REMOTE SENSING APPROACH FOR EXAMINING CHANGES IN WATER USE IN RELATION TO CLIMATE VARIABILITY AND LAND COVER CHANGE

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SUMMARY

Water use related research in Southern Africa is currently critical; this is not only a result of current and projected impacts of climate change on water resources but the growing tension among different water users has increased the relevance of water use monitoring. The overarching purpose of the study was to quantify the relationship between evapotranspiration (ET), land cover change and climatic variability. This was done at two spatial scales, provincial and sub-catchment scale. The Inkomati-Usuthu and Wider Cape areas were used as case study sites for the sub-catchment scale.

The first objective of the study was to define the current water use status of various land cover classes using 2012 annual MOD16 satellite product data. The median ET (mm) and cumulative water use (Mm^3 a^{-1}) were estimated for each land cover class per study area. The results indicated that plantation/woodlots, thicket/dense bush and cultivated perennial land cover classes had the highest annual ET estimates. Land cover classes such as grasslands, shrubland fynbos and low shrubland recorded the highest cumulative water use estimates due to the large areas they cover.

The second objective was to describe the linkages between ET, land cover change and three climatic drivers: air temperature, vapour pressure deficit (VPD) and rainfall. This was done using a 13 year (2000 – 2012) monthly historical data set of ET and climatic variables per land cover class. Multiple regression analysis and correlation statistics were used to analyse the relationships between these, ET as a dependent variable and climatic drivers as independent variables. The results indicated that air temperature and rainfall were more important drivers of ET changes compared to VPD. In terms of the relationship between ET and the climatic variables, the following was determined: a positive relationship was found between ET and air temperature; a negative relationship was found between ET and rainfall in winter rainfall areas while a positive relationship was reported in summer rainfall areas; no clear relationships were found between ET and VPD.

The final objective was to project future changes in water use as a function of climatic and land cover changes by developing a scenario tool for this purpose. Multiple regression equations, means and standard deviations of the climatic variables from the historical analysis were applied in the developed tool. The tool has three main scenarios: land cover change only, climatic change only and a scenario combining the impact of land cover changes and climatic variability on monthly

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water use per land cover class in each study area. The results from the tool showed that reduction of plantation/woodlots has the greatest impact in decreasing water use. In addition to this the results showed that future increase in air temperature and VPD will result in an increase in water use.

This study has been able to describe the relationships between water use, climatic variability and land use. In addition, although the future projections of water use are just estimates, they are useful to initiate dialogues between water users and managers about possible future scenarios.

KEY WORDS

Water resource management, evapotranspiration, land cover change, climatic variability, water use, MOD16, multiple regressions, future projection.

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OPSOMMING

Watergebruikverwante navorsing in Suid Afrika is van kritiese belang. Dit is nie net die gevolg van die huidige en geprojekteerde impak van klimaatsverandering op waterhulpbronne nie, maar die toenemende spanning tussen verskillende watergebruikers het die toepaslikheid van watergebruikmonitering verhoog. Die oorkoepelende doel van hierdie studie was om die verhouding tussen evapotranspirasie (ET), grondbedekkingsverandering en klimaatsveranderlikheid te kwantifiseer. Dit is gedoen op twee ruimtelike skale, provinsiaal sowel as subopvangsgebied. Die Inkomati-Usuthu en Wyer Kaapse gebiede is as gevallestudies vir die subopvangsgebiedskaal gebruik.

Die eerste doel van die studie was om die huidige watergebruikstatus van verskillende grondbedekkingsklasse te definieer met behulp van 2012 se jaarlikse MOD16 satellietprodukdata. Die mediaan ET (mm) en kumulatiewe watergebruik (Mm^3 a^{-1}) is bereken vir elke grondbedekkingsklas per studiegebied. Die resultate het aangedui dat plantasie-, digte bos- en bewerkte meerjarige landbouklasse die hoogste jaarlikse ET-ramings gehad het. Grondbedekkingsklasse soos grasvelde, fynbos en lae struike het die hoogste kumulatiewe waterverbruiksramings aangeteken as gevolg van die groot areas wat hulle beslaan.

Die tweede doel was om die verband tussen ET, grondbedekkingsverandering en drie klimaatsveranderlikes te beskryf: lugtemperatuur, dampdrukstekort (VPD) en reënval. Dit is gedoen met behulp van 'n 13-jarige (2000 - 2012) maandelikse historiese datastel van ET en klimaatsveranderlikes per grondbedekkingsklas. Meervoudige regressie-analise en korrelasiestatistieke is gebruik om die verhoudings tussen ET as afhanklike veranderlike en die onafhanklike klimaatsveranderlikes te analiseer. Die resultate het aangedui dat lugtemperatuur en reënval belangriker bepalers van ET veranderinge was in vergelyking met VPD. In terme van die verwantskap tussen ET en die klimaatveranderlikes, is die volgende bepaal: 'n positiewe verhouding is gevind tussen ET en lugtemperatuur; 'n negatiewe verhouding is gevind tussen ET en reënval in winterreënvalgebiede, terwyl 'n positiewe verhouding in somerreënvalgebiede gerapporteer is; geen duidelike verhoudings is gevind tussen ET en VPD nie.

Die finale doel was om toekomstige veranderinge in watergebruik as 'n funksie van klimaats- en landbedekkingsveranderings te voorspel deur 'n scenario-instrument vir hierdie doel te ontwikkel. Die meervoudige regressievergelykings, gemiddeldes en standaardafwykings van die

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klimaatsveranderlikes uit die historiese analise is toegepas in die ontwikkelde instrument. Die instrument maak voorsiening vir drie scenarios: slegs grondbedekkingsverandering, slegs klimaatsverandering en 'n scenario wat die impak van grondbedekkingsveranderinge en klimaatsverandering op maandelikse watergebruik per grondbedekkingsklas in elke studiegebied kombineer. Die resultate van die instrument het getoon dat die vermindering van plantasies die grootste impak het op dalende watergebruik. Daarbenewens het die resultate getoon dat toekomstige toename in lugtemperatuur en VPD tot 'n toename in watergebruik sal lei.

Hierdie studie was in staat om die verwantskappe tussen watergebruik, klimaatsveranderlikheid en grondbedekking te beskryf. Daarbenewens, hoewel die toekomstige projeksies van watergebruik net ramings is, kan dit nuttig gebruik word om dialoog tussen watergebruikers en bestuurders oor moontlike toekomstige scenario's te bewerkstellig.

TREFWOORDE

Waterhulpbronbestuur, evapotranspirasie, grondbedekkingsverandering, klimaatsveranderlikheid, watergebruik, MOD16, meervoudige regressies, toekomstige projeksie.

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ACRONYMS AND ABBREVIATIONS

AoNC	Areas-of-no-change
CMA	Catchment management agency
CMS	Catchment management strategy
DEA	Department of Environmental Affairs
DEADP	Environmental Affairs and Development Planning (Western Cape)
DWA	Department of Water Affairs
ET	Evapotranspiration
ET_r	Reference evapotranspiration
ET_rF	Fraction of evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
GIS	Geographic information systems
IAPs	Invasive alien plants
LC	Land cover
LU	Land use
MAR	Mean annual rainfall
MERIS	Medium resolution imaging spectrometer
MMD	Monthly mean difference
MODIS	Moderate-resolution imaging spectroradiometer
NASA	National Aeronautics and Space Administration
NASA/EOS	NASA Earth Observation System
NDVI	Normalized difference vegetation index
NFEPAs	National Freshwater Ecosystem Priority Areas

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NLC	National land cover
NWA	National Water Act
NWRS	National Water Resource Strategy
PET	Potential evapotranspiration
SAWS	South African Weather Service
SEBAL	Surface energy balance algorithm for land
SEBS	Surface energy balance system
VPD	Vapour pressure deficit
WMA	Water management area
WRC	Water Research Commission

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CHAPTER 1 INTRODUCTION

Water is an important natural resource; the functioning of ecosystems and the survival of humans depend entirely on this resource (Oki & Kanae 2006). Freshwater as such is a finite and scarce resource and the appropriate management of it is of the utmost importance, especially in South Africa which is considered to be the 30th most water scarce country in the world (DWA 2013a). Averages of annual rainfall show that the global average is about 860 mm while South Africa on average receives 450 mm to 495 mm of rainfall per annum (DWA 2013b). This shows that even without any human influence water security is a challenge (Hedden & Cilliers 2014). In addition to this, the pattern of rainfall is unevenly distributed in the country both geographically and from season to season. This has resulted in the implementation of various measures to ensure equitable distribution and effective storage of water resources for times when below average rainfall is received.

Examples of these measures include the construction of large dams for water storage across the country and the implementation of inter-basin water transfer schemes (Colvin et al. 2013). These are used for the purpose of transporting water from the sources to areas where it is needed such as cities where the demand is higher or drier parts of the country. South Africa currently has more than 600 dams; together these have a combined water storage of about 33 000 million cubic metres, which translates to about 70% of the total mean annual runoff (DWA 2013b).

The quantity of freshwater systems is not the only challenge however, according to the National Freshwater Ecosystem Priority Areas (NFEPAs), which is a classification of freshwater ecosystems in the country, large percentages of rivers and wetlands have undergone significant modifications. More than 60% of rivers are considered threatened while 23% of these have been declared critically endangered. In the case of wetlands, about 65% of these ecosystems are considered to be threatened and about 48% of them declared to be critically endangered (Colvin et al. 2013; Hedden & Cilliers 2014). A number of water users have contributed to the declining state of freshwater resources; these include: industries, forestry, agriculture and mining (Ashton, Hardwick & Breen 2008). In South Africa, it is said that agriculture alone uses up a large percentage of the groundwater and surface water available in the country (Backeberg 1997; Yokwe 2009) and this supports the need for more equitable allocation and management of freshwater.

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The hydrological cycle which provides us with precipitation is a closed system (Oki & Kanae 2006); this means all the water on Earth circulates with no external input from other processes. This closed system is thus primarily responsible for numerous climatic processes on Earth. Functioning of plant dynamics including nutrient and carbon dynamics are all affected or dependent on the hydrological cycle (Oki & Kanae 2006). The main components of the hydrological cycle include precipitation, runoff, streamflow, groundwater storage and evapotranspiration (ET), a combination of transpiration and evaporation.

Evapotranspiration is defined as the combined water lost through soil evaporation and plant transpiration (Mu et al. 2007). Loss through transpiration occurs via a plant's stomata, which are cell openings in the plant's leaves and therefore the higher the stomatal conductance, the higher the transpiration (Mu et al. 2007). According to literature, ET is the second most important component of the hydrological cycle following precipitation (Mu et al. 2007; Mu, Zhao & Running 2011; Ramoelo et al. 2014). This is because of the important role it plays in contributing to the exchange of energy between the surface and atmosphere which in turn influences numerous processes on Earth. In a study to quantify the water balance and produce a flow model for seasonal streams in the Western Cape, Bugan, Jovanovic & De Clercq (2012) found that ET comprised more than 80% of the total precipitation in that particular catchment.

To better understand or predict trends in climatic changes that are likely to occur in the near future it is important to increase our understanding of ET dynamics, its relationship with important climatic variables and its association with human-induced land cover changes, which influence the atmospheric energy balance system. This is especially important in the current advent of the Anthropocene where both natural- and human-induced climatic changes have adverse effects on altering global average temperatures, rainfall patterns, potential evaporation and the frequency of extreme weather conditions (Jovanovic et al. 2012). Studies have reported the sensitivity of ET towards climatic drivers such as: rainfall, wind speed, humidity, air temperature and vapour pressure deficit (Goyal 2004; Vicente-Serrano et al. 2014; Wang, Dickinson & Liang 2012; Zhang et al. 2017). In the case of temperature for example, Moratiel, Durán & Snyder (2010) reported that increased temperatures resulted in an increase in ET. Goyal (2004) reported similar results in India.

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Land cover changes have a significant impact on the energy balance system, which is a primary driver of the hydrological cycle. Changes in vegetation cover for example from grasslands to forest plantations have adverse impacts on the water cycle because of the high water usage of forest plantations due to different structures compared to natural vegetation (Albaugh, Dye & King 2013; Le Maitre, Gush & Dzikiti 2015). A change in vegetation from montane grasslands has the ability to change annual water use from 500 – 800 mm to 1100 – 1200 mm with the introduction of forest plantations (Albaugh, Dye & King 2013). Annual ET from other natural vegetation classes reported for native thicket, savannah and grassland were 775 mm, 685 mm, 640 mm per annum respectively (Meijninger & Jarmain 2014). van Eekelen et al. (2015) estimated that ET from sugar cane plantations in the Incomati catchment was 1044 mm per annum. This highlights that the understanding of the relationship between ET and land cover changes is important for appropriate management of water resources through informed land use decision making. Land use and land cover are related terms but are defined differently. Land use refers to the actual use of a piece of land or area while land cover refers to the physical properties on the ground (Dale 1997). For the purpose of the study, the term land cover holds more relevance in relation to what the study sets out to achieve, however the term also incorporates aspects of land use.

Various methods have been used to quantify changes in ET. These methods include both in situ methods and the use of remote sensing techniques (Bastiaanssen et al. 2005). Although in situ methods have been widely used to provide reliable estimates of ET, these methods lack the ability to account for the spatial variability of ET. This is especially true in very large areas (Jovanovic & Israel 2012; Ramoelo et al. 2014). These in situ techniques include the Bowen ratio method, eddy covariance systems and lysimeters (Glenn et al. 2007; Jovanovic & Israel 2012; Odhiambo & Savage 2009).

With various literature showing how ET can change due to environmental factors such as landscape heterogeneity, topography, climate, vegetation type and soil properties across space there is a need to explore the potential of remote sensing and GIS techniques to capture the changes or variability of ET in relation to these mentioned environmental variables (Jovanovic et al. 2015).

Remote sensing is defined as the process of acquiring information about an object or phenomenon without actual or physical contact with the object under investigation (Aggarwal 2004). This involves the launching and receiving of electromagnetic energy by space-borne satellites and the

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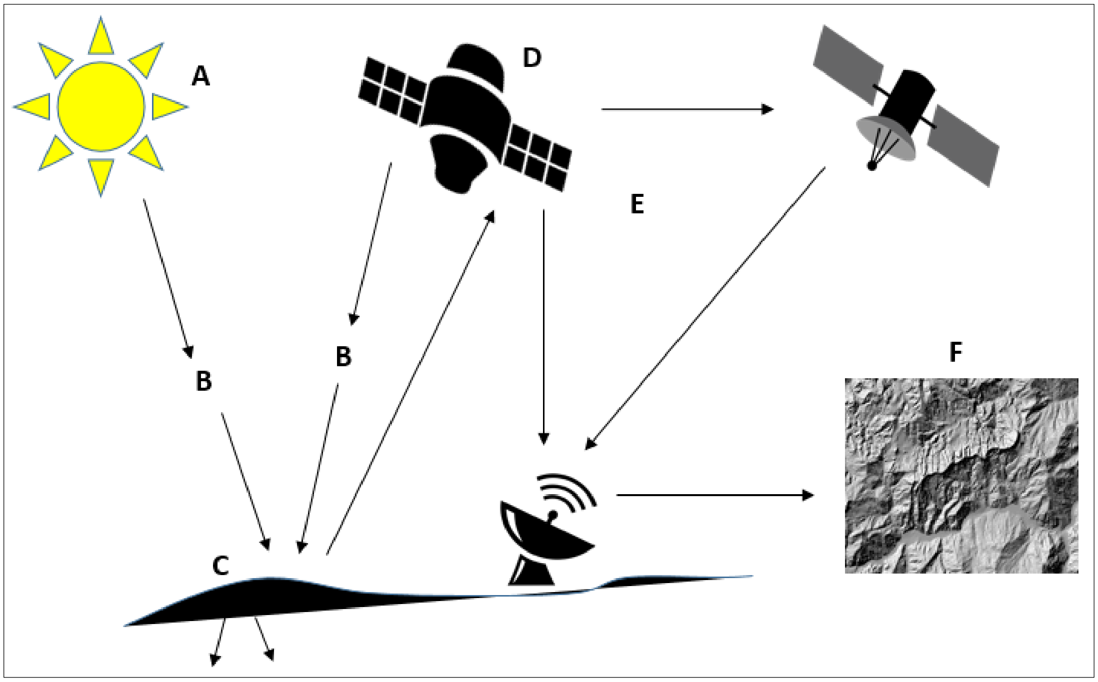
analysis of spectral signatures from the retrieved energy (Aggarwal 2004). The fundamental process used by remote sensing to acquire information about phenomena on the surface of the Earth is shown in Figure 1.1.



Source: Aggarwal (2004)

Figure 1.1 Flow diagram showing the basic principles of remote sensing, from the source of electromagnetic energy to the interpretation and application of the remotely sensed data (A – F).

Figure 1.1 processes are as follows: (A) - Source of electromagnetic waves that are recorded, (B) - Electromagnetic waves as they travel through the atmosphere, (C) - Electromagnetic energy that is radiated interacts with the target objects and the manner of interaction differs according to the energy and the objects properties. Some electromagnetic waves are absorbed while others are reflected back to satellite, (D) - The satellite sensor records the energy reflected back to the atmosphere, (E) – Information recorded by the satellite is transferred to a processing station where the data is processed and produced as raster imagery, (F) - The satellite information processed is produced in digital or electronic forms depending on the use, and these data images are then used to answer specific questions.

The ability of a sensor or satellite to capture a much larger area often decreases the detail in which objects on the ground can be observed (Aggarwal 2004). However, sensors or satellites which have the ability to only view a smaller area show the objects found on the ground in much greater detail

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(Aggarwal 2004). The choice of viewing either a larger area or having a smaller area with better detail quality depends on the application or use to which the images will be put. Another important term is temporal resolution, which is the amount of time taken by a satellite to revisit the same location and acquire information; in other words, the repetitive nature of a satellite (Aggarwal 2004). Temporal resolution is important because almost all natural phenomena occur within a particular time frame which could vary from hourly to seasonally.

