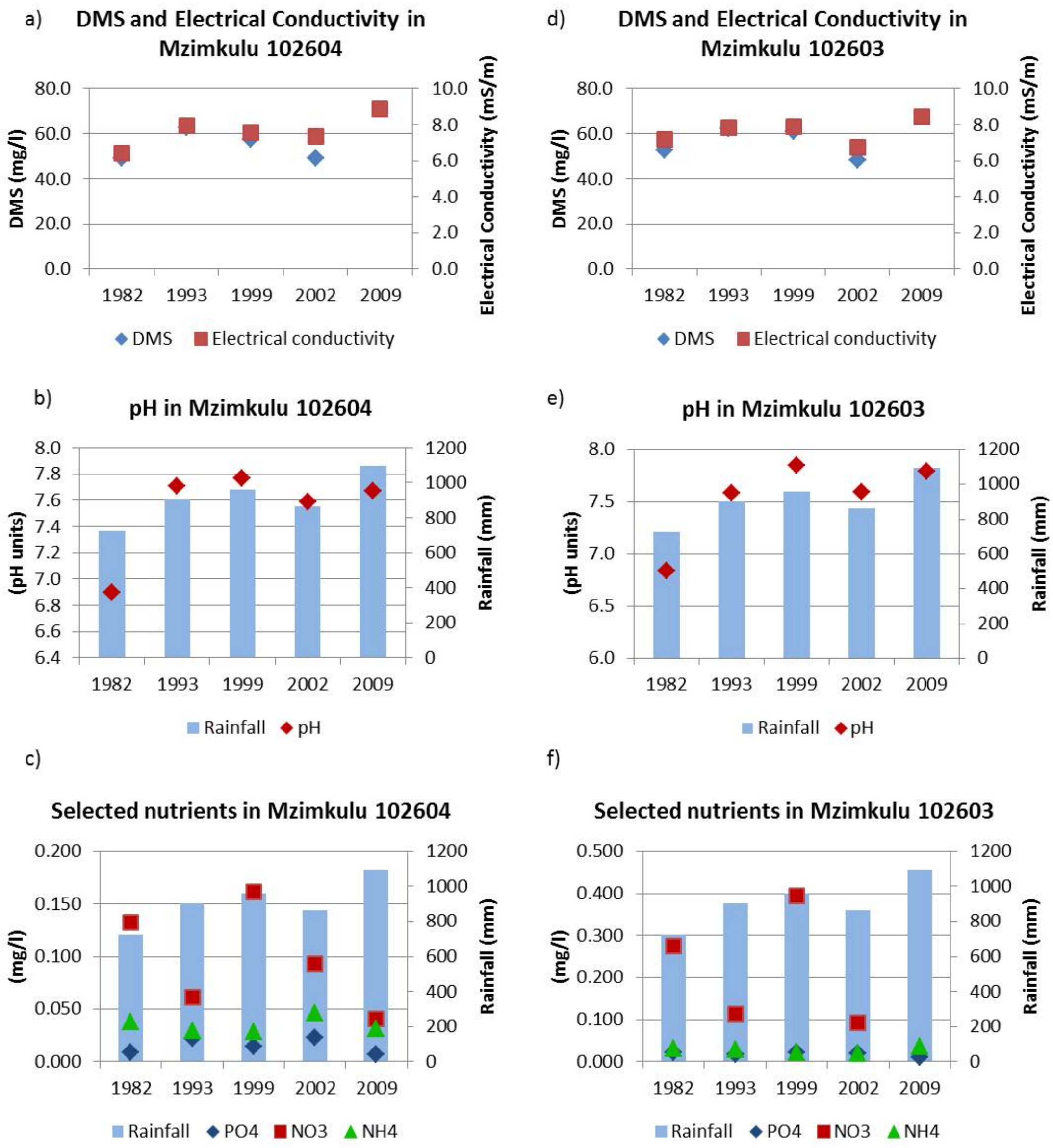


Figure 22. The two upper sub-catchments of Mzimkulu showing selected water quality variables compared over time. DMS = Dissolved Major Salts. a) to c) show values for sub-catchment 102604 and d) to f) show values for sub-catchment 102603.

3.4.2 Correlations between water quality and land cover

One way to compare the correlation between a water quality variable and the land cover of the time is with a regression analysis (Table 9).

All of the significant correlations are positive. Electrical conductivity and ammonium nitrogen increased significantly ($p < 0.05$) with an increase in fynbos, cultivated crops, plantations and urban areas in Duiwenhoks and electrical conductivity increased with wooded/savannah, sugar cane and rural areas in Mzimkulu (Table 9). Phosphates increased significantly with an increase in plantations in Mzimkulu. No other relationships with phosphates or ammonium nitrogen were found, nor with nitrates in both catchments.

Table 9. Correlation regression statistics between land cover classes and selected variables for Duiwenhoks and Mzimkulu.

	EC		PO_4		NO_3		NH_4	
	Duiw.	Mzim.	Duiw.	Mzim.	Duiw.	Mzim.	Duiw.	Mzim.
Grassland	-	0.216 *(0.323)*	-	0.124 *(0.574)*	-	0.257 *(0.237)*	-	0.150 *(0.495)*
Natural – Fynbos / Wooded	0.673* *(0.033)*	0.494* *(0.017)*	0.351 *(0.321)*	0.064 *(0.771)*	0.035 *(0.925)*	0.097 *(0.661)*	0.749* *(0.013)*	0.057 *(0.795)*
Bare unvegetated ground	0.481 *(0.160)*	0.140 *(0.524)*	0.096 *(0.792)*	0.063 *(0.089)*	0.298 *(0.404)*	0.229 *(0.293)*	0.234 *(0.515)*	0.051 *(0.817)*
Cultivated crops	0.743* *(0.014)*	0.211 *(0.334)*	0.247 *(0.492)*	0.216 *(0.322)*	0.075 *(0.837)*	0.248 *(0.254)*	0.732* *(0.016)*	0.109 *(0.620)*
Plantation	0.757* *(0.011)*	0.051 *(0.818)*	0.251 *(0.484)*	0.476* *(0.022)*	0.022 *(0.952)*	0.123 *(0.576)*	0.762** *(0.010)*	0.140 *(0.523)*
Sugar cane	-	0.519* *(0.011)*	-	0.043 *(0.845)*	-	0.110 *(0.619)*	-	0.068 *(0.759)*
Rural	-	0.404* *(0.056)*	-	0.003 *(0.991)*	-	0.393 *(0.064)*	-	0.243 *(0.263)*
Urban	0.727* *(0.017)*	0.208 *(0.342)*	0.282 *(0.430)*	0.375 *(0.078)*	0.041 *(0.910)*	0.134 *(0.543)*	0.756* *(0.011)*	0.088 *(0.691)*

EC is Electrical Conductivity. Water quality values used are the overall average of all data points in the relevant years and adjusted for flow and area, regressed against land cover areas. (The r statistic is shown along with the significance level (*=0.05, **=0.01). The p-values are shown in brackets. Significant cells are shaded. For Duiwenhoks df = 8 and for Mzimkulu df = 21)

Comparing correlations between water quality variables and rainfall, no relationships were found in Mzimkulu and only one significant relationship was observed in Duiwenhoks, between rainfall and phosphates ($F_{1,4}$ = 20.898, p = 0.01).

Table 10. Multivariate regression statistics between land cover classes and selected variables for Duiwenhoks and Mzimkulu.

	EC		PO_4		NO_3		NH_4	
	Duiw.	Mzim.	Duiw.	Mzim.	Duiw.	Mzim.	Duiw.	Mzim.
Adjusted R^2 value	0.527	0.219	0.856	0.444	0.380	-0.124	0.775	-0.204
F-stat and (significance)	3.004 *(0.154)*	1.773 *(0.167)*	11.713 *(0.017)* *	3.197 *(0.028)* *	2.101 *(0.246)*	0.696 *(0.690)*	7.207 *(0.039)* *	0.534 *(0.813)*
Intercept	-0.893	0.859	-0.005	0.002	0.040	0.035	-0.009	0.024
Grassland	-	-0.0001 *(0.838)*	-	-0.0000 *(0.070)*	-	-0.0000 *(0.725)*	-	0.0000 *(0.757)*
Natural – Fynbos / Wooded	0.007 *(0.814)*	-0.007 *(0.810)*	0.0000 *(0.869)*	0.0000 *(0.609)*	-0.0004 *(0.152)*	-0.001 *(0.302)*	0.0001 *(0.181)*	0.001 *(0.671)*
Bare unvegetated ground	0.330 *(0.251)*	0.002 *(0.845)*	0.002 *(0.008)* **	0.0000 *(0.264)*	0.001 *(0.593)*	0.0001 *(0.694)*	0.002 *(0.037)* *	0.0002 *(0.761)*
Cultivated crops	0.042 *(0.177)*	0.0006 *(0.975)*	0.0001 *(0.007)* **	0.0000 *(0.694)*	0.0002 *(0.290)*	0.0009 *(0.297)*	0.0002 *(0.041)* *	-0.001 *(0.458)*
Plantation	1.920 *(0.256)*	0.0009 *(0.629)*	0.007 *(0.029)* *	0.0000 *(0.019)* *	-0.007 *(0.590)*	-0.0000 *(0.731)*	0.008 *(0.086)*	-0.0000 *(0.600)*
Sugar cane	-	0.038 *(0.520)*	-	-0.0000 *(0.561)*	-	0.003 *(0.221)*	-	-0.004 *(0.442)*
Rural	-	-0.015 *(0.262)*	-	-0.0000 *(0.591)*	-	-0.0007 *(0.130)*	-	-0.0003 *(0.751)*
Urban	-8.85 *(0.279)*	0.133 *(0.672)*	-0.039 *(0.019)*	0.0008 *(0.453)*	0.011 *(0.846)*	-0.014 *(0.283)*	-0.052 *(0.043)* *	0.030 *(0.259)*