Remote sensing models for ET measurement use the reflected irradiance to estimate ET over time and space with three commonly used remote sensing models based on the surface energy balance that calculate ET as an energy balance residual. Examples of such algorithms include: the Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen et al. (1998), the Surface Energy Balance System (SEBS) which was developed by Su (2002) and the Mapping Evapotranspiration at High Spatial Resolution with Internalized Calibration (METRIC) which was developed by Allen, Tasumi & Trezza (2007). An algorithm which is of particular interest in the current study is the MOD16 global ET product, developed by Mu et al. (2007).

The MOD16 algorithm uses satellite data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite with a 1 km x 1 km spatial resolution (Jovanovic et al. 2015; Ramoelo et al. 2014). The algorithm was originally conceived by Cleugh et al. (2007) based on the Penman-Monteith approach. The data used in this algorithm includes vegetation data and surface meteorological variables such as incoming solar radiation, vapour pressure deficit and air temperature (Cleugh et al. 2007; Mu, Zhao & Running 2011). The algorithm was re-evaluated (Mu et al. 2007) and modified (Mu, Zhao & Running 2011) for use in the MOD16 product. On a national scale, MOD16 was first evaluated in South Africa by Jovanovic et al. (2015), however various studies have validated the application of this algorithm (Munch et al. 2013; Ramoelo et al. 2014). The generic equation of MOD16 global ET algorithm is given as:

Equation 1-1

$$ET = T_c + E_s + E_i$$

where T_c is the canopy transpiration (T);

E_s represents the soil evaporation (Soil E); and

E_i is the canopy evaporation (E).

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The exploration and use of remote sensing techniques for water resource management in South Africa are of utmost importance, as these data sets have the potential to be used to quantify supplementary water use from various land cover classes and this could increase the functionality of water resource management and allocation.

1.1 PROBLEM STATEMENT

Evapotranspiration is an important component of the hydrological cycle and changes to this component ultimately affect water availability. Factors such as climatic variability and its influence on ET have been studied globally, however opportunities to use remotely sensed data to understand the interaction of ET, land cover changes and climate drivers at localised scales still exist. At localised scales, the role of land cover changes is important to consider, especially because of the direct influence that land cover changes have on atmospheric processes such as surface reflectance which impacts ET and as a result the hydrological cycle. Therefore, there is a demand for studies that investigate the relationship between ET, which informs water use or availability, climatic variability, as both a human and natural consequence, and land cover change as a direct human occurrence. The availability of satellite remote sensing products and land cover data offers the opportunity to study these relationships that are important for water resource management and allocation. Since evapotranspiration is a complex process, interacting with numerous climatic drivers, and the lack of understanding of how these drivers influence ET, reduces our ability to determine how ET is likely to change in the future. In addition, the uncertainties in the projection of these climatic drivers cause greater confusion when attempting to plan for anticipated changes in water availability.

To address this, there is a need to explore methods that offer the potential to capture both the spatial and temporal heterogeneity of ET and these require the use of satellite remote sensing and GIS techniques. The advantage of having such long-term data sets means that historical changes can be used to project possible future scenarios and therefore make better-informed decisions under large uncertainty.

According to Jovanovic et al. (2015) in situ or ground measurements do not have the ability to capture spatial and temporal heterogeneity of ET, since these methods are limited in their ability to reconstruct the relationships of ET with water use and climatic variability over large spatial and temporal scales. The uses of remotely sensed methodologies provide a more efficient way of

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capturing data within a larger area. In addition, they provide the benefit of being able to work with a large temporal data set which is critical for studying long term historical trends.

In addressing these gaps, the study will seek to answer the following questions:

1. Who are the major water users at a catchment and provincial scale?
2. What is the relationship between ET, climatic changes and land cover changes?
3. Are these relationships (in question 2) consistent at different spatial scales (provincial / catchment)?
4. What are the anticipated changes in ET as a function of future climate and land cover changes?

1.2 AIM(S) AND OBJECTIVES

To answer these questions, the study has set the following overarching aim and measurable objectives. These were in line with the larger Water Research Commission Project (K5/2520/1) titled "Integrated land use and water use in Water Management Areas, with a view on future climate and land use changes".

The aim of this research is to describe and model the linkages between ET, land cover change and climatic variability at different spatial scales.

To achieve the research aim, three objectives have been outlined:

- To quantify current water use status per land cover class by extracting annual (2012) ET estimates for various land cover classes from remote sensing data (MOD16 data product).
- To model the historical linkages between ET, land cover and three climatic drivers: rainfall, air temperature and vapour pressure deficit using temporal MOD16 remote sensing data (2000-2012).
- To project future changes in ET as a function of designed scenarios of land cover change and climatic variability using a tool developed for the purpose.

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1.3 RESEARCH SIGNIFICANCE

Water related research in Southern Africa is currently at its highest demand. The reason for this is not only related to the current and projected impacts of climate change but the growing tension between the need for development and the need for equitable water resource management. In addition to this there is growing competition from within the different water users such as agriculture, domestic, industrial and environmental uses (Vörösmarty et al. 2010). With the pressure and competition mounting, coupled with the increase in human population in the country, there is a need to quantify how much water is being used, and by which users or sectors. Only once we have an understanding of this information, will progress towards appropriate water resource management be made. Furthermore, since ET plays a significant role in the functioning of many Earth processes, our understanding of how ET varies spatially and its most important climatic drivers, will increase our ability to accurately predict how it is likely to change in the future. This can be done by designing possible land cover change and climatic scenarios. Scenario planning is an important tool in preparing for an uncertain future since it allows the planners to investigate and therefore plan for various possible scenarios (Star et al. 2016).

1.4 RESEARCH DESIGN AND METHODOLOGY

The research design and methodology describes the theoretical approach followed by the research to answer the earlier outlined questions. In this section, the approach used to achieve research objectives and research aim is explained and justified. The study aims to describe and model the linkages between ET, water use and climatic variability at different spatial scales. This research can be classified as both a descriptive and evaluative type of study in that it provides a representation of the factors associated with changes in ET over a period. Although causality is not assumed in the study, linkages and correlations between the different factors are described. In order to be able to do this, secondary data in the form of remotely sensed images of climatic variables and rainfall station data are used to carry out the research. The data in the study are analysed quantitatively since the factors (dependent and independent) are described as statistically manipulated data (e.g. means and medians) and these are then analysed using multiple regression techniques. In its nature, the research is deductive in that multiple independent variables are used to understand ET dynamics, but ultimately the aim is to describe which variables alter ET the most and should be prioritised for water resource management purposes.

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Figure 1.2 shows the research design and flow of research chapters to follow. Chapter 1 introduces the research topic, the research problem, the questions the study seeks to answer and the specific aims with the objectives. This first chapter places the entire study into perspective. Chapter 2 reviews important subjects that are core to this research study. These include topics such as water resource management in South Africa, ET, land cover changes, the hydrological cycle and climatic variability (Figure 1.2).

Chapter 3 explains the procedures used to extract and analyse the data sets. Two sets of data were extracted: (1) the first data set was used to answer the question of the current water use status in South Africa from 2012 ET data and the latest (2013/14) national land cover map (Figure 1.2); while (2) the second set of data extracted was used to answer the question of the historical relationships between ET, climatic variability and land cover changes. To achieve this, a 13-year (2000 – 2012) historical data set of remotely sensed climatic variables (including ground station rainfall) and ET were analysed using multiple regression analysis at a monthly frequency. The multiple regression equations are then used for the final objective to project future changes in ET. To achieve this, a land cover and climatic variability scenario tool was developed.

Chapter 4 describes the results, first the current water use status (2012) at a sub-catchment and provincial scale. Thereafter historical relationships of ET, climatic variability and land cover results are described at both a sub-catchment and provincial scale (Figure 1.2). Results are described using regression summaries, time series data and summary tables. Example results from the scenario tool are also shown in this chapter. In Chapter 5 the results from the previous chapter are discussed and research questions are answered. In the final chapter (Chapter 6), conclusions and recommendations from the research are provided. In addition to this, the research aims, set in the beginning, are revisited.

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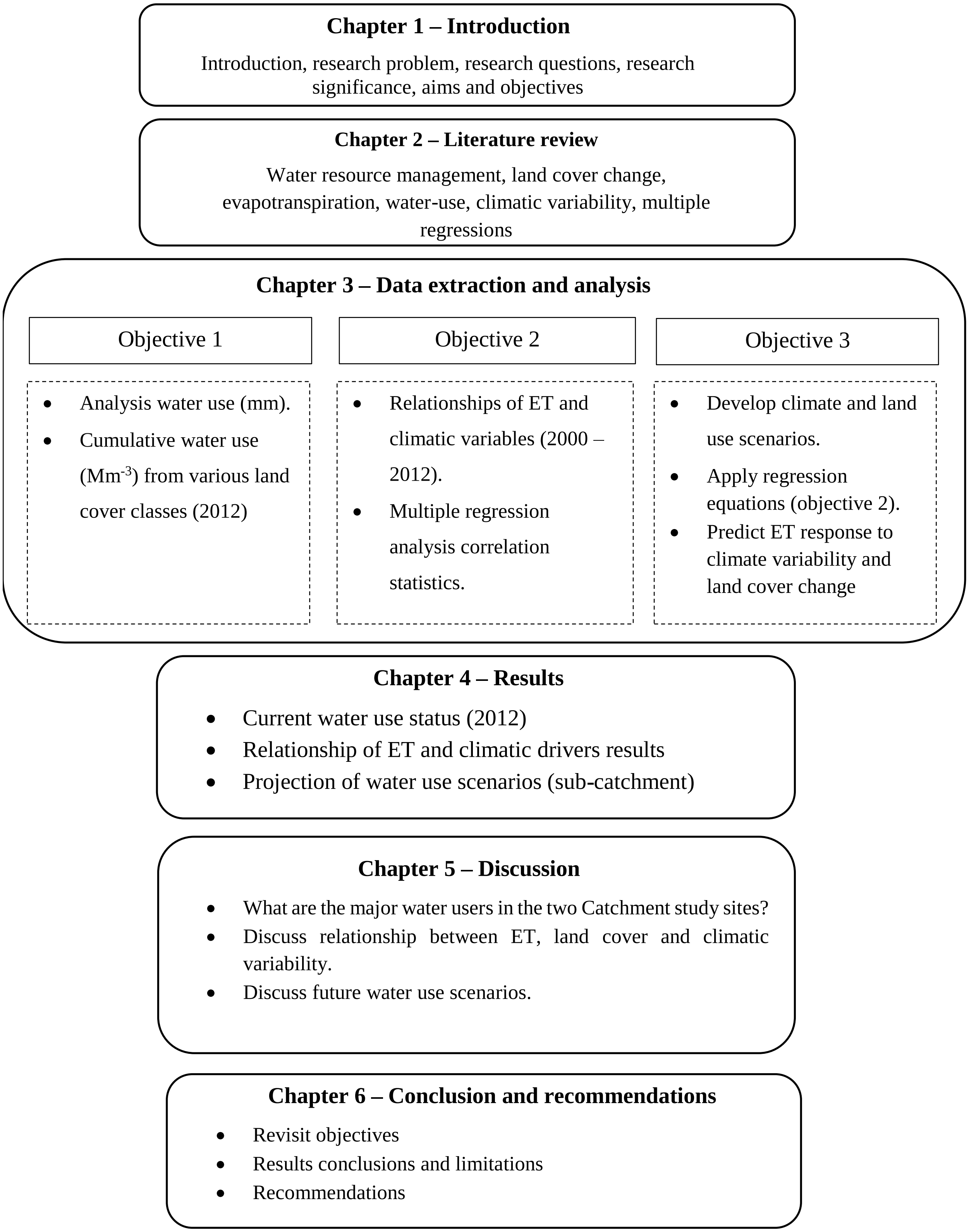

Figure 1.2 Flowchart outlining the conceptual research methodology followed. Shown in each rectangle are each chapter's title and content covered.

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CHAPTER 2 LITERATURE REVIEW

The importance of water as a resource cannot be overstressed; appropriate management and allocation of the resource equitably to all water users is a legal obligation on the government, which has been placed by the Constitution of South Africa. With this task Government uses policies, strategies and regulations to ensure equitable allocation and better management of water. At a more localised scale the ability to monitor the allocated water for the management of the resource is a priority. Surface energy balance processes such as evapotranspiration (ET) are important to understand because of the role they play in global atmospheric processes such as the hydrological cycle. The development of research focused around understanding ET at localised scales coupled with the realisation of the importance of monitoring it at a larger, more spatially variable scale and the limitations of conventional monitoring methods have increased research interest in exploring the potential of remote sensing as a tool to monitor ET. In this literature review the importance of water resource management is put into context within the South African environment. Within this, the water use of major water users in the country are reviewed and the impacts of these on water quantity and quantity highlighted. The importance of the hydrological cycle is discussed, focusing more on the process of ET as the second most important component of the hydrological cycle. The advancements made in the development of various remote sensing algorithms for monitoring ET as an alternative to conventional in situ methods are discussed. In addition, the importance of understanding land use and land cover changes as a key variable in estimating ET is also highlighted. Lastly, the chapter highlights the importance of scenario planning in decision making within water resource management.

2.1 WATER RESOURCE MANAGEMENT IN SOUTH AFRICA

Water resources are governed by numerous bodies or statutes in South Africa, from the highest national level to local or municipal levels. According to the Bill of Rights in the second chapter of the Constitution, a safe environment that is not harmful to a person’s well-being is a basic human right. This means that, for example, everyone has a right to safe and clean water resources that are not harmful to the individual’s health. The Constitution goes further to state that all individuals have the responsibility to prevent the degradation of natural resources for future generations. This stresses the need to not only use but to protect environmental resources such as our water.

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The South African National Water Act (36 of 1998) (NWA) is then a legislative instrument that is used to provide guidelines and provision for the use and management of water resources at national level. One of the purposes of the National Water Act is to ensure equitable distribution of water resources; use that is beneficial for the public and facilitates water demand in light of social and economic development. Another important function of the act is that it provides regulations for water use, protection, development and guidelines for the provision of water use licences. To keep to its obligations, the NWA develops strategies, policies and regulations for water resource management; the National Water Resource Strategy (NWRS) is an example of a strategy developed by the Minister of Water and Forestry (DWA 2013a). It serves as a tool that is used for the purpose of driving the implementation of the policies set out in the NWA.

The National Water Resource Strategy provides a strategic framework for the development, use and protection of water resources for the entire country and management of water resources at catchment or regional level. To fulfil its purpose, the NWRS performs the following tasks (DWA 2013a):

- Sets specific strategies, objectives and plans for overall water resource management country-wide.
- Determines water resource allocation by determining how much water can be used by various users, and how much should be reserved for human and environmental needs.
- Ensures equitable water use to be able to meet future water needs.
- Facilitates the classification of the country into water management areas (WMA),
- Determines water needs for each WMA and facilitates the transfer of water between WMAs where surpluses or deficiencies exist.
- Develops Catchment Management Agencies (CMA) that operates within each WMA and manages water resources using a developed Catchment Management Strategy (CMS).

Catchment management agencies are responsible for water resource management within a defined WMA; the CMS sets out the following responsibilities for the CMA (DWA 2013a):

- Development of an overall framework to be applied for water resource management in the WMA.

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- Development of an appropriate strategy for water allocation to both existing and new water users.
- Ensure protection, use, development and conservation of water resources within the WMA (Schreiner & Van Koppen 2002).

Lastly, due to the number of different water users existing within a catchment, CMAs are also responsible for the management of water use tension between users which include, for example, municipal, industrial (mining) and agricultural water users.

2.2 CURRENT WATER USE STATUS IN SOUTH AFRICA

South Africa is considered to be the 30th driest country in the world; the country's annual rainfall ranges between 450 mm and 495 mm while the global annual rainfall average is considered to be around 860 mm to 1033 mm per year (Hedden & Cilliers 2014). Since rainfall is unevenly distributed in the country, this means that some WMAs receive more or less rainfall than others. This increases the need for the implementation of measures that ensure the equitable distribution of water resources. The construction of large dams and the implementation of inter-basin water transfer schemes which transport water from one WMA to another are examples of measures which are used to ensure there is sufficient water for use in each WMA (Colvin et al. 2013).

There are a number of competing water users in South Africa; at different WMAs, there are different dominant water users that may depend on the natural resources available in the area or the general climate of the area that may be conducive to particular land uses over others. Generally, the Government uses a registration system to monitor how much water is being used by what type of water user; the registration system is also responsible for ensuring that compliance is maintained and this can be done through verification processes. Water use is defined as any activity that impacts on the quality, quantity and the general surrounding environment where water resources are found to occur (DWA 2013a). Water use activities are activities that interact with water, through: taking water from a source, water storage activities that reduce the flow of streams, activities that alter the flow of a stream and remove groundwater from groundwater sources. The water use sectors that have a large impact and potential threat to water resources in South Africa include agriculture, mining, domestic, forestry and invasive alien plants.

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2.2.1 Agriculture

Agriculture is an important water use sector in South Africa; the sector contributes significantly to the creation of jobs and has a 3% contribution to the total gross domestic product (GDP) of the country (Hedden & Cilliers 2014). Over 1.3 million hectares (ha) of land are irrigated by commercial and subsistence farmers, the most dominant type being the former who use up to 90% of the agricultural land. In terms of its water use, agriculture is considered to be the highest water user across the country with approximately 57% of water resources allocated to this sector alone (Hedden & Cilliers 2014). The quantity of water used is not the only cause for concern in the agricultural sector; the impact of agriculture on water quality is also a great challenge that has gained much attention. The increase in the human population has led to the intensification of agricultural practices, and this has resulted in the increased impact on water resources such salinization, nutrient leaching and soil erosion.

2.2.2 Mining

The mining sector is an important industry in terms of the overall GDP contribution to the country and its impact on water resources. Although only using approximately 3% of the total water distributed, the mining industry has adverse impacts on water resources, particularly water quality (Haggard, Sheridan & Harding 2015). The main impact of mining on water resources has been mainly the pollution of water resources (Ochieng, Seanego & Nkwonta 2010). The pollution of water sources such as rivers and lakes has major health impacts especially for people living in rural areas who use rivers directly as a source of water. In the Witwatersrand region located in Johannesburg, a study by Naicker, Cukrowska & McCarthy (2003) showed that polluted and acidified groundwater from mining areas can contribute up to 20% of the total stream discharge.