EC is Electrical Conductivity. Water quality values used are the overall average of all data points in the relevant years and adjusted for flow and area, regressed against land cover areas using a multiple linear regression using the linear least squares computation. (The green rows relay statistics regarding the multivariate regression, while the rest of the table reports coefficients in the first line and ANOVA p-values in brackets for each class. The significance level is reported (*=0.05, **=0.01). Significant cells are shaded. For Duiwenhoks df = 5,4 and for Mzimkulu df = 8,14)

Multivariate statistics provide a better picture of how the multiple variables interact with each other on the water quality variable. There was a significant multiple regression model between phosphates and land cover in Duiwenhoks ($F_{5,4}$ = 11.713, p

= 0.017), phosphates and land cover in Mzimkulu ($F_{8,14}$ = 3.197, p = 0.028), and between ammonium nitrogen and land cover in Duiwenhoks ($F_{5,4}$ = 7.207, p = 0.039).

These results are quite different to the simple regressions, with no significant correlations shown for electrical conductivity and nitrates for any of the land cover classes, and no significant correlations were found in Mzimkulu except for phosphates in plantations ($p < 0.05$). In Duiwenhoks, significant relationships were found between phosphates and an increase in bare land, cultivated crops and plantations, and between ammonium nitrogen and an increase in bare land, cultivated crops and urban areas (Table 10).

CHAPTER 4
DISCUSSION

The focus of this study was to identify links between land use and water quality and hoped to show that an increase in anthropogenic activities led to a direct negative effect on the water quality. It also aimed to show that the more established catchment in the Western Cape would show little change in land cover over time, in contrast to the more rural Mzimkulu catchment. The results indicate that this change in land cover did in fact take place as expected, and the link to water quality variables was also in line with expectations.

4.1 LAND COVER CLASSIFICATION

4.1.1 Spatial differences between catchments and temporal changes in land cover within the catchment areas

The most noticeable difference in the land cover results between the two catchment areas is that Duiwenhoks displayed negligible change while Mzimkulu displayed a much larger and more noticeable change in land cover over time. This was expected due to the characteristics of the towns and surroundings and the location of the catchments, where the Western Cape is more developed and established and the Kwa-Zulu Natal Province is much more rural and has more potential for change.

Duiwenhoks:

Only one land cover class changed significantly and is thus the only change that can be truly commented on. The area covered by bare, unvegetated ground changed significantly in the whole catchment with the biggest increase occurring between 1987 and 1990, followed by a decrease again in following years. This change occurred in an area where little anthropogenic changes were observed, as expected, so it is likely that the change in bare areas is due to a drought. Unfortunately the rainfall data for the area does not extend earlier than 1994, making it impossible to explore this theory.

Non-significant observations could still provide clues to future trends, although these hold less importance than significant findings. Fynbos is the main class of natural vegetation, as most others are transformed by man, and is a good indication of how much the catchment has been negatively affected from an ecological point of view. Fynbos covered much the same area from 1987 to 2000 and then increased slightly to 2009, while the area of cultivated crops reduced. It is likely that some fields were allowed to recover to their natural vegetative state for grazing of livestock. Urban areas increased minimally from 1987 to 2009, and the area covered by plantations increased slightly.

Therefore, the land cover in the Duiwenhoks catchment did not change much at all, and no obvious change occurred before and after Apartheid. As this is an area that has been farmed for many years with very few settlements, this finding is as expected.

Mzimkulu:

Assessing the catchment as a whole, there were significant changes in all land cover classes besides urban areas. It was hypothesised that bare ground, rural areas, urban areas and cultivated grains and sugar cane would increase in Mzimkulu with the increase in people moving into the area after Apartheid.

Although not significant, urban areas did increase, with the biggest change occurring between 1990 and 1997, which corresponds with the end of Apartheid and resultant movement of people. These findings are in agreement with the hypothesis. Rural areas were also found to increase the most between 1990 and 1997, again coinciding with the end of Apartheid. The increase in population would also require more cultivation (grains and sugar cane) and bare areas would increase with the increase in rural areas as the ground is intentionally swept bare around the houses as per tradition, and the increase in cattle and overgrazing can also cause erosion and bare areas (Tainton 1999). Bare ground, cultivated areas and sugar cane therefore increased as expected. It is possible that some of the bare ground classified in 2009 could be due to a drought, as the catchment had below average rainfall from 2007 to 2009. In the Mzimkulu catchment grasslands are the ‘natural’ class. Grassland increased from 1984 to 1997, then dropped dramatically between 2002 and 2009. This corresponds with an increase in bare ground and cultivated grains, suggesting a transformation to these classes.

4.2 WATER QUALITY AND LAND COVER

4.2.1 Temporal and spatial changes in water quality in each catchment

It was found that increased flow had a flushing effect for most nutrients on a seasonal time-scale (Kingdon *et al.*1999). In this sense a flushing effect refers to the increase in dissolved major salts and nutrients discharged in the water with an increase in flow rate, or in other words, when the river floods it brings with it accumulated salts and nutrients from upstream. This relationship was observed in the study, where all water quality variables studied showed a close correlation with flow rate where all values increased during periods of high flow and decreased during low flow. As Kingdon *et. al.* (1999) stated, as increased flow had a flushing effect on a seasonal time-scale it can be deduced that this flushing effect would also occur on an annual scale. This assumption is used in the analyses of the results in this study. The flow rate corresponded with rainfall figures and where the peaks in areal discharge are evident on the graphs, an unusually high amount of rain fell in those months. The peak in June in sub-catchment 102608 corresponds to an unusual amount of rain that fell in this month, outside the typical rainfall season. This illustrates how closely the flow rate is tied to rainfall in the study area. This was also found in a study done by Bolzern *et al.* (1980) who devised a real-time forecast system of flow rates from rainfall data.

MacNish (1988) found that ammonium nitrogen and nitrate nitrogen led to a decrease in soil pH. In the study pH values seemed unrelated to phosphates, nitrates and ammonium nitrogen.

The upper, mountainous sub-catchment of Duiwenhoks consisted mainly of fynbos (55.58 %) followed by crops (14.78 %). The lower sub-catchment had a majority of crops (45.23 %), followed by fynbos (38.74 %). This sub-catchment also had urban areas, although small, which the upper catchment did not have. The higher values of electrical conductivity in the lower sub-catchment can thus be explained by the higher presence of crops and urban areas, as well as the fact that it is likely to have a cumulative effect from runoff in the upper sub-catchment too.

The sharp increase in nitrates in Duiwenhoks between 2001 and 2009 in the upper sub-catchment corresponds with a decrease in area of bare ground, crops and plantations, and an increase in fynbos. No correlations were found between nitrates and land cover and due to the fact that the other variables didn't also behave in the same manner the response is most likely not due to changes in rainfall. In the lower sub-catchment the peak in nitrates around 2000 corresponds with an increase in bare ground (which is not due to reduced rainfall), but this correlation is not significant.

In Mzimkulu, the largest change between 2002 and 2009 in the upper sub-catchments was an increase in plantation. During this time there was an increase in electrical conductivity and pH values which could be attributed to this change. The peaks and dips of nitrates in Mzimkulu cannot be explained by land cover nor do they seem to be driven by rainfall patterns. More water data of a higher quality would be required to explore the links to land cover in more depth.

4.2.2 Correlations between water quality and land cover

Although there were significant correlations in the simple linear regression, these could be misleading as they only take one variable into account, when in a real life scenario all variables play a role simultaneously. The results from the multivariate regression were focused on for this reason. The significant relationships existed between phosphates and land cover in both catchment areas, and between ammonium nitrogen and land cover in Duiwenhoks. The significant classes regarding phosphates in Duiwenhoks were bare ground and cultivated crops, and plantations featured in both catchments as being significant. Ammonium nitrogen had a significant correlation with bare ground, cultivated crops and urban areas. It is expected that phosphates and ammonium nitrogen would increase with these land cover types, and fits with the hypothesis of the study.

4.3 LIMITATIONS OF THE STUDY AND THE POTENTIAL FOR FURTHER STUDY

While in theory there are many Landsat images available for any point on earth, not all of those are cloud-free. This reduces the number of images available, especially in months that are during the rainy season. Added difficulty comes in when images need to be mosaicked or compared with another area in the same time-frame, where it becomes important to find imagery for all areas in question taken during the same year, month and if possible even the same week. To find imagery that meets all these requirements is tricky, as was shown in this study. By resorting to imagery that was obtained in different years means that the classification derived therefrom is less directly comparable, while using imagery obtained in different seasons means that changes picked up in the classification could merely be seasonal changes. It would have also been more ideal to have time-frames of years that are more evenly spaced with a similar amount of years between images, but due to the limitations described above this was not possible.