2.2.3 Domestic (urban and rural)

Domestic or municipal water use, which includes both urban and rural water use, is a high water use sector that has major impacts on water resources; it is estimated the sector uses up to 27 % of the total water available. In rural areas, the impact is less to do with the quantity of water used and more around the impact that these areas have on water quality. This is mostly linked to the lack of provision of basic services that sees waste in its various forms making its way into water sources and causing high levels of pollution. The same impact is also observed in urban areas where municipal discharges into water sources cause a build-up in nutrients in riparian systems, which

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over time, if not managed, can lead to the eutrophication of the system which is harmful for humans and for aquatic biodiversity (DWAF 2002). Other water resource impacts in urban areas include the increase in impervious surfaces which increase runoff significantly which can change the natural hydrology of rivers and channel large quantities of waste into water sources.

2.2.4 Forestry

Forests cover a significant portion of the country's land surface; according to (Shackleton 2004) forest types include natural or indigenous forests (350 000 ha) which are found mostly in KwaZulu-Natal and the Eastern Cape, commercial plantations (1.35 million ha) which predominately occur in KwaZulu-Natal, the Eastern Cape and Mpumalanga, and lastly, Savannah/woodlands (42 million ha). Forests in South Africa generally have conservation importance especially Savannah woodland because of its role in providing habitat for wildlife while also being an integral part of rural communities which still depend on wood for most of their livelihood (Shackleton 2004). The most dominant commercial plantations include softwood species such as pine, eucalyptus and wattle. Commercial plantations are a major revenue generating sector and contribute significantly to the country's GDP, however forestry is also considered a major water user because of its stream reduction activity.

2.2.5 Invasive Alien plants (IAP)

IAPs have become a threat not only to water resources but to the overall biodiversity. These species are found on land, in surface waters and in marine ecosystems. The combined coverage of IAPs in the country is estimated to be 1.8 million ha (Le Maitre, Versfeld & Chapman 2000); provinces which are heavily invaded are the Western Cape, Mpumalanga, KwaZulu-Natal and Limpopo (Le Maitre, Versfeld & Chapman 2000). Impacts of IAPs on water resources generally include changes in water quality status as a result of increased nutrient concentration by some species of invasive plants, alteration of aquatic ecosystem balances as a result of their dominance and decreased streamflow because of their high water usage (Chamier et al. 2012). In the year 2000, the estimated combined water used by IAPs was 3 300 million m^3 per year (Chamier et al. 2012).

2.3 COMPONENTS OF THE HYDROLOGICAL CYCLE

The hydrological cycle is a representation of the circulation of water between masses of the Earth; these include the ocean, the atmosphere and the land mass. This closed cycle includes the various

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forms or states that water takes as it circles around the Earth. Added to that, the cycle illustrates that water is indeed a finite resource; this means that all the water on Earth circulates around with no external input from other sources (Oki & Kanae 2006).

This system is primarily responsible for numerous climatic processes on Earth. Functioning of plant dynamics including nutrient and carbon dynamics are all affected or dependent on the hydrological cycle and the general exchange of energy since large amounts of energy are required to convert water between different phases (Oki & Kanae 2006). The main components of the hydrological cycle include precipitation, runoff, streamflow, groundwater storage and ET. The two most important components are precipitation and ET, a combination of evaporation and transpiration, discussed in depth later. These processes are responsible for ensuring the availability of water from the surface of the Earth.

Evaporation is the process by which water in a liquid state is converted into water vapour in the presence of sufficient energy, usually in the form of solar radiation and returned back into the atmosphere (Arnell 2005). The amount of water returned into the atmosphere depends on factors such as the albedo of the particular surface as well as temperature (Arnell 2005). Albedo is the reflective potential of a surface and depends mostly on the properties (e.g. colour or roughness) of the surface (e.g. grass and snow have differing reflective potentials). The presence of vegetation on the surface will also affect reflective potentials, due to properties such as the leaf area or canopy cover (Arnell 2005), when compared to bare ground. An important component to consider when discussing the process of evaporation is temperature, since an increase in temperature has been associated with an increase in water vapour (Arnell 2005; Huntington 2006).

Transpiration is the second component of ET used to return water back to the atmosphere. Transpiration is the water that is lost by a plant via stomatal openings. This process involves the movement of water from the plant's root systems into stomata found on the leaves from where it is released into the atmosphere (Zhang et al. 2017). Stomatal conductance in plants is a major agent responsible for controlling the rate of transpiration in plants. The conductance is referred to as the rate at which plants allow the passage of water through their stomata. Therefore a higher stomatal conductance results in a higher rate of transpiration in a plant (Zhang et al. 2017). In the absence of an external source of water, the increase in transpiration rate results in plant dryness.

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Collectively evaporation and transpiration are known as ET as previously mentioned. Studies report that between 60–80% of precipitation on the land surface is returned to the atmosphere by the process of ET (Mu, Zhao & Running 2011; Vörösmarty, Federer & Schloss 1998), and this means that ET is the second most important component of the hydrological cycle (Mu et al. 2007; Mu, Zhao & Running 2011).

The process of ET is altered significantly by global climate processes, both natural- and human-induced. In addition, land cover and land use changes alter the Earth's surface energy balance and therefore impact on the ET. As such, it is important to broaden our understanding of how climatic variability and land use changes affect ET; our understanding of this will help inform future water resource planning decisions in the advent of inevitable climatic and land use changes.

2.3.1 Water use responses to climatic variability

Climatic variability is defined as the natural variability in climate and occurs within a short period of time ranging from months to a few decades. In contrast to climate change, it may not occur because of human activities. Although these climatic variations are short and natural they have significant impacts on water resources. According to Goyal (2004) an increase in air temperature would increase ET because increases in air temperature expand the capacity of air to retain water. The effects of wind speed on ET can differ depending on plant conditions and humidity in the surrounding environment. Wind speed is responsible primarily for removing vapour in the air, and as such, increased wind speed has the ability to increase or decrease ET (Goyal 2004). Roderick et al. (2007) reported that declines in pan evaporation were mostly found to be as a result of decreases in wind speed with temperature and humidity changes not being significant enough to alter the pan evaporation. Humidity can be estimated as the deficit in vapour pressure to the saturation vapour pressure; increases in air temperature increase the vapour pressure deficit and therefore increase ET (Goyal 2004).

There are two main climatic factors that cause responses in ET (Jung et al. 2010; Liu et al. 2013): the first is the change in atmospheric evaporative demand for water vapour which is often attributed to increases in air temperature when moisture is sufficient; secondly, changes in ET can occur as a result of a limitation in moisture supply. Jung et al. (2010) investigated global ET trends over a 27 year period using remotely sensed data, in situ measurements and meteorological data, showing that there was an increased trend in global ET between 1982 and 1992, however, from

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1998 the global ET trends showed a decline. A significant positive correlation (r = 0.84) was found between ET and temperature variation during the period when the increase in ET trends was observed (Jung et al. 2010). Using soil moisture data from the Tropical Rainfall Measuring Mission's (TRMM) microwave imager and ET data from the FLUXNET, it was determined that the decline in global ET between the years 1998 and 2008 was as a result of a decline in soil moisture in parts of the globe, particularly in the Southern Hemisphere (Jung et al. 2010).

2.3.2 Water use responses to vegetation and land use changes

Land cover and land use are related terms but differ in their true definition; land cover refers to the actual physical property found on the ground (Dale 1997). Examples of land cover classes include forests, or non-vegetated ground. Land use, on the other hand, refers to the actual use or purpose for which the particular land is utilised; this could be commercial farming or recreational areas (Dale 1997). Land use provides information on the activity that takes place within an area but no information on what is physically on the ground. Within the context of spatial variability of ET, land cover is the more commonly investigated variable since this directly relates to physical properties on the ground which alter the surface energy balances and therefore ET.

In general changes in land cover have the potential to lead to a reduction (or increase) of ET which results in the weakening (or strengthening) of the hydrological cycle process, precipitation and runoff (Vörösmarty, Federer & Schloss 1998). In addition, land use and land cover changes affect catchment water resources by altering components such as the catchment's soil properties, infiltration, interception rates and groundwater recharge (Baker & Miller 2013; Zheng et al. 2016).

2.3.2.1 Water use and vegetation changes

The conversion of natural vegetation to commercial forestry is a historically growing trend in the country (Dye & Versfeld 2007; Le Maitre, Gush & Dzikiti 2015). This shift from shallow rooted, short and seasonally dormant species to deep-rooted, tall, evergreen species has major implications for water resources because of the high water usage of the latter kind of species (Gush 2006). Eucalyptus is a common example of such a species, particularly in South Africa where the demand for wooden products has seen the distribution of eucalyptus increase exponentially (Albaugh, Dye & King 2013). A general conclusion reached by numerous studies is that such vegetation changes are associated with an increase in ET (Le Maitre, Gush & Dzikiti 2015). The typical ET range for

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montane grasslands and fynbos shrublands is between 500 mm and 800 mm per annum; however for forest plantations the annual ET can range between 1100 mm and 1200 mm (Dye & Versfeld 2007; Albaugh, Dye & King 2013). In a review paper, Dye & Versfeld (2007) showed the differences in measured transpiration from a eucalyptus tree (*Eucalyptus grandis*) (Figure 2.1a) and montane grassland (Figure 2.1b).

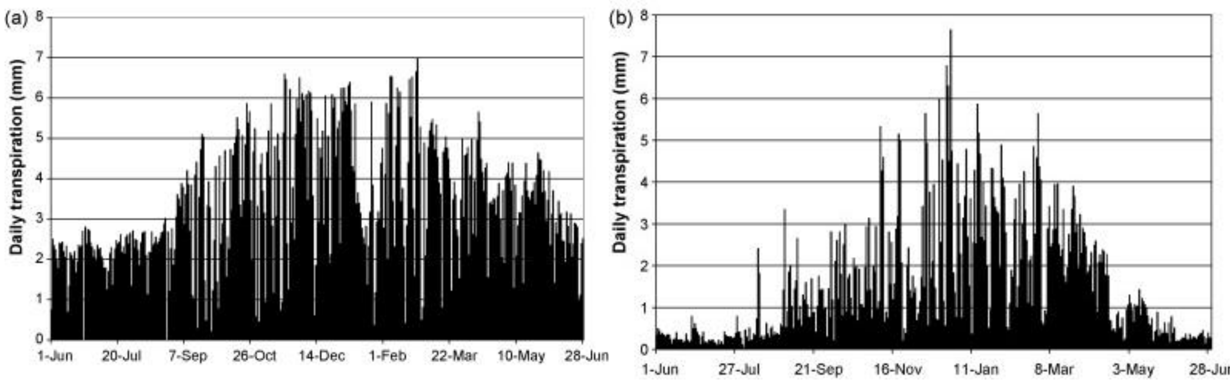

Figure 2.1 Differences in the daily transpiration (mm) measurements recorded from (a) 3 year old eucalyptus stand in the Sabie district and (b) montane grassland in Cathedral Peak, South Africa (Dye & Versfeld 2007).

In the summer months (November – February) the transpiration rates are relatively similar because of the high transpiration in the grasslands. However, major differences in transpiration occur in the non-growing season when eucalyptus transpiration still remains high compared to the montane grassland which is dormant during the winter low rainfall season (Figure 2.1).

Dzikiti et al. (2016) estimated the water saving potential of the removal of *Eucalyptus camaldulensis.* The study compared water use between a site infested with the eucalyptus species and one that had been cleared, to understand the impact on streamflow of clearing the invasive species. The site that had been cleared and the invaded site reported significant differences in summer but no significant differences in water use during the winter months. As a result of the increase in leaf area index in the grasses found in the cleared site, the water use between the two sites was relatively similar (Dzikiti et al. 2016). These results show that although the average transpiration from native vegetation and invasive plantation may be marginally different when conditions such as water availability are optimal for both species, the overall cumulative water use of invasive species is higher because they are evergreen and hence their distribution is a concern for water resource management.

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Meijninger & Jarmain (2014) investigated the impact that alien invasive species clearance has on total ET and water availability in KwaZulu-Natal and the Western Cape that are considered to be among the most highly invaded areas. The results showed that higher ET was measured in sites that were infested with alien invasive species compared to sites that had been cleared or had natural vegetation such as grasslands, thicket or fynbos. In the Western Cape, the average measured ET for native thicket and fynbos biomes was 575 mm to 520 mm per annum respectively (Meijninger & Jarmain 2014). The measured ET for alien invaded areas was as high as 850 mm, while sites where the alien invasives had been cleared had a measured ET of 780 mm. In KwaZulu-Natal, measured ET for sites with native thicket, savannah and grasslands were 775 mm, 685 mm and 640 mm per annum respectively. Sites with invasive alien species had an average ET of 875 mm, with cleared sites measuring ET at 825 mm per annum. In addition, the results also show that ET values are higher in KwaZulu-Natal compared to the Western Cape, and this was attributed to the observed higher rainfall averages and high NDVI values in KwaZulu-Natal (Meijninger & Jarmain 2014).

2.3.2.2 Water use and land use changes

Spatial variation of ET as a function of land use and climatic variability was investigated by Shoko et al. (2015) in Matebeland located in the south western part of Zimbabwe. Landsat 8 images were used to generate the land cover data used for land use determination and ET was derived using the Surface Energy Balance System (SEBS) algorithm applied to MODIS satellite images. The results showed that although there were temporal and spatial differences in the monthly ET measured in Matebeland between the years 2000 and 2012, statistically significant spatial differences were reported between the investigated land cover classes while temporal differences between the years were not significant (Shoko et al. 2015). An overall decreasing ET trend was observed between the years 2000 and 2012 with maximum monthly ET (43 mm) recorded in October 2000, linked to high rainfall as a result of a tropical cyclone. Spatial variation results of ET followed the strong rainfall gradient which sees rainfall increase from the west to the eastern part (Shoko et al. 2015). In terms of the variability of ET as a function of land cover changes, deciduous shrublands with sparse vegetation recorded the highest mean ET, followed by croplands, open deciduous shrublands and salt hardpans (Shoko et al. 2015).

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Similarly in the Inkomati basin, a study by van Eekelen et al. (2015) found that commercial eucalyptus and pinus plantations recorded the highest annual evaporation (1151 mm), followed by natural forest classes consisting of natural forest and woodlands (1091 mm). Sugarcane classes recorded an annual evaporation of 1044 mm while irrigated agriculture classes which excluded sugarcane measured 920 mm. Lastly evaporation from grassland and shrubland classes were 633 mm and 661 mm respectively (van Eekelen et al. 2015). The study estimated direct and indirect water withdrawals using remote sensing approaches with ET derived from the Surface Energy Balance Algorithm for Land (SEBAL) and rainfall data from local ground stations and satellite imagery data sources.

2.4 EVAPOTRANSPIRATION MONITORING

With the importance of ET highlighted, emphasis must be drawn to the importance of monitoring and understanding this process. Approaches used to monitor ET can be categorised as conventional methods and remote-sensing-based methods (Shoko et al. 2015), the latter having only recently been gaining research recognition particularly in developing countries like South Africa.

Evapotranspiration can be measured as potential evapotranspiration (PET), actual evapotranspiration (ET) or reference evapotranspiration (ET_0) (Łabędzki et al. 2011); the difference is that PET is defined as the ET that would be measured in an area given that there is sufficient moisture and optimal growth conditions (Chen et al. 2005; Łabędzki et al. 2011). At this point of maximum water availability the ET would potentially reach its maximum and would only be limited by climatic or atmospheric conditions; it is also assumed that other growth conditions such as disease and soil fertility are insignificant (Thornthwaite 1948; Chen et al. 2005; Łabędzki et al. 2011). Actual ET, on the other hand, is the actual amount of water that is lost from the surface of the Earth given the amount of moisture available and therefore actual ET is limited by moisture availability. Growth conditions in actual ET estimates are not assumed to be optimal and it factors in conditions such as disease, water shortages and water logging (Łabędzki et al. 2011). Reference ET, also known as the ET of a reference crop, normally grass or alfalfa, is defined as the ET of a hypothetical crop with specific conditions such as height (0.12 m), surface resistance (70 $s.m^{-1}$), and albedo (0.23). The Penman-Monteith equation (described later, Equation 2-2) is the commonly used method for estimating reference ET for a given surface under the specified conditions (Łabędzki et al. 2011). The estimation of reference ET assumes that there is always sufficient water

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available for plant growth, eliminating the effects of soil conditions and making climatic factors the only parameters affecting the reference ET (Łabędzki et al. 2011). Lastly, the provision of a reference crop for the estimation of reference ET allows efficient estimation of ET from other surfaces since it can be related to the crop types and growth stages (Łabędzki et al. 2011).

Monitoring and understanding ET variations is highly important for various applications, for example, the assessment of moisture availability over large areas for irrigation scheduling, or the quantification of catchment water budget requirements (Glenn et al. 2007). ET influences the energy flux, therefore it is important for incorporating into scenarios based on climate change or weather forecasting. According to studies (Mu et al. 2007; Jovanovic et al. 2015), monitoring of ET can be problematic due to the complexity of the process, especially because of spatial variability affecting numerous surface and atmospheric factors that alter the ET (Mu et al. 2007; Jovanovic et al. 2015). This problem worsens in semi-arid to arid environments where ET flux is much smaller than in areas of high rainfall (Jovanovic & Israel 2012; Ramoelo et al. 2014).

2.4.1 Surface energy balance

Global ET is often calculated as a residual of the surface energy balance (Figure 2.2), the balance of energy between the atmosphere and the surface of the Earth. It describes how net radiation is partitioned between heating the ground, heating the ground cover and the atmosphere. The energy balance equation is given as (Bastiaanssen et al. 1998):

Equation 2-1

$$R_n = G_0 + H + \lambda E$$

Where R_n is net radiation;

G_0 is the soil or ground flux;

H is the sensible heat flux; and

λE_i is the latent heat flux.

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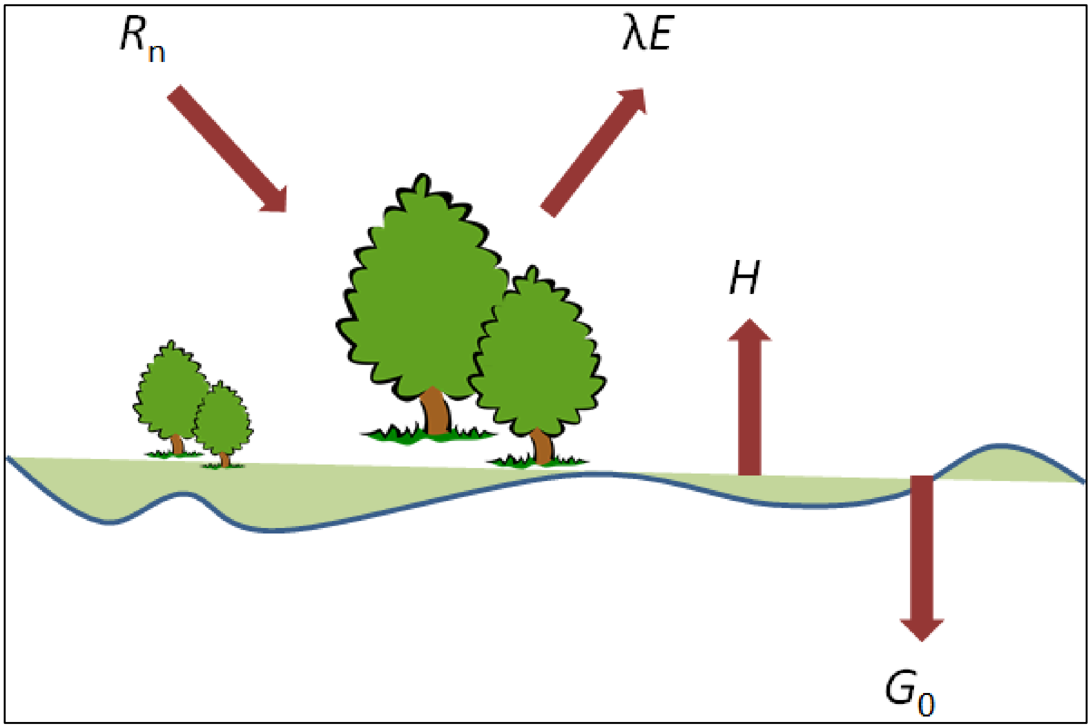

Figure 2.2 Surface energy balance diagram showing the four components which include: Net radiation (Rn), latent heat flux (λE), sensible heat flux (H), and soil heat flux (G_0). This shows the partitioning of energy between the ground and the atmosphere.

The net radiation (R_n) represents the total available energy. The soil or ground heat flux (G_0) is energy lost due to ground heating and this variable is positive when directed away from the surface into the ground. The sensible heat flux *(H)* represents energy lost by the surface through transferring heat to the atmosphere and this is positive when directed away from the surface into the atmosphere. The latent heat flux (λE) is the energy lost from the surface through evaporation (Bastiaanssen et al. 1998).

2.4.2 Penman – Monteith equation

The Penman-Monteith equation was developed to calculate the total evaporation and transpiration from the Earth's surface (Allen et al. 2005). The method combines the energy balance with mass transfer and uses four main climatological variables: wind speed, temperature, solar radiation and relative humidity (Allen et al. 1998; Allen et al. 2002; Allen et al. 2005; Mu, Zhao & Running 2011). According to Allen et al. (2005), the Penman-Monteith equation was initially developed by Penman by combining the surface energy balance and mass transfer approaches to estimate ET

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from an open water surface. The equation was later improved by Monteith to include a surface resistance term and an improved aerodynamic resistance term (Allen et al. 2005).

The Penman-Monteith equation is given as follows (Allen et al. 1998);

$$\lambda ET = \frac{\Delta(R_n - G) + PaCp\,(\frac{e_s - e_a}{r_a})}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad \textit{Equation 2-2}$$

where	λET	is the latent heat of water vaporisation ($J.m^{-2}.s^{-1}$);
	R_n	is the net radiation ($J.m^{-2}.s^{-1}$);
	G	is the soil heat flux ($J.m^{-2}.s^{-1}$);
	e_s	is the saturated vapour pressure of the air at a specific height (Pa);
	e_a	is the mean vapour pressure of air at a specific height (Pa)
	Pa	is the mean air density ($Kg.mol^{-1}$);
	Cp	is the specific heat capacity ($J.Kg^{-1}.K^{-1}$);
	Δ	is the gradient of saturation vapour pressure-temperature relationship ($Pa.°C^{-1}$);
	Γ	is a constant ($0.066\ kPa.K^{-1}$); and
	r_s / r_a	is the surface and aerodynamic resistance.

The equation also includes resistance factors, the surface (r_s) and aerodynamic resistance (r_a) terms. The surface resistance term (r_s) represents resistance of vapour flow through the stomata, the total leaf area and the soil surface resistance to vapour flow. The aerodynamic resistance term (r_a) represents resistance of air flowing over vegetation surface and upward.

2.4.3 Conventional methods of evapotranspiration monitoring

Conventional methods of monitoring ET can be grouped into three categories: water balance approaches, micro-meteorological approaches and meteorological approaches. These methods have been widely used in research studies where in some cases satisfactory results were produced (Odhiambo & Savage 2009) while in others numerous limitations or potential ways of improvements were demonstrated (Chen et al. 2005; Glenn et al. 2007; Odhiambo & Savage 2009; Ramoelo et al. 2014). One of the biggest challenges with conventional methods of monitoring ET include that point-based methods do not have the ability to accurately capture the ET variability

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across large landscapes (Ramoelo et al. 2014). Data availability has also been recognised as a challenge when using flux towers for measurements; as these methods have high sensitivities to weather conditions around the site. Ramoelo et al. (2014) reported that at severe weather conditions flux towers tend to produce inaccurate values or totally missing data for some days. Although the conventional methods of monitoring ET have their limitations, they are useful for smaller areas such as farming areas. This provides the opportunity for the development of other methods that could be upscaled to monitor larger geographical areas (smaller spatial scales). The next section will highlight the three conventional methods (water balance approach, meteorological and micro-meteorological methods), followed by remote sensing based approaches.

2.4.3.1 The water balance method

The water balance method is a hydrological approach to estimating ET in a given catchment; according to Zhang, Dawes & Walker (2001), it is also an approach that is used to understand how the partitioning of rainfall in a particular catchment can be affected by changes in catchment conditions such as runoff and groundwater storage. The water balance method requires clear knowledge of a catchment's rainfall and discharge data which includes, for example, groundwater storage and outflows (Zhang, Dawes & Walker 2001). The equation for determining the water balance of a catchment is given by (Zhang, Dawes & Walker 2001) as;

Equation 2-3

$$P = ET + R + D + \Delta S$$

where P is precipitation;
ET is actual ET;
R is the runoff;
D is the recharge to groundwater; and
ΔS_i is the change in soil water storage.

Precipitation (P) is the largest and most important component of the hydrological cycle and can vary significantly within large catchments spatially and temporally. The ET is the second largest component of the water cycle as previously mentioned; it is responsible for returning approximately 80% of the water on the Earth's surface back to the atmosphere. The evapotranspiration component in the water balance is highly affected by the type of vegetation

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present in a catchment (Zhang, Dawes & Walker 2001). Runoff (R) is largely correlated with the rainfall component and this is also affected by the slope, moisture conditions and soil type. According to Zhang, Dawes & Walker (2001) the type of vegetation present in a catchment area affects rainfall interception and therefore hinders a portion of the rainfall from reaching the surface. Recharge and soil water storage components are generally the smallest components of the water balance equation; over large spatial and time scales estimate measurements of recharge can be obtained from knowing rainfall and ET (Zhang, Dawes & Walker 2001).

2.4.3.2 Meteorological approaches

Meteorological approaches used for the estimation of reference ET are methods which make use of meteorological and climatological data (Jovanovic & Israel 2012). This approach involves using measured station data at fixed points to calculate reference ET, and this is one of the disadvantages of such methods since they are unable to capture the spatial variability of ET (Chen et al. 2005). In addition to this, since most methods used to estimate reference ET are developed for specific sites, they are often not applicable in other areas. An example of such methods include the Thornthwaite method (Chen et al. 2005). The Thornthwaite method is an approach based solely on the measurement of temperature and latitude to determine the ET of a particular area (Chen et al. 2005). Challenges observed while evaluating this method in China included that the method was unable to capture the temporal variability of ET, possibly because of the importance of missing variables not taken into account, such as wind speed, solar radiation and humidity (Chen et al. 2005). This was observed after spatial and temporal variations in regional ET estimated with the Thornthwaite method were compared to estimates from pan evaporation (Chen et al. 2005). Methods such as the Penman-Monteith described above (2.4.2) are often used to assess or validate the performance of other meteorological methods (Chen et al. 2005), because of their sound physical foundations and universal applicability. In the end once reference ET has been estimated using these methods, there is then a need to convert the estimates into potential- and actual ET.

2.4.3.3 Micro-meteorological methods

Micro-meteorological methods use sophisticated equipment fixed at a certain location to compute ET using the measured sensor data. Examples of these methods include eddy covariance flux towers, the Bowen ratio and scintillometry (Glenn et al. 2007; Odhiambo & Savage 2009;

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Jovanovic & Israel 2012; Ramoelo et al. 2014). These methods generally measure the moisture fluxes in and out of a canopy; and the eddy covariance flux tower has the ability to measure carbon dioxide fluxes. Challenges with micro-meteorological methods generally include that they use sophisticated equipment which can be costly and require highly trained individuals to operate (Glenn et al. 2007). In addition to this, these methods are point measurements and have a limited radius that they are able to cover.

Improvements in remote sensing algorithms present an opportunity to accurately monitor changes in ET for larger geographical extents and over longer periods. Studies have assessed the performance of remote sensing algorithms that calculate ET as a residual of the energy balance, including: the Surface Energy Balance System (SEBS), the Surface Energy Balance Algorithm For Land (SEBAL), Mapping Evapotranspiration At High Resolution With Internalized Calibration (METRIC) and the Moderate-Resolution Imaging Spectroradiometer (MODIS) based global algorithm, the MOD16 satellite product. These studies have estimated ET at different spatial scales and have shown the potential of remote sensing to provide more efficient ways of monitoring ET variability (Bastiaanssen et al. 1998; Allen, Tasumi & Trezza 2007; Mu et al. 2007; Cleugh et al. 2007; Jovanovic et al. 2015).

2.4.4 Remote sensing as a tool for monitoring evapotranspiration

Principally, as explained in the introduction, remote sensing is defined as the process of obtaining information about the properties of an object on the surface of the Earth without there being any actual physical contact. Remote sensing applications in water resource management offer an indirect technique of monitoring ET. This is done by using a sequence of equations in remote sensing algorithms that convert ground-based spectral radiances recorded using space-borne satellites into ET flux estimates (Bastiaanssen et al. 2005; Shoko et al. 2015). The improvements provided by remote sensing applications in comparison to in situ measurements include wider spatial coverage and application to both smaller and larger areas (Bastiaanssen et al. 2005; Jovanovic & Israel 2012). This advantage has been a driver for the increased application of remote sensing techniques in water resource management (Glenn et al. 2007). Lastly, remote sensing techniques offer a more cost-efficient manner of operating environmental monitoring studies, particularly at larger spatial scales where it would be costly to monitor on the ground especially on a frequent basis (Ramoelo et al. 2014). The next section will describe examples of some

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commonly used remote sensing based ET algorithms, including SEBAL, SEBS, METRIC and MOD16.

2.4.4.1 Surface Energy Balance Algorithm for Land (SEBAL)

The Surface Energy Balance for Land Algorithm is a remote sensing algorithm based on the surface energy balance equation (Bastiaanssen et al. 1998) that uses physical relationships, satellite and meteorological data to estimate ET (Jovanovic & Israel 2012). The algorithm was formulated by Bastiaanssen et al. (1998). In addition to remotely sensed data, meteorological data are also applied in the algorithm to estimate ET, these data sets include: wind speed, solar radiation, humidity and air temperature (Jarmain et al. 2007). To generate the net radiation (Rn) term in the energy balance equation (Equation 2-1), SEBAL uses surface albedo, surface emissivity and temperature. To compute the soil heat flux (G), the algorithm uses surface temperature, surface albedo and the Normalized Difference Vegetation Index (NDVI). Sensible heat flux is computed using surface temperature, roughness and wind speed. A self-calibration procedure is applied to estimate extreme dry (H = Rn – G) and wet (H = 0) conditions on the pixels. Finally, latent heat flux (λE) is obtained as the residual of the energy balance (Jarmain et al. 2007; Jovanovic & Israel 2012). One of the major advancements made in the development of SEBAL is the use of a near-surface temperature gradient indexed to the radiometric surface temperature giving it the large advantage of not requiring surface temperature calibration (Allen, Tasumi & Trezza 2007). In addition to this, SEBAL requires less input for application, however it has a wide range of applicability. The description of the full SEBAL algorithm can be found in Bastiaanssen et al. (1998) and Bastiaanssen et al. (2005).

In the Western Cape, the SEBAL algorithm was used to understand the usefulness of SEBAL for water use efficiency measurements on farms (Jarmain et al. 2007). The estimated ET and water yield of grapes from the SEBAL model were compared with field water balance data. The study was carried out in four grape producing areas in the Western Cape over two growing seasons. The results found that the SEBAL algorithm was able to estimate the evaporation and the yield of grapes. The total evaporation from SEBAL was found to be within 18% of that which was measured using field data while the yield estimated from satellite data was found to be within 5% of that which was measured by field measurements. Overall the results showed that the SEBAL algorithm has the ability to produce accurate ET results at small-farm spatial scale.

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A similar regional study was conducted in the Low-Middle Sao Francisco River Basin in Brazil where SEBAL ET and water productivity parameters were assessed (Teixeira et al. 2009). Satellite estimations of ET were compared to field measurements to determine the applicability of remote sensing in regional scale water productivity studies (Teixeira et al. 2009). Results showed that there was only a 4.7% difference in the ET estimated by satellite and that measured in the field for natural vegetation in 2004. In the year 2005 this difference dropped to 4.1% in natural vegetated areas. In an irrigated site, the differences were 0.6% and 0.5% in the years 2004 and 2005 respectively (Teixeira et al. 2009). Overall, the results showed that irrigated orchards had recorded much higher ET compared to natural vegetated sites. The improvements in these results from previous studies were due to local calibrations which had been applied to the SEBAL algorithm (Teixeira et al. 2009).

2.4.4.2 Surface Energy Balance System (SEBS)

The Surface Energy Balance System is a single-source model that was developed by Su (2002) to measure atmospheric and surface evaporative fractions using satellite, meteorological and radiation information (Van Der Kwast et al. 2009). Single-source models use one resistance term and assume that a single temperature and humidity value is sufficient to represent all surfaces (Van Der Kwast et al. 2009); this is one of the major differentiating factors of SEBS compared to SEBAL (Wang, Parodi & Su 2008).

The SEBS algorithm consists of three data inputs; satellite data components calculated using reflectance and radiance include: albedo, surface temperature, emissivity, fractional vegetation cover and leaf area index (Su 2002; Van Der Kwast et al. 2009). In the absence of the required vegetation information, the NDVI is utilised. Meteorological data components include: air pressure, temperature, humidity, and wind speed at a defined reference height (Van Der Kwast et al. 2009; Su 2002). In addition, SEBS uses radiation data, which is either measured directly or can be modelled. These include downward solar radiation and downward long-wave radiation (Su 2002).

Rwasoka, Gumindoga & Gwenzi (2011) studied ET trends based on SEBS algorithm in different land cover types in the Manyame catchment, a headwater catchment in the Manyame River located in Zimbabwe. Results showed that high ET fluxes were recorded in broad-leaved and closed-leaved deciduous forest types compared to savannah type environments. Smaller ET fluxes were

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recorded from closed-leaved to open-leaved grasslands and this was said to be due to plant-to plant competition between the woody species and grasses, resulting in an overall loss of moisture and as such low ET fluxes (Rwasoka, Gumindoga & Gwenzi 2011). The overall results of the study showed that the SEBS algorithm is appropriate for application in the determination of actual ET in water resource management studies, and the use of spatial data for inputs such as air temperature and surface roughness, improves the accuracies of the algorithm (Rwasoka, Gumindoga & Gwenzi 2011).

Van Der Kwast et al. (2009) investigated the sensitivity of SEBS algorithm inputs; according to this study, estimated sensible heat fluxes were found to be accurate when a single land cover class is captured on the satellite footprint. When more land cover classes are introduced into a single footprint, errors were introduced by land surface variables such as surface temperature (Van Der Kwast et al. 2009). Disadvantages of SEBS highlighted by Gibson et al. (2013) included that users reported inaccuracies when applying the model in environments that were not primarily agriculture.

2.4.4.3 Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC)

The Mapping Evapotranspiration at High Resolution with Internalized Calibration algorithm was developed by Allen, Tasumi & Trezza (2007), and it also calculates ET as a residual of the energy balance (Allen, Tasumi & Trezza 2007; Allen et al. 2011). Similar to SEBAL, in the METRIC algorithm, net radiation (R_n) is calculated using narrow-band reflectance and surface temperature; soil heat flux (G) is estimated using net radiation, surface temperature and vegetation indices; and sensible heat flux (H) is estimated using surface temperature, surface roughness and wind speed (Allen, Tasumi & Trezza 2007).

The METRIC model, like SEBAL, uses a near surface temperature gradient giving it the advantage of not requiring absolute surface temperature calibration (Allen, Tasumi & Trezza 2007). In addition to this, and unique to METRIC, is that it is developed using reference ET compared to SEBAL which uses the evaporative fraction to extrapolate instantaneous ET (Allen, Tasumi & Trezza 2007). METRIC is primarily developed for use with high-resolution imagery with a resolution of 30 m, and as such can only be applied at regional scale (Allen, Tasumi & Trezza 2007). The METRIC model was tested by Irmak et al. (2011) at regional scale to determine the

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spatial and temporal variations of a fraction of reference evapotranspiration (ET_rF) map generated using METRIC. The study used Landsat images and the results were compared to field measurements obtained using the Bowen ratio method (Irmak et al. 2011). METRIC ET results were in agreement with the results obtained from the Bowen ratio method (Irmak et al. 2011). According to this study the METRIC model showed great potential for use and application in other studies estimating ET in larger environments and for longer temporal periods; however, for this to be achieved, accurate calibration and improvements of the model needed to be made (Irmak et al. 2011).