Another big limitation was the lack of water quality data in South Africa. The first aspect that was found to be missing was long-term water quality data at the river mouth, in estuaries as well as just upstream of the estuaries. There are also relatively few river monitoring stations per catchment that span a long period of time. The variables measured could also be increased to include other appropriate variables that are becoming the new focus on water quality. There were many gaps in the data and finding a full year's worth of data for both flow and water quality variables was challenging, and to find data that met those requirements while at the same time falling over the same years as were selected for the land cover classification was not even possible in all cases. Long-term data are very valuable and care should be taken that the correct variables are collected methodically without long periods of gaps in the data.

The study did not aim to analyse in detail the hydrological contribution of each land use class to the discharge. Although the study identified a statistical relationship in the form of loose correlations between land cover types and water quality, it was beyond the scope of this project to analyse if this is supported by the hydrology of the different land uses in the catchments. For example, while it was shown that there is a positive correlation between phosphates and plantations, the reason behind this was not yet explored. It could also be that a land cover class increased in size at the same time that a water quality variable increased, but it does not necessarily mean that the change in that particular class caused the change in water quality. A further analysis of actual processes leading to leakage of nutrients to water would be needed for each surface type to more fully understand the relationships between hydrology and land use. The focus of this study was on GIS and remote sensing, rather than on hydrological processes.

Much smaller study sites with less heterogenous areas could be studied to identify a more direct causative effect of land cover on hydrology and on water quality. Other aspects for further study include identifying the amount of water each land cover class contributes to the river system, and how that water reaches the river – by surface runoff or by groundwater. The type and amount of nutrients each class contributes to the system could also be explored.

The dynamics in catchment areas are vast and complex, and by using the correlations found in this study one could use it as a starting point to study the processes behind these correlations. There is much opportunity for further study in this field, particularly in countries such as South Africa where water quantity and quality could be compromised, and where relatively little work has been done to date.

CHAPTER 5
CONCLUSIONS

The study shows that the hypothesised change in land cover was accurate, with land cover in Duiwenhoks not changing much at all but showing significant changes in the Mzimkulu catchment. The temporal and spatial changes in land cover differed greatly between the two catchment areas. These findings are in line with the hypothesis that Mzimkulu, with its more rural and less developed area would display more change than Duiwenhoks and that the change would include an increase in urban and rural areas along with the resultant increase in bare ground, cultivated grains and sugar cane. The time in which these changes took place was also as expected, coinciding with the end of the Apartheid era.

It was also shown that there is a correlation between land cover types and water quality. Water quality variable values were shown to be higher when land cover types consisted of more cultivated crops, urban areas, plantations and rural areas. Although water quality variables showed a strong correlation with flow rate, in some cases a change in water quality values could not be explained by rainfall and its resultant runoff and discharge. Nitrates were found to increase with an increase in cultivated crops in Duiwenhoks and with an increase in rural areas, bare ground, cultivated grains and sugar cane in Mzimkulu. Ammonium nitrogen was found to increase with an increase in cultivated grains, plantations and bare ground. Phosphates were shown to increase with an increase in bare ground, cultivated grains and plantations.

The multivariate analysis suggested that significant relationships were present between phosphates and land cover in both catchments, and between ammonium nitrogen and land cover in Duiwenhoks. Classes that displayed significance related to phosphates were bare ground, cultivated crops and plantations, and those that displayed significance related to ammonium nitrogen were bare ground, cultivated crops and urban areas. The findings regarding land cover change as well as the relationships between land cover and water quality were in accordance with the hypotheses of the study.

A shortcoming identified in the study was the difficulty of sourcing water quality data. The number of water monitoring stations could be increased, and stations should be added to estuaries due to their importance and to obtain water quality variables close to the river mouth to add another aspect that could be compared with the higher reaches of the catchment. Variables should be recorded regularly over a long time-period to make future studies like this possible using long-term data.

Studies such as these have the potential to explore more correlations between water quality and land cover, as well as other factors that could have on effect on water quality. Results from such future studies could then be used in conjunction with climate models to predict future water quality changes. Water is our lifeblood, and if we can predict potential problems before they become too serious, we could help avert serious problems with water quality in the future.