2.4.4.4 Moderate-Resolution Imaging Spectroradiometer (MODIS)

The MOD16 global ET algorithm uses data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite at a 1 km spatial resolution and estimates ET on an 8-day time frame. It is founded on the principles of the Penman-Monteith equation (Equation 2-2) and it also calculates ET as an energy balance residual (Jovanovic & Israel 2012; Mu et al. 2007; Ramoelo et al. 2014). The algorithm uses land cover data, leaf area index, fraction of absorbed photosynthetically active radiation and meteorological data from MODIS to compute estimates of potential and actual ET (Jovanovic & Israel 2012). The model was originally adopted from the algorithm developed by Cleugh et al. (2007) which was developed for global surface evaporation based on the Penman-Monteith method (Mu et al. 2007). The algorithm was then further developed by Mu et al. (2007), to calculate ET as the sum of vegetation transpiration during daytime and wet soil evaporation. It was then modified by Mu, Zhao & Running (2011) to include three new terms in the overall ET calculation as well as to improve some existing components. Added components included: intercepted canopy precipitation, wet soil evaporation and night-time ET. The MOD16 algorithm gives ET as a sum of canopy transpiration, soil evaporation and canopy evaporation (Jovanovic et al. 2015). The flow chart below (Figure 2.3) shows the components and formulation of the MOD16 algorithm and the full description of the improved MOD16 algorithm is described by Mu, Zhao & Running (2011).

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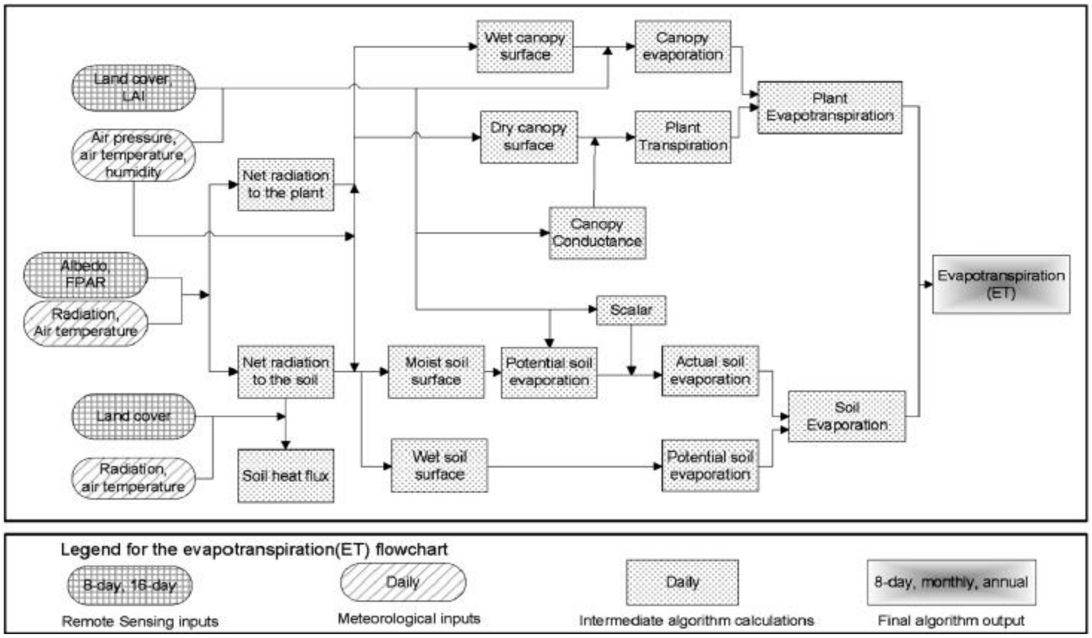

Adapted from Mu, Zhao & Running

Figure 2.3 Global terrestrial evapotranspiration algorithm based on the Moderate Imaging Spectroradiometer (MOD16).

Numerous studies have applied the MOD16 algorithm for monitoring spatial variations of ET. In South Africa the algorithm was first tested on a national scale by Jovanovic et al. (2015). This study was done to assess the spatial variation of ET and the interdependency between ET and other variables used in the development of the MOD16 algorithm (Mu, Zhao & Running 2011). Spatial distribution of ET and variables such as canopy evaporation, soil evaporation and transpiration were found to be the highest in the tropical wet eastern parts (Jovanovic et al. 2015). This was correlated with higher rainfall received in the eastern part of the country compared to the western parts. From the results it was concluded that ET (which is 67% rainfall) in South Africa is driven by mainly two factors and these include rainfall patterns and evaporative demand.

The MO16 global ET product was validated in a small-scale savannah ecosystem in Kruger National Park using an eddy covariance flux tower data. The results showed that high correlation was observed between ET and rainfall; this was both for the data from the flux tower and the MOD16 satellite. However, numerous discrepancies were found when trying to compare the MOD16 ET data to the flux tower data (Ramoelo et al. 2014). These were due to various flux tower and MOD16 limitations such that at a smaller scale, the evaporation from the soil and transpiration from the plants are affected by very site-specific factors such as the heterogeneity of

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the landscape and the microclimate of the site. Therefore, they ultimately affect the estimation of ET by the MOD16 satellite (Ramoelo et al. 2014). The height of the sensors in the eddy covariance flux tower is also a possible reason for the inaccuracies found in the data. According to Ramoelo et al. (2014), sensor height influences the footprint of the satellite, which in the end does not correspond well with the one covered by the MOD16 pixels, and this requires footprint modelling to be corrected. In addition to this, factors related to local calibration of the MOD16 algorithm may have contributed to the observed discrepancies in the satellite measurements.

2.5 SCENARIO BUILDING IN WATER RESOURCES MANAGEMENT

Planning for the future is often linked to increased uncertainty. This often results from the presence of multiple driving forces involved in determining the possible future outcome. Scenario analysis is a method that is used to deal with challenges of planning under uncertainty by analysing impact of various scenarios. According to Haasnoot & Middelkoop (2012) these scenarios are hypothetical futures which reflect on the past to assist in developing action plans for the future. Differing from predictions or forecasts, in scenario planning multiple outcomes are obtained as possible futures instead of producing a single most likely outcome (Dong, Schoups & Van de Giesen 2013). An important exercise in scenario planning involves the identification of important and interrelated elements which are at play in the system (Mahmoud, Gupta & Rajagopal 2011). In water resource management planning for example, some of the most important elements to reflect on would include changes in weather or other natural events and in addition, changes in human behaviour which drive their interactions with water resources (Haasnoot & Middelkoop 2012). Scenario development was used by Mahmoud, Gupta & Rajagopal (2011) to address water management related issues in North Arizona. According to this study, there are five key stages involved in scenario planning: defining the scenario, construction of scenarios, analysis of scenarios, assessment of scenarios and lastly, the risk management (Mahmoud, Gupta & Rajagopal 2011). In addition, this study alluded to the challenge of inherent subjectivity experienced during scenario development, and this highlighted the need to have diversity in terms of areas of expertise during scenario development sessions. In a review of the application of scenarios to inform water policy in the Netherlands, Haasnoot & Middelkoop (2012) stated that the use of scenarios guided a paradigm shift from future prediction to the exploration of multiple futures and this improved decision making.

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2.6 LITERATURE REVIEW SUMMARY

The literature review has drawn attention to the importance of water as a natural and human resource and focus has been made on South Africa, which is considered a water scarce country. The threats to the country's water quality and quantity have been briefly discussed. More importantly the continued pressure on this scarce resource from various water users is highlighted and this shows that there is a need for methods of quantifying water use for more efficient water planning and allocation. Realising the different elements and drivers interacting to drive changes in water resources (quality and quantity) emphasises the potential role of scenario generation in water resource management.

Understanding of the terrestrial water cycle forms part of the actions towards achieving efficient use of water resources. Evapotranspiration as the second most important component of the water cycle has been widely researched. The interaction of ET with other climatic, atmospheric or spatial variables makes it very variable both in space and in time. Since humans do not have the ability to directly control most variables that influence ET it is important that more focus is placed on the interaction of ET with changes in variables such as land cover since this variable is to a certain extent directly altered by humans. There are numerous methods which have been developed for the monitoring of ET, more common ones being the field-based methods which involve the use of water balance calculations, meteorological data and sophisticated equipment which calculate ET for localised areas (Chen et al. 2005; Odhiambo & Savage 2009; Senay et al. 2011; Jovanovic & Israel 2012).

Although these methods have been widely applied, their inability to be upscaled for larger area coverage monitoring has been a long-standing disadvantage (Jovanovic & Israel 2012). This has given the development of remote sensing based methods the advantage given their potential spatial and temporal scale capabilities. Examples of such algorithms which calculate ET as an energy balance residual discussed in the literature review include SEBAL, SEBS, METRIC and MOD16 (Bastiaanssen et al. 1998; Su 2002; Allen, Tasumi & Trezza 2007; Mu et al. 2007). There is a need for continued development and application of remotely sensed satellite data and research looking into the interactions of ET and other variables that alter it; such research is critical for the continued development of remote sensing technology and the improved understanding of the process of ET in general.

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CHAPTER 3 RESEARCH METHODS

There are three main sections in the Research Methods chapter of the study: the first section (3.1) provides a description of the different study sites representing the spatial scales of investigation. The second section (3.2) provides a description of the data extraction process followed in the study; lastly, section three (3.3) describes how the extracted data were analysed in order to respond to questions outlined in the introduction section. Data sets used in the study included MOD16 satellite data product, rainfall data and land cover data sets with reclassified land cover classes. The zonal statistics function was used to extract statistical data from the satellite data products. Two rainfall data sources were used in the study: the first one was ground station rainfall data with stations from different provinces with the number of stations per province based on data availability. The second rainfall data set was spatially modelled rainfall data which was modelled using the station data and the Schulze (2006) long-term rainfall data set; full descriptions of these data sets are provided later in this section. Two land cover data sets were used: the 2013/14 National Land Cover (NLC) data was used because it was the most up-to-date land cover data available for the country. The second land cover data set used for the purpose of the study was named areas-of-no-change (AoNC) and represents land cover classes which remained unchanged between 2000 and 2012. A full description of this data set is provided later (3.2.1.2). Figure 3.1 shows the research methods and analysis flow chart.

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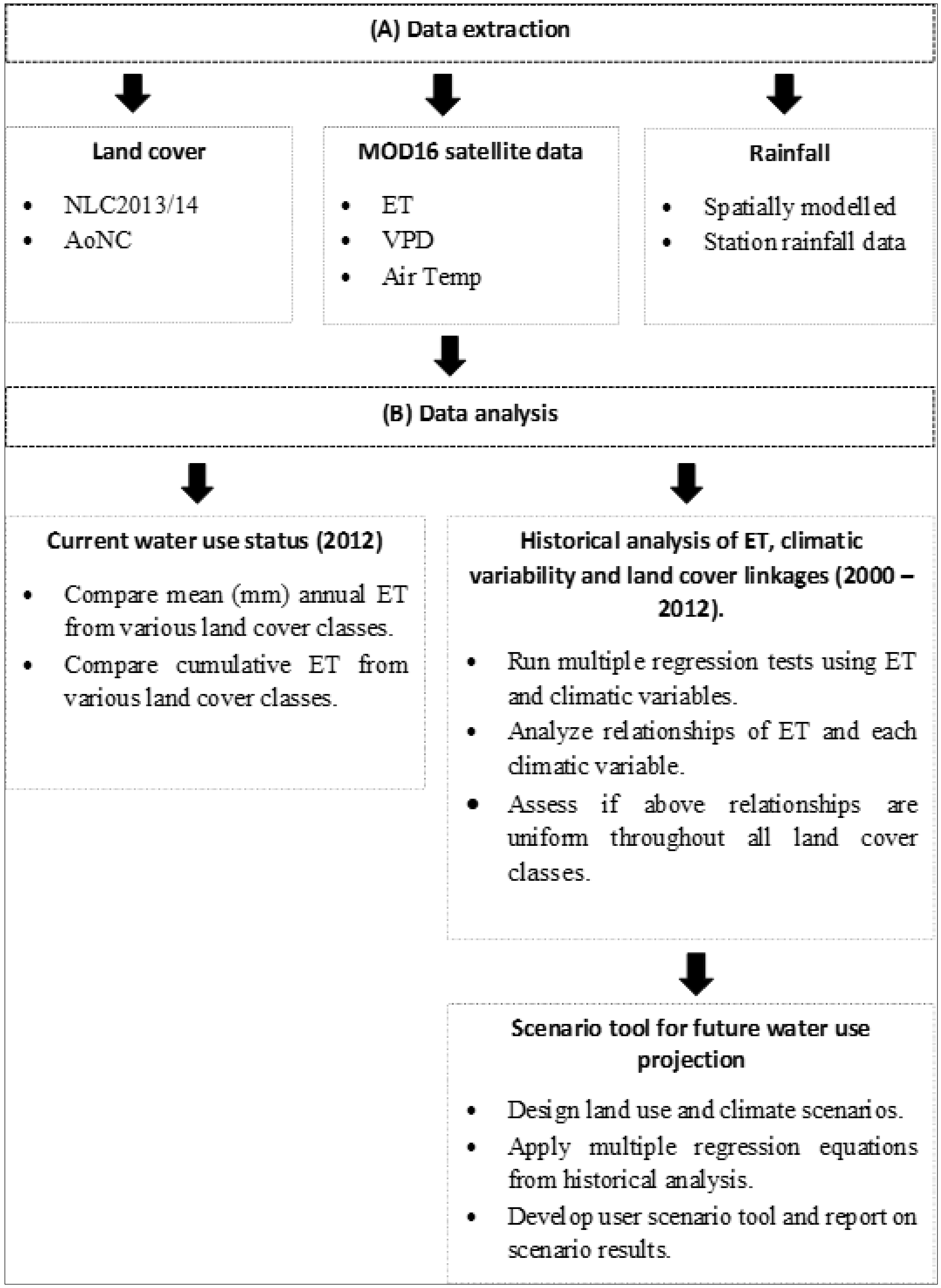

Figure 3.1 Research methods and materials flowchart showing the data sets extracted in the study and how they were analysed. (A) Shows type of data sets extracted in the first part of the section and (B) shows the data analysis done.

The first part of the data analysis was done to determine the current water use of various land cover classes at provincial and catchment scale. The MOD16 2012 annual ET data and the NLC2013/14

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data were used for this analysis assuming these data sets represent the current status due to data availability. The aim of the second part of the data analysis was to determine the linkages between ET, climatic variability and land cover changes. To do this, estimates of ET from MOD16 as a response variable were used and vapour pressure deficit (VPD) and temperature from the MOD16 satellite imagery were used as predictor variables. The last predictor variable was rainfall. To determine the links between these variables, multiple regression analysis and Pearson correlation tests were applied. The final part was the development of a water use scenario tool; the tool was developed in order for users to be able to project future ET trends which occur as a function of land use and climate variability.

3.1 INTRODUCTION TO STUDY SITES

There are two spatial scales used to inform our study; the first is national scale (Figure 3.2). The second spatial scale is sub-catchment level and for this spatial scale two case study areas were used. The first sub-catchment is the Inkomati (Figure 3.4) located in the Mpumalanga within the Inkomati Water Management Area (WMA), while the second sub-catchment is the Wider Cape area (Figure 3.5) located in the Western Cape mostly within the Berg Water Management Area.

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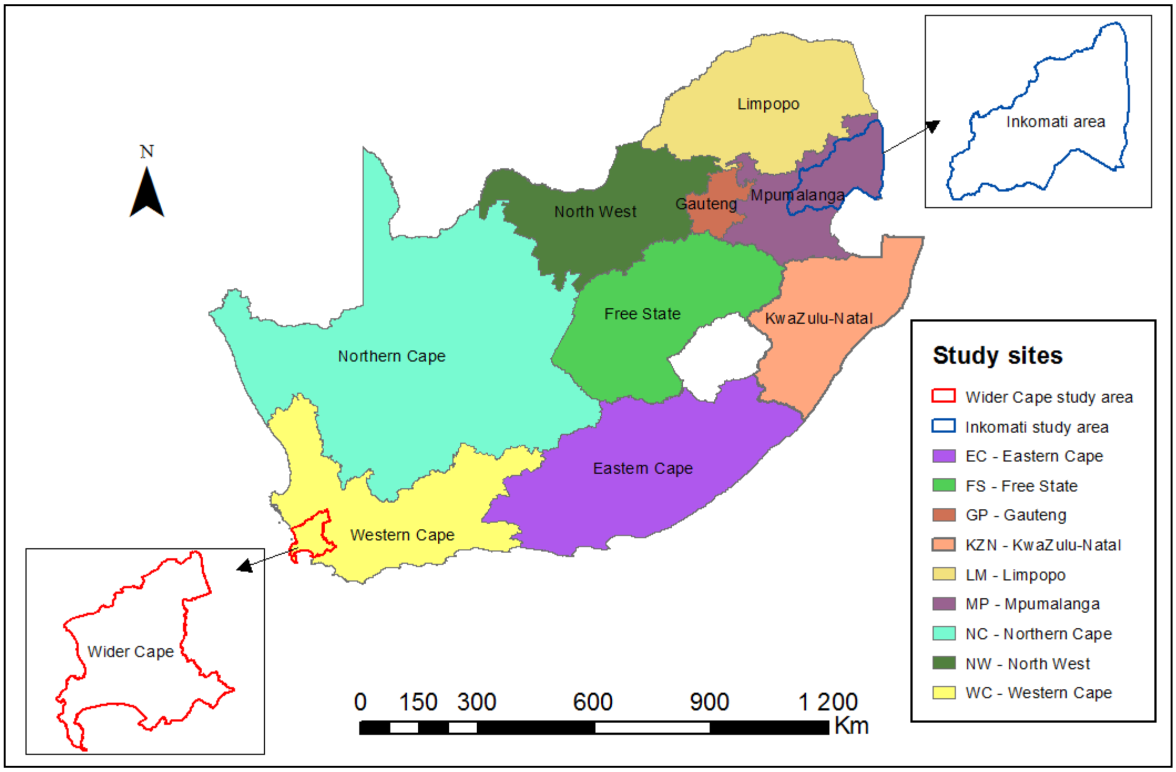

Figure 3.2 Study spatial scales of investigations.

The national scale of investigation was conducted on the nine official provinces of South Africa as shown above (Figure 3.2). The two sub-catchment scale study areas occur in geographically and climatically different environments thus making them ideal for understanding the role of climatic drivers. The following section describes each of the study sites in more detail. Description of the climate, geology, elevation and general land cover / land use in each site is provided.

3.1.1 Description of study sites

3.1.1.1 Provincial

The first spatial scale of investigation is at national level and has been subdivided into the nine official provinces of South Africa (Figure 3.3). South Africa is generally very heterogeneous both spatially and climatically resulting in the observed differences in the climate, land cover type and elevation between the nine provinces.

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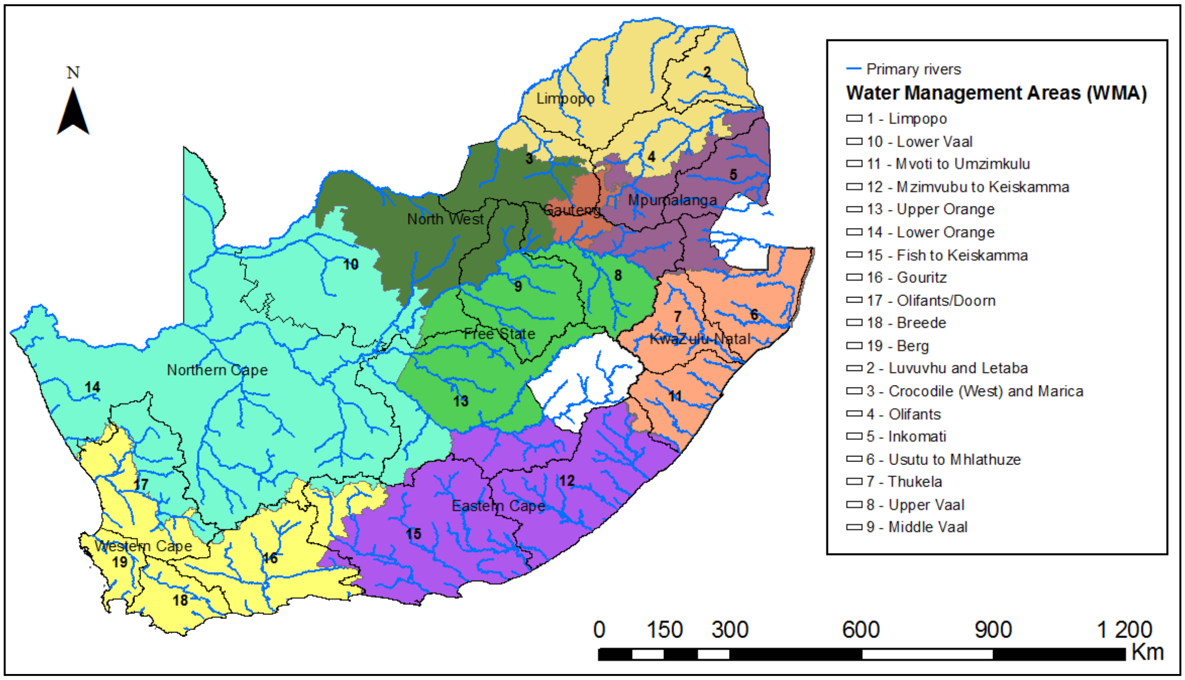

Figure 3.3 National provincial boundaries and Water Management Areas (WMAs) in South Africa.

South Africa has a decentralised strategy for water management; the country has a total of nine Catchment Management Agencies (CMAs), and these CMAs manage a total of 19 Water Management Areas spread across the country. Five WMAs occur within the Western Cape, these include the Fish to Keiskama, Gouritz, Oliphants/Doorn, Breede and Berg (Collins & Herdien 2013). Water Management Areas within Mpumalanga include Inkomati, Oliphants, Usuthu to Mhlathuze and the Upper Vaal WMA.

3.1.1.2 Sub-catchment

The second scale of investigation is at a sub-catchment scale. The first study site, Inkomati catchment (Figure 3.4) is located in the north-eastern part of the country, in Mpumalanga (25° 21’ 40.09” South and 31° 03’ 45.58” East). Though parts of the larger catchment area extend into Swaziland and Mozambique, the largest part (61%) occurs within South African borders (Waalewijn, Wester & van Straaten 2005; de Lange et al. 2010). The study focuses only on the South African portion of the catchment.

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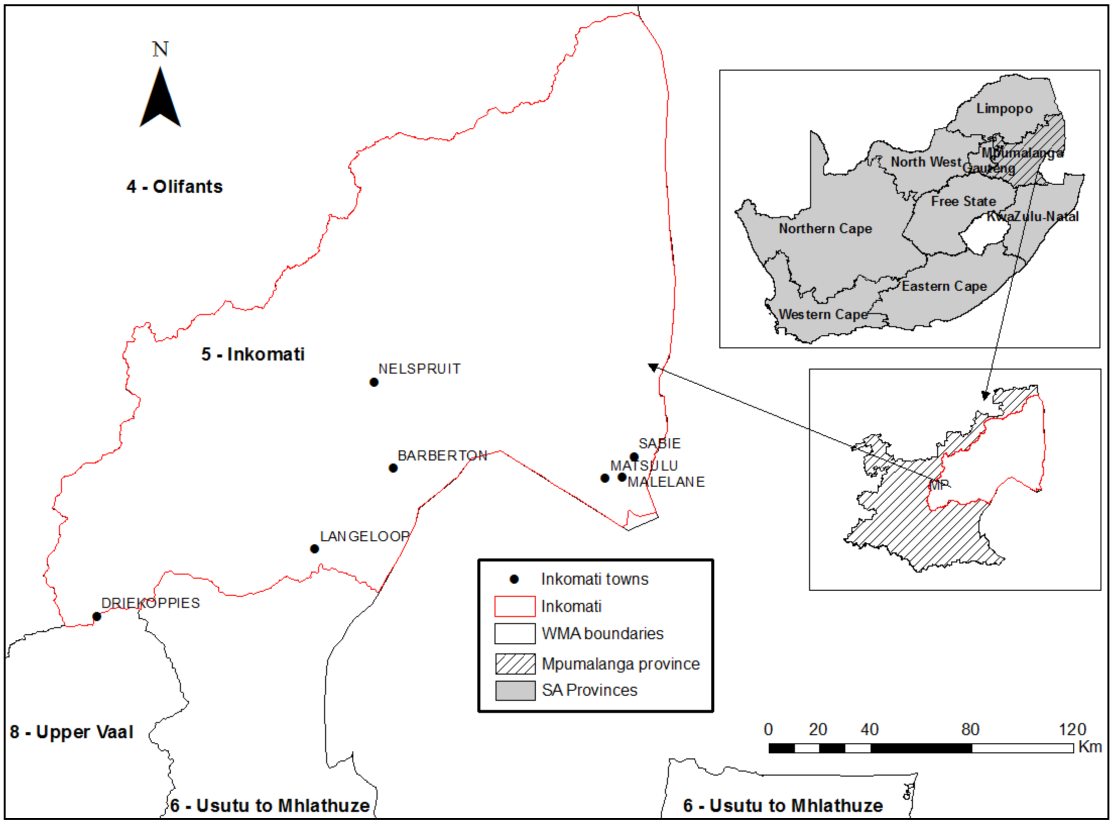

Figure 3.4 Inkomati area map showing the area boundaries, Water Management Area and the Mpumalanga province.

According to the last updated National Land Cover map, the three most dominant land cover classes in the Inkomati area include woodland/open bush, thicket/dense bush and grasslands. The land cover class descriptions are taken from the NLC2013/14. In considering general water use from the various land uses in the area, commercial irrigation is said to account for more than 60% of the total water used in the Inkomati area (de Lange et al. 2010). Afforestation is the second largest water user, followed by urban water use, mining and lastly industrial bulk water users that can also be classified under urban users. Irrigated crops in the area generally include tobacco, grain, sugarcane and other tropical fruits. Mbombela (formerly Nelspruit) is the largest urban area in the Inkomati and other less developed areas are found on the periphery of the city.

The Wider Cape area (also known as Greater Cape Town) is located in the Western Cape (33° 44' 56.04" South and 18° 45' 12.97" East), found mainly a portion of the Berg WMA (Figure 3.5).

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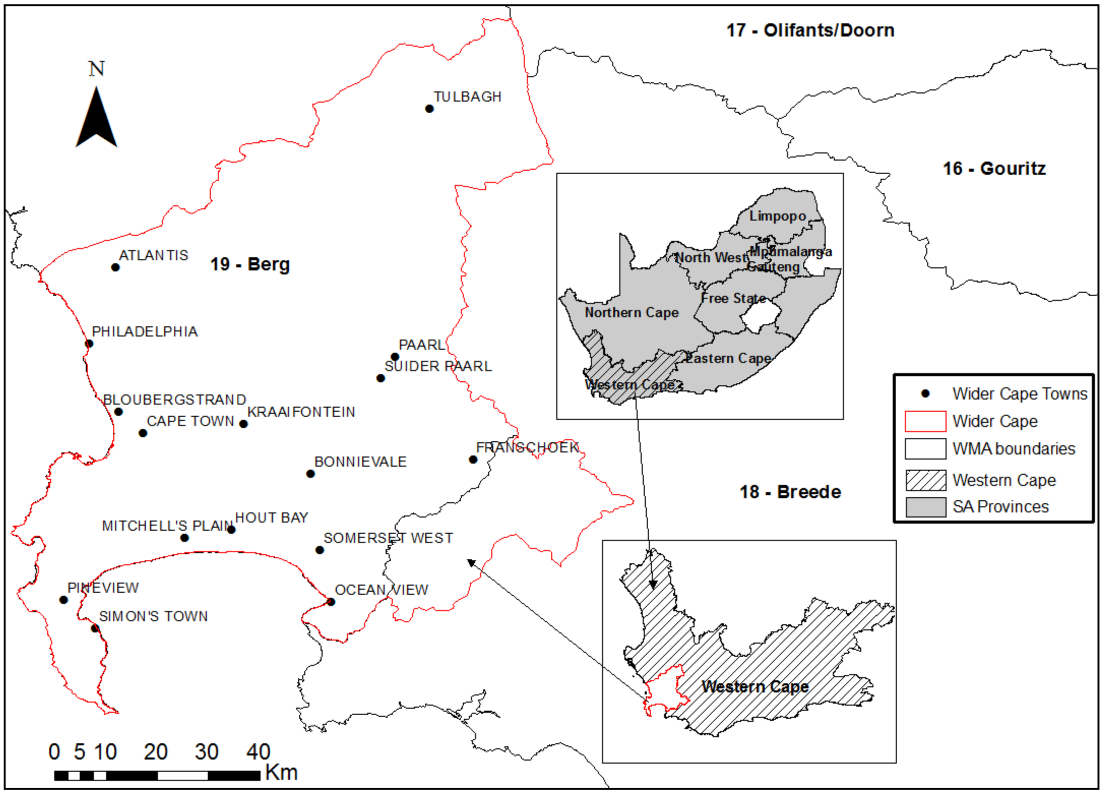

Figure 3.5 Wider Cape area map showing the area boundaries, Water Management Area and the Western Cape province.

The Wider Cape area is generally labelled as water stressed with the demand for water fast exceeding the supply. In addition to this there are great pressures on existing sources of water such as declining water quality, changes in climate affecting normal rainfall patterns and a fast growing population particularly in urban areas (Crane & Swilling 2008). The area hosts more than 70% of the total population of the Western Cape resulting in intense pressures on water supply especially for urban usage (Crane & Swilling 2008). As a result urban water use is the largest water use sector in the Wider Cape area. To sustain water supply there is strong interest for the exploration of aquifers in the area to augment the city's water supply. Exploration of such alternative water sources is important for the area since there is already significant pressure on surface water supplies which are now struggling to meet supply requirements (Crane & Swilling 2008; Ziervogel, Shale & Du 2010).

According to the Western Cape State of Environment Report (DEADP 2013), water supply in the larger Berg WMA is supplied by sources such as surface water (57%), water transferred from the Breede WMA through transfer schemes (27%), groundwater (8%) and others such as reusable

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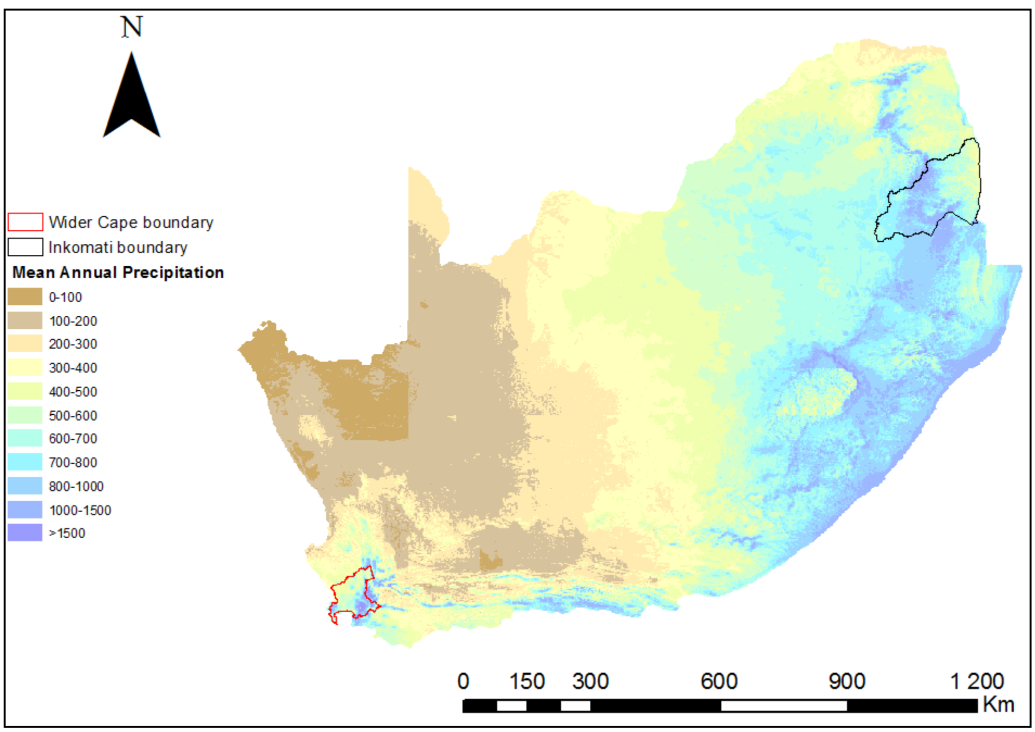
return flows (7%). Major users of the water include urban-based activities (54%), water used for irrigation (42%), and other uses such as ecological reserve (3%), afforestation (1%) and alien invasive plants (1%). Plantations found in the area comprise pines, wattle and gums, known to be large consumers of water and the cause of reductions in stream flows (DEADP 2013).

3.1.2 Climate

Rainfall is highly variable spatially and temporally across the country, and seasonal periods of low rainfall see many parts of the country becoming vulnerable to drought. Rainfall patterns also follow a strong gradient, which causes rainfall to increase from the western to the eastern part of the country as can be seen on the annual rainfall map below (Figure 3.6). Although the national annual mean rainfall is estimated to be between 480 mm and 500 mm, it is said that approximately 21% of the areas around the country receive rainfall below 200 mm per annum. Historical rainfall records show a progressive increase in extreme precipitation events in many parts of the country especially in the south western and eastern parts (Easterling et al. 2000; Groisman et al. 2005).



Source: WR2012

Figure 3.6 Countrywide mean annual rainfall (mm). Inkomati (black) and Wider Cape (red) study sites delineated in the map.

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In terms of the general temperature variability in the country, greater variations in average temperatures exist between the eastern and western parts of the country and less variation is observed in the southern to northern gradient. This is due to the different oceanic currents experienced: the western part of country experiences the colder Benguela current while the eastern part experiences the warmer Agulhas current (Walker 1990). Long term studies of temperature trends have reported historical increases in annual mean temperatures across the country; most of these studies report a general increase in temperature maxima and decline in extremely low temperature conditions (Kruger & Shongwe 2004; Kruger & Sekele 2013).

The Inkomati area occurs in a summer rainfall region (subtropical climate) where rainfall occurs during summer months and peaks between December and February. Low rainfall periods occur in the winter months. The mean annual rainfall experienced in the Inkomati rages between 400 mm and 1000 mm per annum with rainfall in other adjacent parts located in high-lying areas reaching about 1500 mm per annum (de Lange et al. 2010). Rainfall in the western part of the area is generally higher than in the eastern parts. Temperatures in the area peak in the summer months (in particular, January) and lowest temperatures are experienced in the winter (in particular, June) generally summers are hot with winters experiencing cool temperatures. Mean annual temperatures range between 17 °C and 21 °C.

The Wider Cape case study site occurs in a winter rainfall region, with rainfall peaks experienced in the winter months between May and September while periods of the lowest rainfall occur in the summer season between November and February (DWAF 2004). This part of the country is known to experience the highest variations in rainfall because of the extreme annual minima and maxima of rainfall received, making it vulnerable to disasters such as drought. Average annual rainfall received in the area ranges from 150 mm to 600 mm per annum (DWAF 2004). The highest rainfall in the area occurs in the southern mountainous parts and decreases further north. Mean annual temperatures in the area range between 16 °C and 18 °C from the western coastal parts to the easternmost part with average maximum daily temperatures of above 29.4 °C experienced in January and average minimum daily temperatures below 5 °C occurring in the month of June (DWAF 2004).