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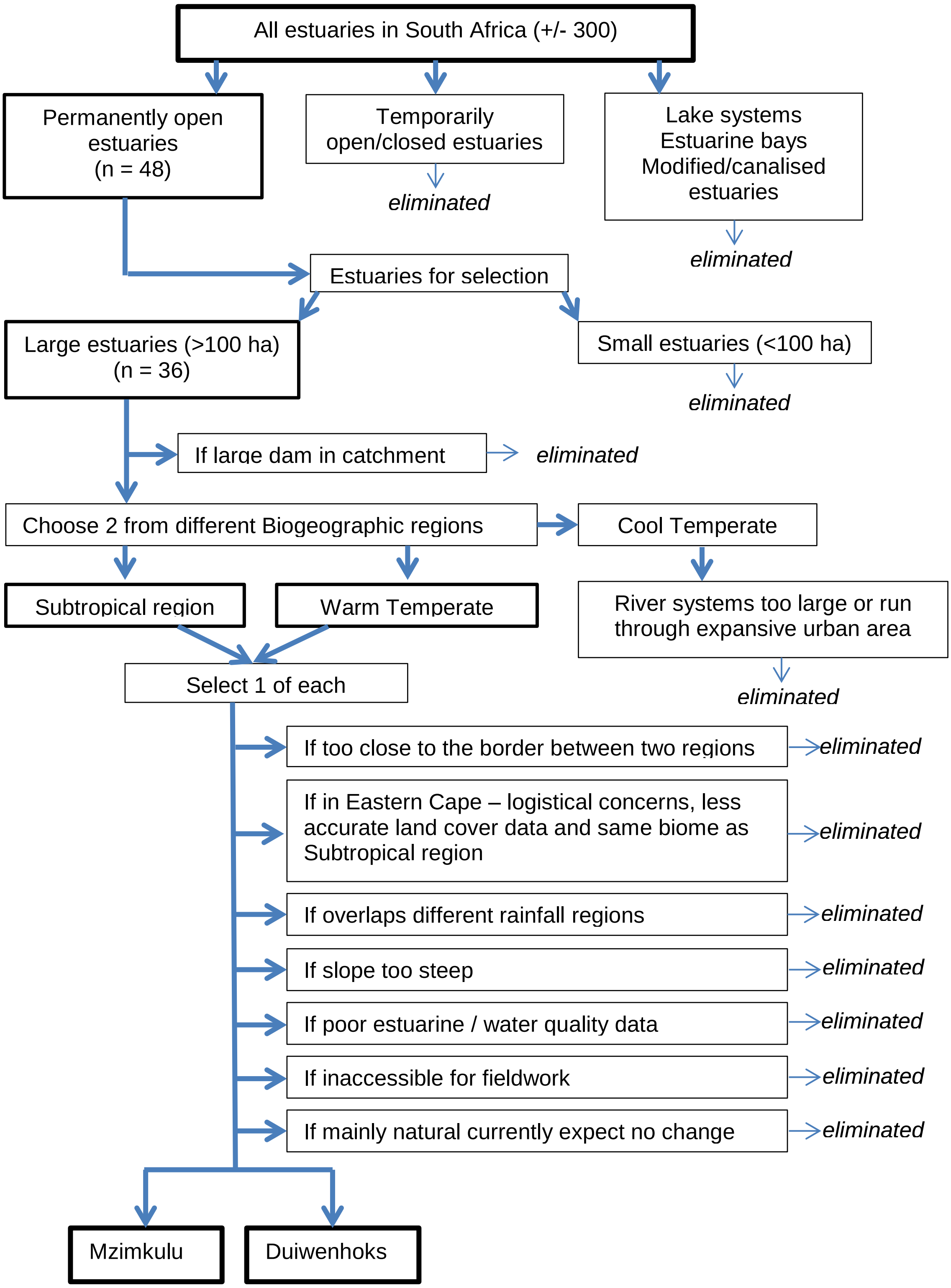
Appendix A.



Flow chart indicating the decision making criteria in site selection of estuary catchments based on estuarine characteristics for the project. (Classification and numbers according to Whitfield (2000) and van Niekerk & Turpie (2010).)

Appendix B.

Geology and natural vegetation

Duiwenhoks:

The geology forms part of the Cape Supergroup and is characterised by bands of Arenite, Conglomerate, Shale, Sedimentary and Limestone running east to west as one moves from the Langeberg mountains in the north to the coastline (ENPAT) (Figure B1a).

The Duiwenhoks catchment lies within the Fynbos biome and the following bioregions: Southern Fynbos, Eastern Fynbos-Renosterveld, East Coast Renosterveld, South Coast Fynbos and South Strandveld (Mucina & Rutherford 2006). Figure B1b shows the natural vegetation types in the catchment.

The fynbos vegetation is dominated by evergreen or partly deciduous shrubs and small trees, frequently with leathery leaves, similar to the European Mediterranean vegetation. Plants depend on fire for germination or flowering, making fire an essential element in the reproductive cycle and hence growth of fynbos.

Mzimkulu:

Looking from the Drakensberg to the mouth of the Mzimkulu catchment, the geology includes Basalt, Arenite, Mudstone, Dolerite, Shale, Tillite, Gneiss and Marble (ENPAT) (Figure B2a). The geology in this region forms part of the Stormberg Group, Beaufort Group and Volksrust Formation, all part of the Karoo Supergroup (Mucina & Rutherford 2006).

The Grassland biome, Savannah biome and Indian Ocean Coastal Belt all fall within the Mzimkulu catchment. Bioregions include Drakensberg Grassland, Sub-escarpment Grassland, Sub-escarpment Savannah, and the Indian Ocean Coastal Belt (Mucina & Rutherford 2006) (Figure B2b).

While in the upper catchment the vegetation is dominated by grasslands, toward the mid catchment it is dominated by savannah and towards the coast thicker, taller vegetation characteristic of the coastal belt prevails.

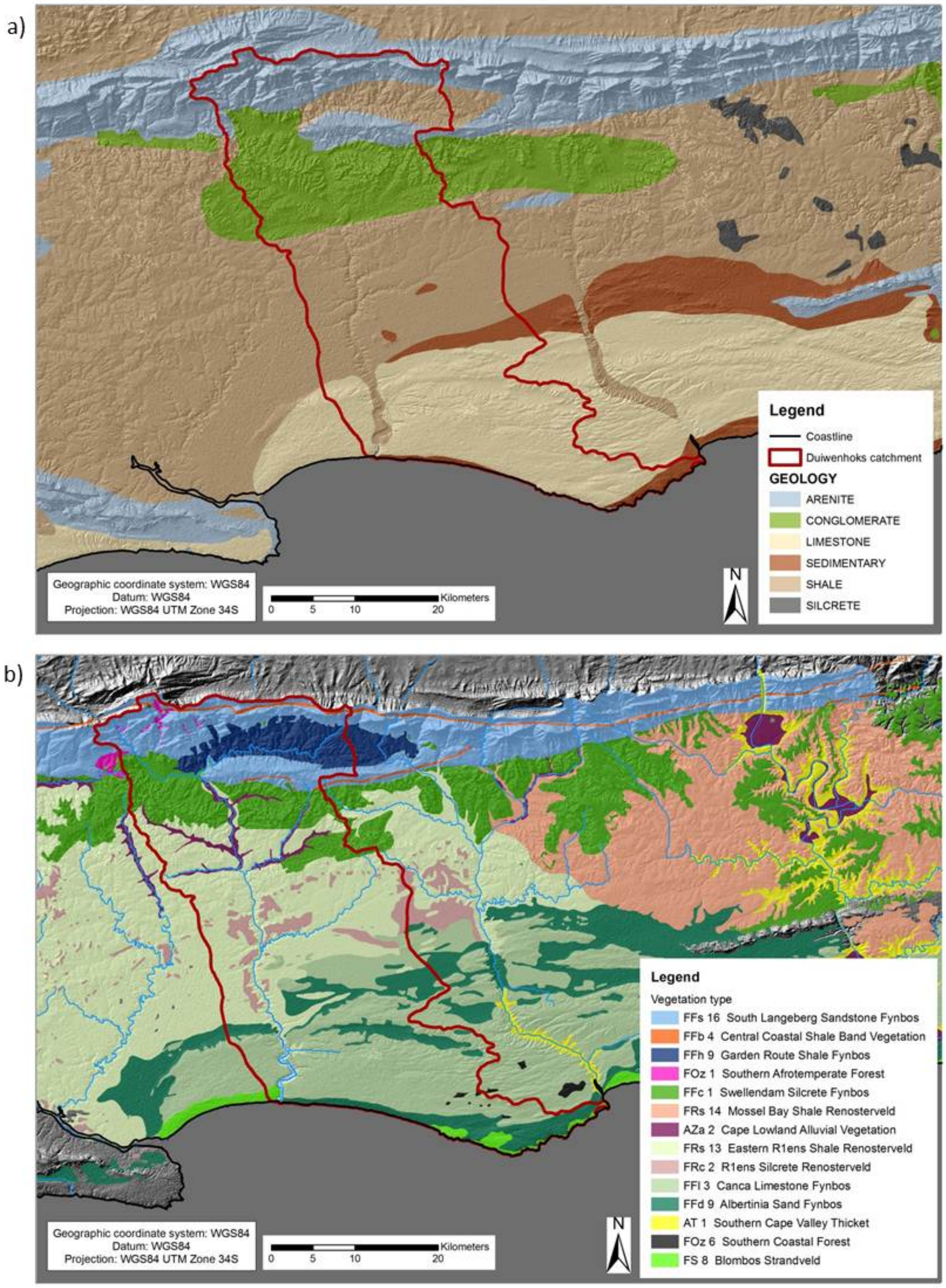


Figure B1. Duiwenhoks catchment area: a) Geology b) Vegetation. (Data source: Geology – ENPAT (Environmental Potential Atlas) of the Department of Environmental Affairs and Tourism, South Africa (2001); Vegetation – Mucina & Rutherford (2006); Hillshade derived from ASTER GDEM – a product of METI and NASA)