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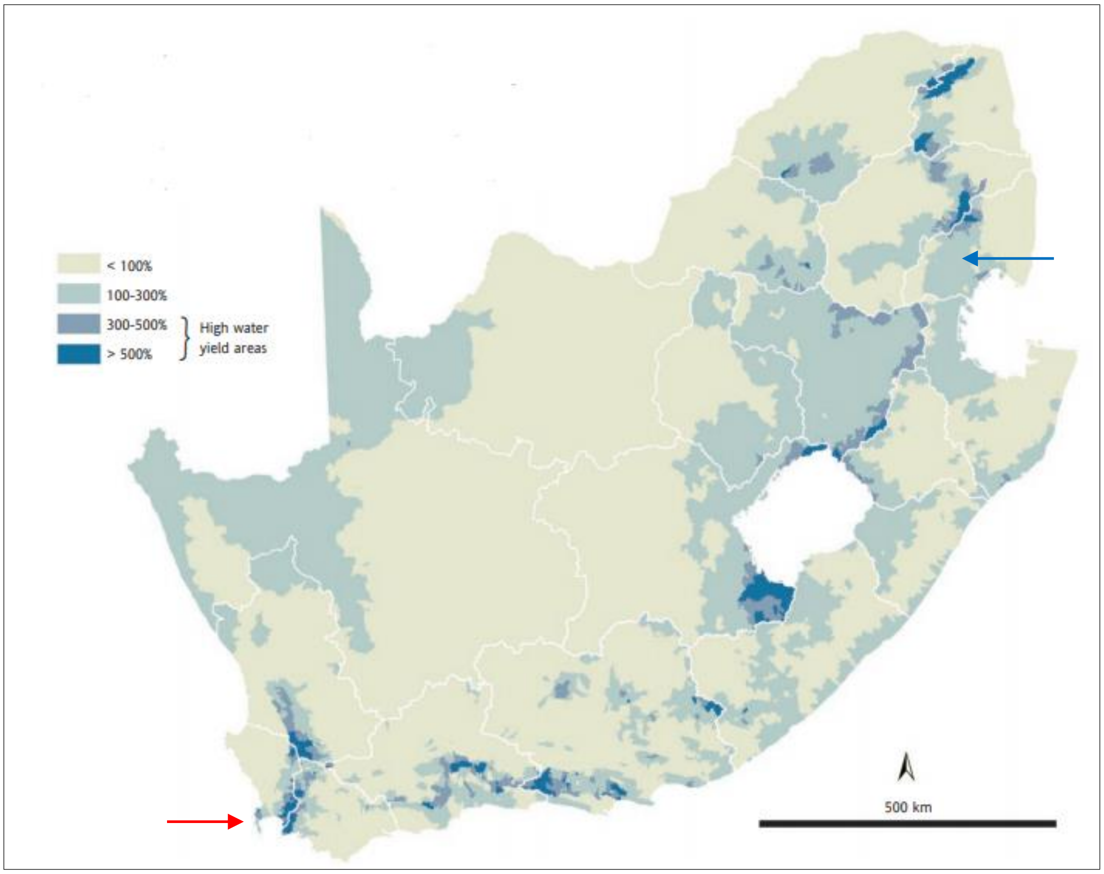
3.1.3 Hydrology

High water yield areas are defined as the areas where the mean annul runoff is at least three times larger than the average annual runoff of the larger catchment (Nel et al. 2011). South Africa has a number of these areas that are considered a priority for conservation purposes because of their important role in hydrology as a supplier of water to other drier parts of the country. These areas are shown in a map (Figure 3.7) obtained from Nel et al. (2011).



Nel et al. (2011)

Figure 3.7 South African areas of high water yield. Wider Cape location indicated by red arrow and Inkomati location indicated by blue arrow.

The map shows that there are more areas of high water yield located in the eastern to south-eastern parts of the country compared to the western, and the central parts of the country are the driest, following the pattern observed in the annual rainfall map (Figure 3.6). The high water yield areas make up only 4% of the area of the country and it is said that only 18% of these areas are under

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formalised protection (Nel et al. 2011). According to the map, the two sub-catchment study sites occur within the high water yield areas (300 – 500%).

3.1.4 Geology

South Africa has a high geological diversity; some geological formations are formed of mineral deposits and are therefore found to be rich in minerals while others consist of sedimentary rocks that occur as a result of many years of continued wind and erosion. The most predominant geological types in South Africa include Ecca, Kalahari and Adelaide that cover about 15% of the total area individually (Figure 3.8). To show these, geology type map adopted from Council of Geosciences was used (Figure 3.8). Variations in geology are important because they play a significant role in the types of soils found in a particular area which in turn govern the kind of land uses which are to take place in the area, for example, the type of agriculture.

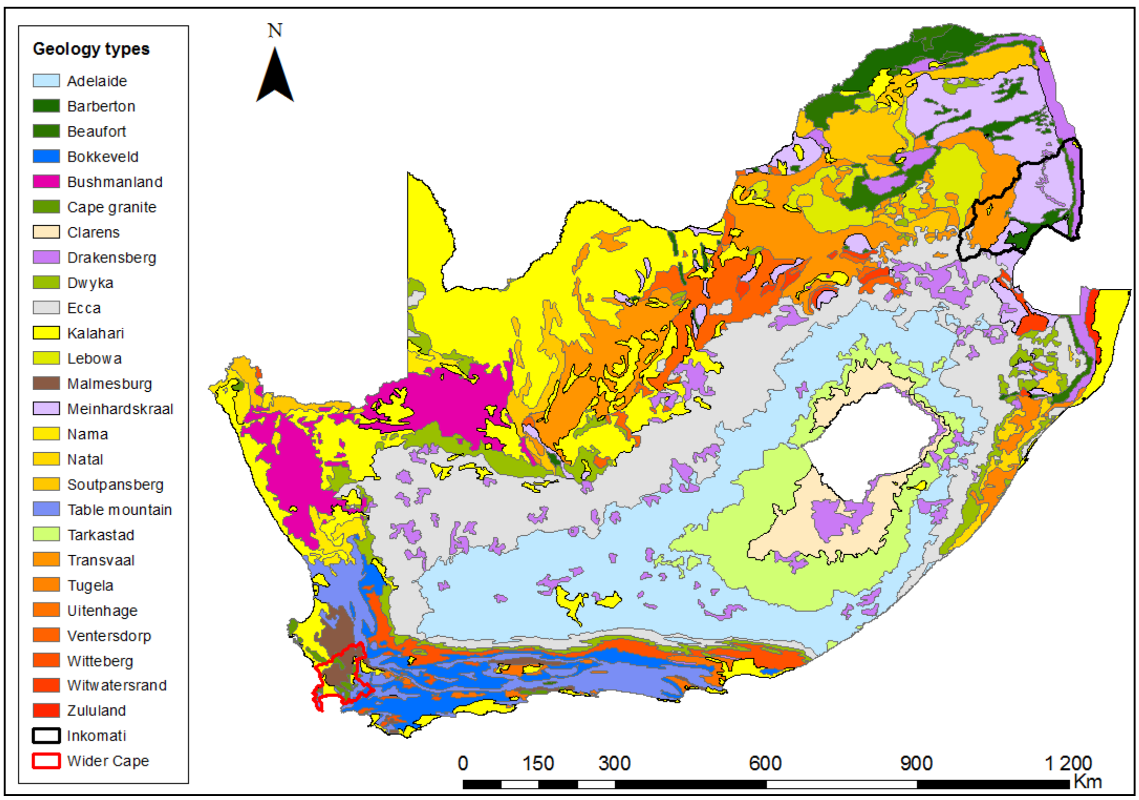

Figure 3.8 South African geology types. Delineated are the two sub-catchment study sites (red – Wider Cape and black – Inkomati area).

According to the geology map, in the Inkomati, the Meinhardskraal granite, Drakensberg and Barberton greenstone belt are the predominant geological types covering almost 70% of the

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Inkomati area. In the Wider Cape, Malmesbury (41%) is the largest geological type followed by the Table Mountain group (19%) and the Cape granite (17%).

3.1.5 Elevation

Elevation is a major driver of climatic variability across broad areas, influencing both temperature and rainfall patterns. South Africa has a large elevation range, with the highest elevation, approximately 3472 m, found in KwaZulu-Natal (Figure 3.9). The elevation map below was obtained from the USGS web portal.

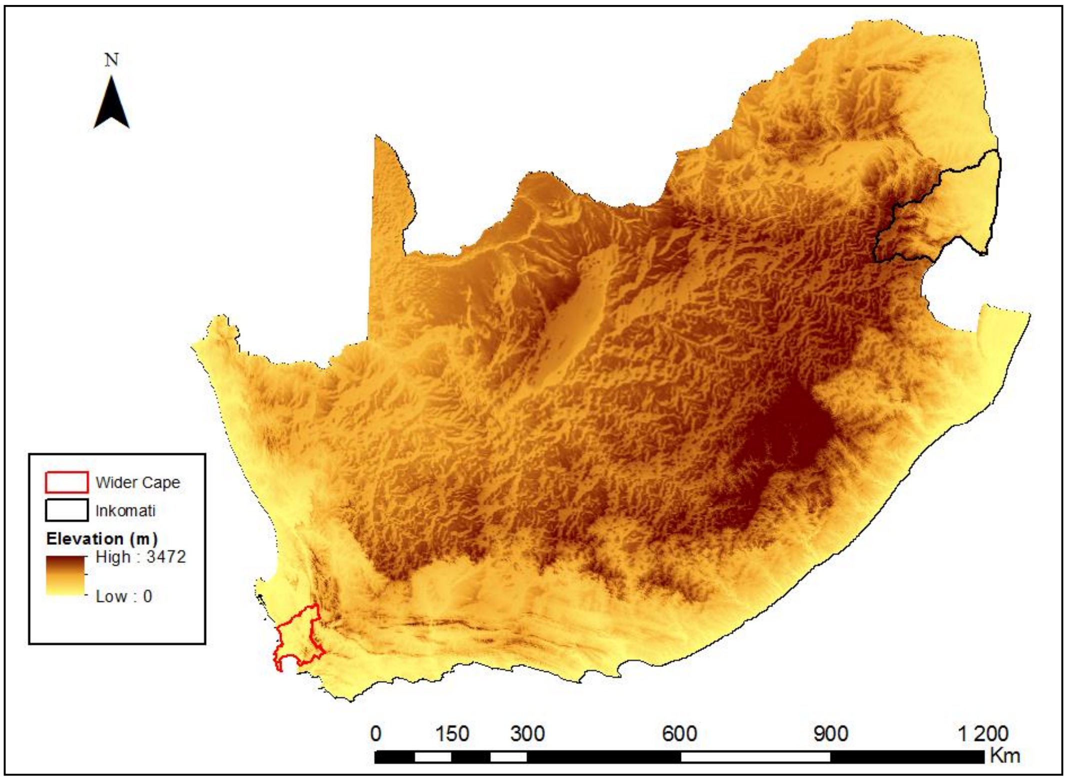

Figure 3.9 South African elevation (0 – 3472 m).

The Inkomati elevation ranges from 106 m to 2274 m and the topography of the area is generally divided in two: a plateau located on the western side is approximately 2000 m above sea level; and the eastern marginal lands which are located approximately 140 m above sea level. The Wider Cape area has relatively heterogeneous elevation, with the overall elevation ranging between 0 m and 1915 m. The next section describes the data extracted and analysed.

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3.2 DATA EXTRACTION

This section describes the different data sets that were used and the process followed to extract data for analysis. These data sets include: (1) land cover data sets (2) MODIS satellite imagery data – ET, temperature (ºC) and vapour pressure deficit (kPa); and (3) Rainfall data – monthly totals (mm).

3.2.1 Land cover data

There are two land cover data sets used in the study, the first is the latest NLC map product (NLC2013/14) that has been reclassified to 21 land cover classes (Figure 3.10). The second land cover data set is derived from the NLC2013/14 and the NLC1990. This land cover data was named the areas-of-no-change (AoNC) since it represents classes that have remained consistent between 1990 and 2013 (Figure 3.11), further explained below.

3.2.1.1 National land cover (NLC2013/14)

The NLC2013/14 is the latest updated version of the national land cover map, and this map was used for the current water use analysis (Figure 3.10). The NLC2013/14 product was generated using Landsat 8 data (2013 – 2014) by a private entity and made publicly available by the Department of Environmental Affairs. The data set contains a total of 72 classes and land use information for the entire country with a spatial resolution of 30 m (Ngcofe & Thompson 2015).

For the purpose of this study, the national land cover product classes were generalized into 21 comprehensive land cover classes in order to facilitate and simplify data processing and lastly to ensure that water use comparisons between the different land cover classes are simplified (Figure 3.10).

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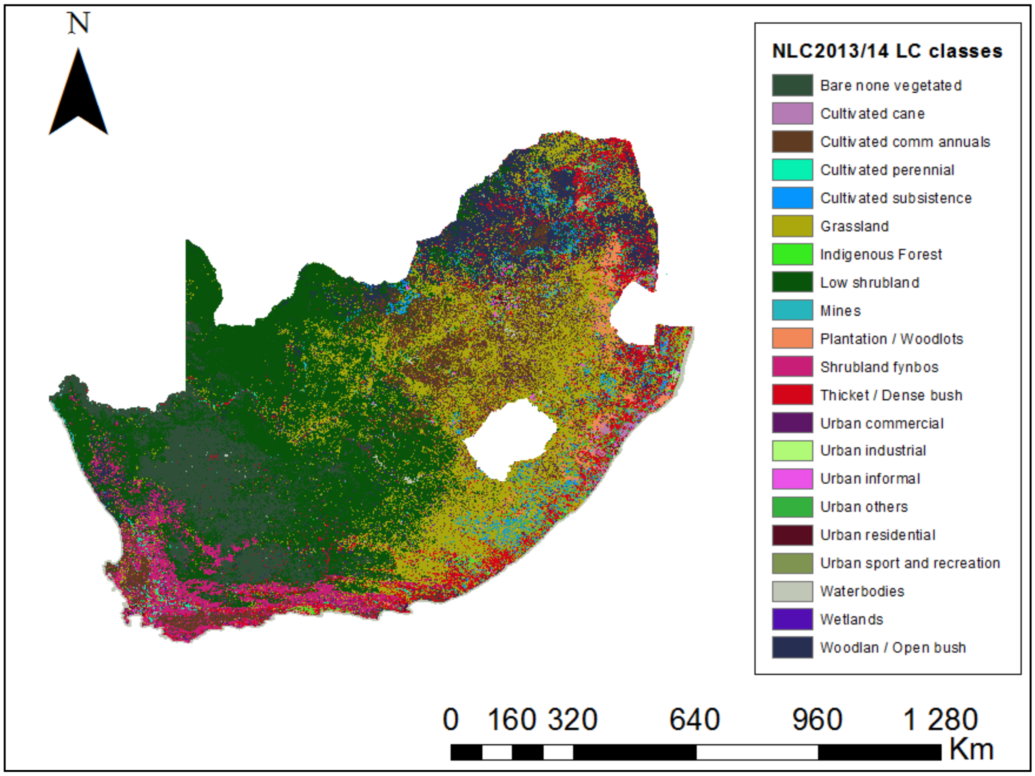

Figure 3.10 Reclassified 2013/14 national land cover map showing 21 land cover classes derived from the original 72 land cover classes.

A table listing the original land cover classes which were reclassified is available in the appendix A. This table (Table A.1) shows how the original 72 classes were combined to form the 21 land cover classes used for current land cover and water use analysis.

3.2.1.2 Areas-of-no-change (AoNC) classes

The areas-of-no-change analysis was performed to determine land cover classes which have remained consistent or unchanged from before the beginning of the study period and after the study period (2000 – 2012). To do this, a land cover map from before the study period (NLC1990) and the land cover map after the study period (NLC13/14) were compared to identify the classes that had not changed. According to the user report, the two land cover maps are regarded to have similar accuracy (GeoTerraImage 2016). The method used to achieve this involved firstly matching land cover classes in the NLC1990 to classes in the NLC2013/14 by identifying classes that had the highest pixel overlaps. Classes that did not occur in the NLC1990 were assimilated into existing classes in the NLC2013/14 with similar characteristics. The sugarcane class is an example of a

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land cover that was not identified in the NLC1990 data set and was therefore assimilated into the cultivated perennials land cover class.

The AoNC analysis was performed as part of the WRC project K5/2520/1, deliverable 5b and it was then applied in this study for analysis. The national AoNC land cover map is shown in Figure 3.11.

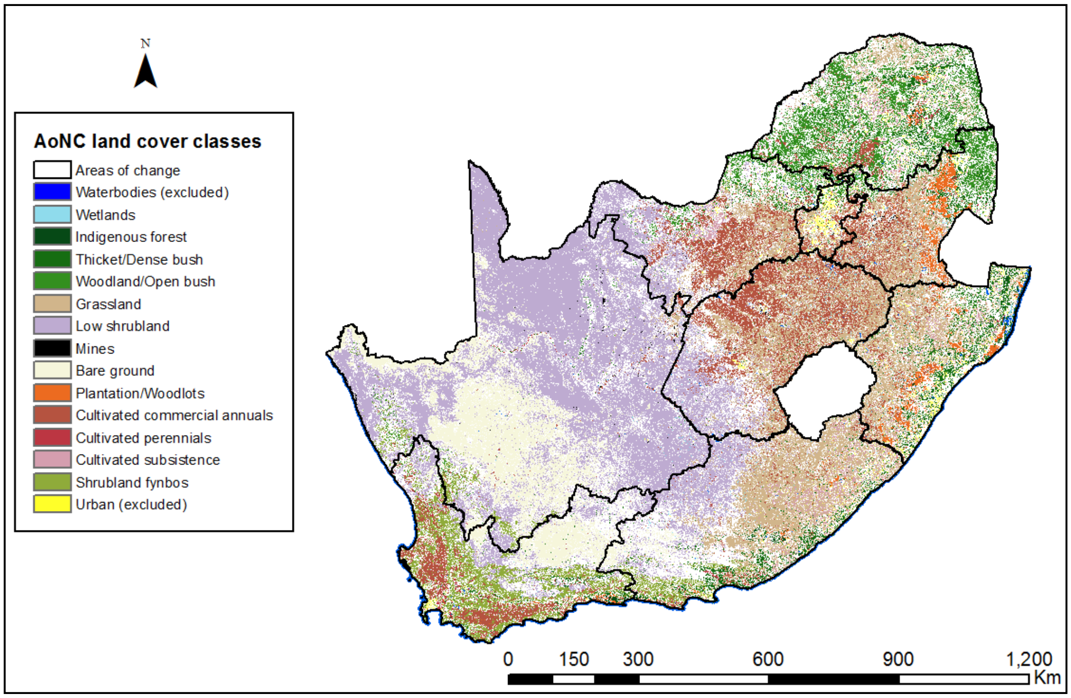

Figure 3.11 Provincial land cover classes map showing areas-of-no-change classes determined by comparing NLC1990 and NLC2013/14.