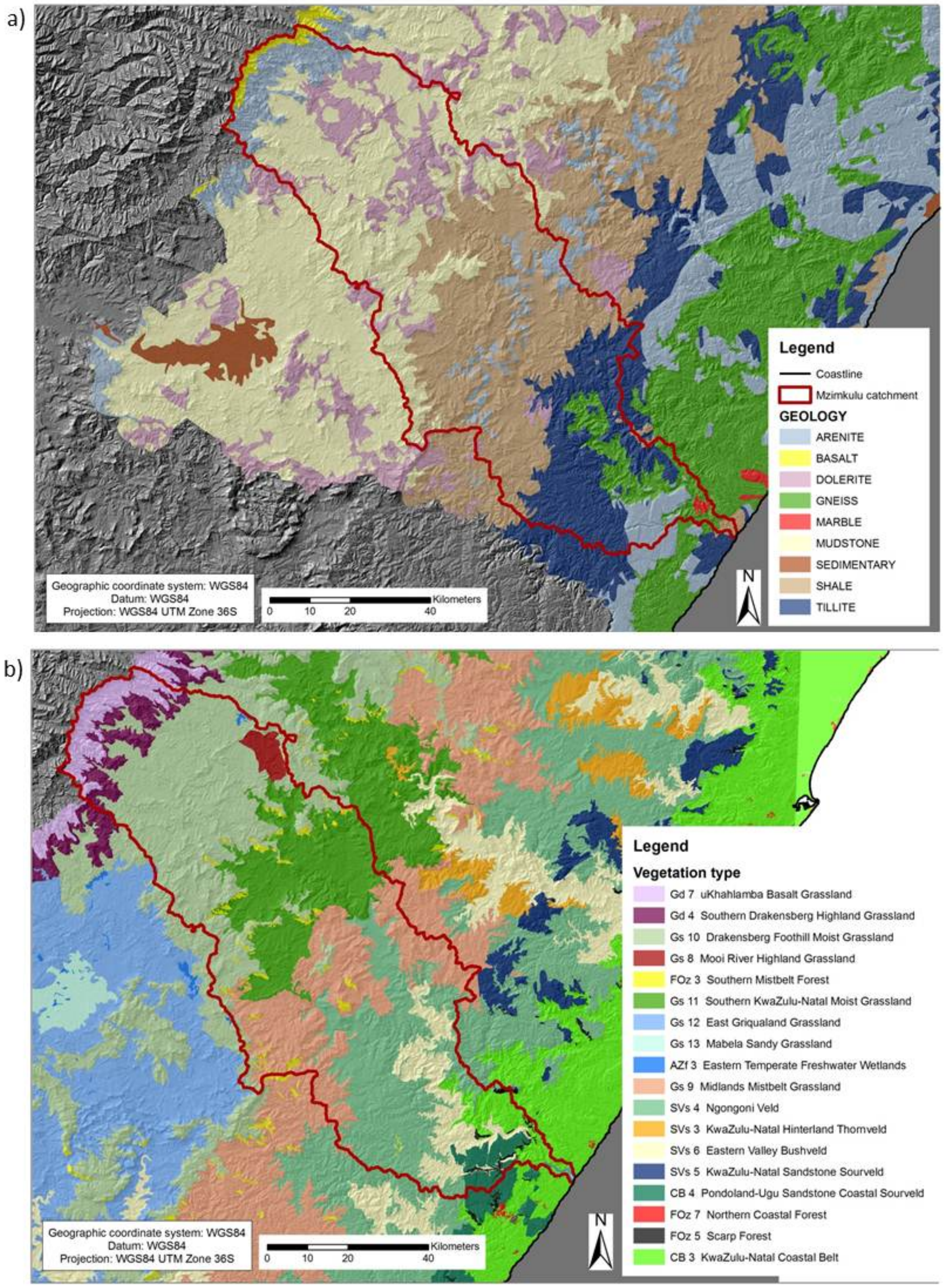


Figure B2. Mzimkulu catchment area: a) Geology b) Vegetation. (Data source: Geology – ENPAT (Environmental Potential Atlas) of the Department of Environmental Affairs and Tourism, South Africa (2001); Vegetation – Mucina & Rutherford (2006); Hillshade derived from ASTER GDEM – a product of METI and NASA))

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