Although shown in the AoNC map, the urban and waterbodies land cover classes were not included in the analysis for the following reasons: (1) ET from urban land cover classes is not adequately estimated by the MOD16 satellite product and was therefore removed; (2) ET estimated from waterbodies is a function of evaporation. Therefore since this does not factor in transpiration it does not provide sufficient information on water use.

The AoNC map was then extracted for the Inkomati and Wider Cape sub-catchments using the ArcGIS extract by mask function (Figure 3.12).

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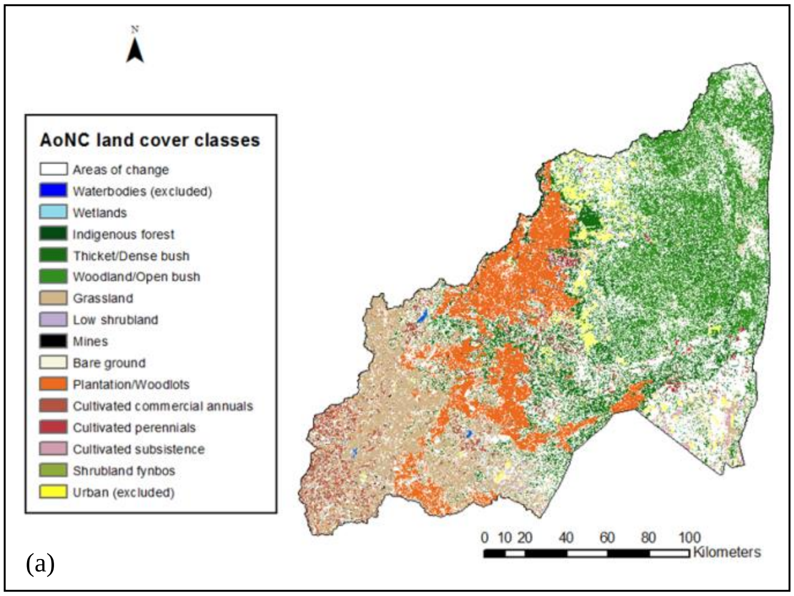

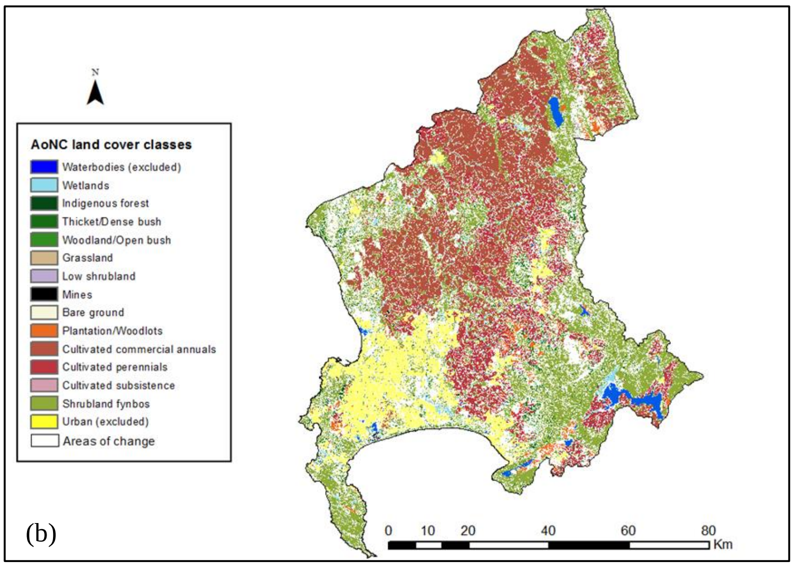

Figure 3.12 Areas-of-no-change (AoNC) map showing consistent classes in – (a) Inkomati area and (b) Wider Cape area.

From the Inkomati areas-of-no-change map (a) the largest consistent land cover classes include grasslands (28%) plantation woodlots (24%) and woodland/open bush (24%). In the Wider Cape area (b) the largest consistent land cover classes were cultivated commercial annuals (40%), shrubland fynbos (37%) and cultivated perennials (16%).

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3.2.2 MOD16 satellite ET product

The MOD16 satellite data product was developed as part of a NASA/EOS project aimed at exploring the use of remote sensing techniques to estimate ET from global land vegetated surfaces (Running et al. 2017). The global ET satellite data was produced at a 1 km resolution at the following intervals: 8 day, monthly and annual. In addition to ET data produced (Running et al. 2017), ancillary data produced include latent heat flux (LE), potential evapotranspiration (PET) and potential latent heat flux (PLE). For this study, MOD16 data included the following: ET, vapour pressure deficit and average air temperature.

To extract the data, the zonal statistics function in ArcGIS (version 10.4) was used in the ModelBuilder tool to implement iteration. The aim of the iteration was to extract statistical data (e.g. mean, median, standard deviation) from the multiple MOD16 remotely sensed images for further analysis. Figure 3.13 shows the workflow used and overall process followed in ArcGIS using geoprocessing tools in the ModelBuilder to extract the data. Using this method, statistics were extracted from 468 raster data sets for variables ET, vapour pressure deficit (VPD) and average air temperature.

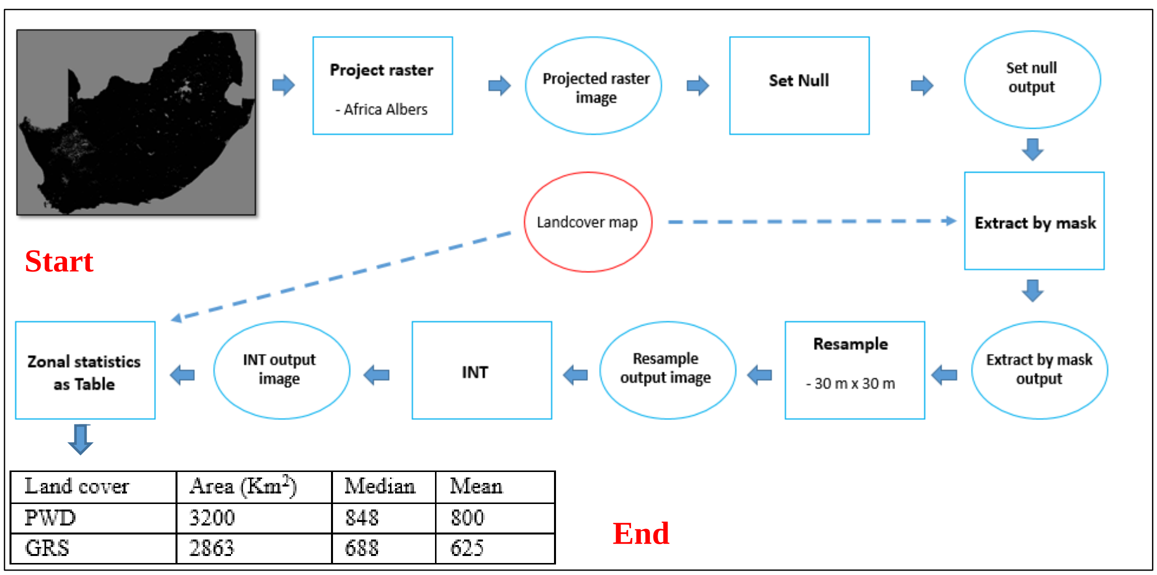

Figure 3.13 ModelBuilder tools (ArcGIS 10.4) and steps followed during the extraction of data from MOD16 raster data sets. Input data and ArcGIS geoprocessing tools used to process the data are shown. The process begins with a raster file (start) and the output is a zonal table with summary statistics (end).

The block arrows in Figure 3.13 indicate the flow and the process followed in ArcMap using the geoprocessing tools in the rectangular boxes. The oval shapes show outputs derived from each of

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the tools used. The line arrows show stages on the process where land cover data (shown by red oval shape) was used as an input data. The initial step in the model is projection of the raster (.tif) images from geographic to projected coordinate system (Africa Albers Equal Area) using the *project raster* geoprocessing tool. To remove outlier values that would otherwise affect the mean values in the data, the *set null tool* was used to eliminate or nullify values which meet a specific condition and replace them with NoData values. For this exercise, the tool was used to remove cells deemed to be out of range based on the MOD16 image specifications. The *extract by mask* tool was used to extract a specific area from the original input raster and the boundaries or area extent extracted is defined by the input mask feature. As an example in this particular study, the catchment boundaries defined in the land cover map were used to extract MOD16 data of the same area. Data (e.g. ET) for a particular province or catchment was extracted from the larger national ET map.

To further ensure that the boundaries of the land cover and the MOD16 product data overlaid exactly, the land cover data set (areas-of-no-change or NLC2013/14) was used as a snap raster in this step. For this data extraction, the *Resampling* tool was used to resample the MOD16 images resolution from 1 km to 30 m to match the resolution of the land cover map. The *Resampling* tool is a tool used to redefine the resolution of a raster image by changing the cell sizes of the raster but keeping the extent unchanged. The *integer tool (Int)* was subsequently used on the extracted MOD16 raster data to convert each cell value in the raster image into an integer value.

Once these steps were completed, the *zonal statistics as table* geoprocessing tool was used to extract statistical data including mean, median and sum per land cover for each processed image. Tables were produced for each of the months in the entire observation period (2000 – 2012) and these tables were then combined to produce a time series for trend analysis.

3.2.3 Rainfall

Two rainfall data sets were used in the study to represent spatially variable rainfall; the first data set was rainfall station data obtained from the South African Weather Service shown in Figure 3.14. The rainfall data acquired was of monthly totals (mm) from 2000 to 2012 for stations located across all nine provinces (Figure 3.14). It was then used for historical analysis of ET and climatic variability trends at provincial scale. The full list of the station names and geographic coordinates in the various provinces can be found in the appendix (Table A.2).

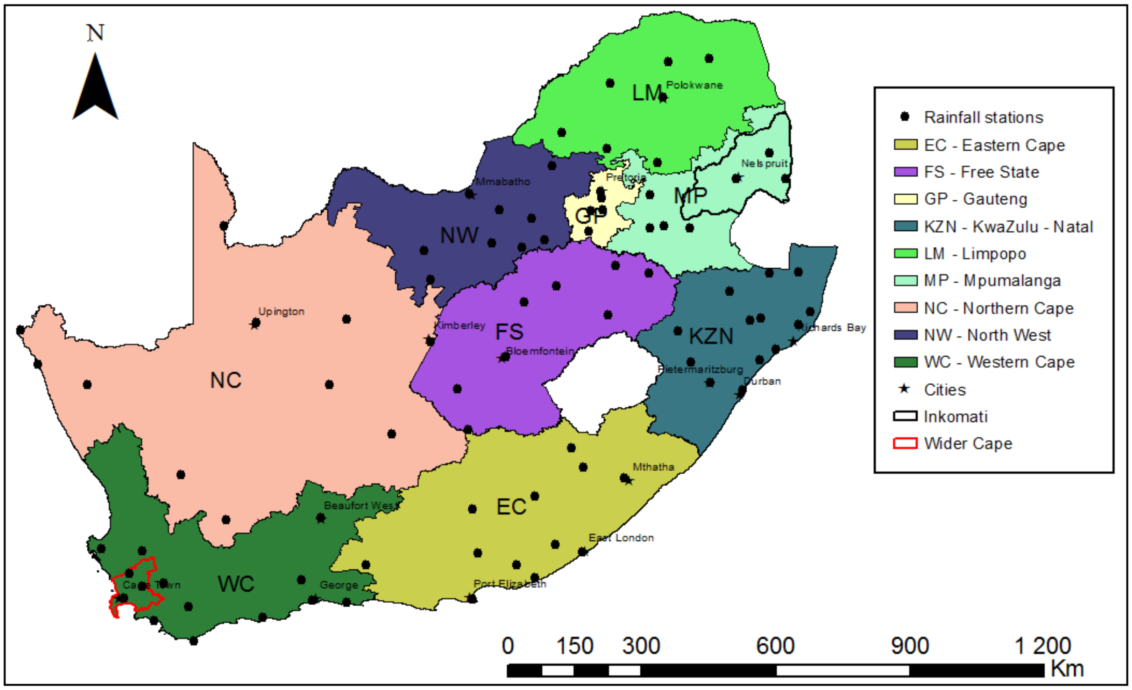

Figure 3.14 Distribution of rainfall stations used for provincial rainfall data.

The number of stations used per province depended entirely on data availability and the geographic distribution of the stations and this ground station rainfall data was then used to estimate spatial rainfall for the Inkomati and Wider Cape areas for the study period. Spatial rainfall data was modelled using the following procedure: (1) SAWS ground station rainfall were plotted in each sub-catchment study site; (2) mean annual rainfall (MAR) for each rainfall station point was extracted from the Schulze (2006) long-term annual rainfall map (spatial); (3) annual long term rainfall was converted to monthly average rainfall that was then used to subtract monthly averages from the SAWS ground station data; (4) monthly mean difference (MMD) for each area was determined and added to the spatial long-term monthly rainfall. The modelled rainfall data set was used in the analysis of historical variability in the Inkomati and Wider Cape areas. The modelled rainfall data was produced as part of WRC project K5/2520/1, deliverable 7b and it was then applied in this study for analysis. The following section describes the processes followed to analyse the extracted data.

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3.3 DATA ANALYSIS

The first sub-section in the data analysis describes how current water use (2012) status was analysed at a provincial and case study level, in the Inkomati and Wider Cape areas. This is followed by details of the process used to analyse the relationship between ET, land use and climatic variability for all the study sites as indicated in Figure 3.1(B).

3.3.1 Current status (2012)

Annual (2012) ET data was used to estimate water consumption from the various land cover classes. The annual ET data was extracted using the ModelBuilder method depicted in Figure 3.13 (p51) at provincial and sub-catchment scale. The latest updated national land cover data (NLC2013/14) was used to extract land cover information. Mean and median ET was estimated per land cover class. The water use consumption was derived using the mean annual ET (mm a^{-1}) for each land cover class and the area covered by the land cover class. The annual median ET (mm a^{-1}) estimates from the different land cover classes, as well as the cumulative water use (Mm^3 a^{-1}), a function of the mean ET and area covered by land cover class were represented in the form of graphs and summary tables in the two case study areas and at provincial scale for comparison purposes. This was done to answer questions related to which land cover classes currently use the most or the least amount of water. The following section describes the data analysis methods followed to analyse the linkages between ET, land cover change and climatic variability using a historical (2000 – 2012) monthly data set.

3.3.2 Historical analysis (2000 – 2012) - Climatic changes and ET

The variables used for this analysis were ET as the dependent or response variable and average air temperature (T), vapour pressure deficit (VPD) and rainfall (R) as independent or predictor variables. These variables were extracted for each land cover class in the AoNC land cover data to understand the linkages that exist between ET, climatic variability and land cover changes. The two statistical tests used to analyse these data include the correlation test and multiple regression analysis.

Correlation measures the strength of the linear relationship between two variables; the relationship strength is shown by the R^2-value measured in the relationship between the two variables. A regression test is not only useful for determining the presence of a relationship between variables

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but also informs us about the proportion of variability in the response variable that can be explained by the predictor variable (Cohen et al. 2013). The value of R^2 ranges between 0 and 1, the former indicating no relationship and the latter indicating a very strong relationship (Cohen et al. 2013). Multiple regressions in particular are used to determine the combined effect of more than one predictor variable on a single response variable (Cohen et al. 2013). In addition, multiple regressions are also used as predictive statistics since they have the ability to predict an unknown value from two or more variables using their regression coefficients; these predictions are made based on the coefficients of the known values and the intercept.

A multiple regression equation with three variables is given as (Grace & Bollen 2005):

$$y = c + X_1*A_1 + X_2*A_2 + X_3*A_3 \qquad \text{Equation 3-1}$$

Where	y	is the response (dependent) variable;
	c	is the intercept;
	X	is the predictor (independent variable) and
	A	is the coefficient or slope for each predictor variable.

The assumption made in multiple regression is that the response variable (y) has a linear relationship with each predictor variable and that the predictor variables have an additive effect on the response variable. The intercept (c) of the regression is defined as the mean value of y when all X=0, the point where the fitted regression line crosses the y axis. The results from the multiple regression also provide information on the variable that has the most effect in altering or causing a measureable change in the response variable. Determination of the coefficients or slope (A) values of each predictor variable allows for the prediction of y at any specific values of the predictor variable. Knowing the slope value gives us an understanding of how much the response variable can change with one unit change in the predictor variable. A positive slope means that the relationship between the two variables is positive, and vice versa. This is important for research studies seeking to predict how the changes in predictor variables alter the response variable.

At provincial and sub-catchment level, monthly median ET trends from 2000 to 2012 in different land cover classes were compared. This was followed by a comparison of the time series trends of ET with the different associated climatic variables. Finally, multiple regression analysis of ET (response) variable and associated predictor variables (air temperature, vapour pressure deficit and rainfall) was performed at provincial and sub-catchment level. R^2 was used to measure the strength

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of the relationships. R^2 values and root mean square error (RMSE) were determined for each land cover class per month in each sub-catchment. The RMSE was calculated between the MOD16 satellite product ET and the multiple regression equations-derived ET estimates.

The next section describes the development of the water use scenario tool; the water use projections calculated in the tool are based on multiple regression equations from the historical analysis results.

3.3.3 Scenario tool for future water use projection

The water use scenario tool is an interactive tool for projecting future water use changes as a function of land cover change and designed scenarios of climatic variability. Scenarios for the tool were developed specifically for the two sub-catchments, Inkomati and Wider Cape during a Focus Group Discussion (FGD) was held with participants from the City of Mbombela and the City of Cape Town. There were 26 attendees in total and the group included students, researchers, and individuals working within the water management areas who make water use or water resource management based decisions on a frequent basis. The discussions were led by a focus group leader who requested the participants who had been divided into two groups (representing the two study sites) to outline changes in climate and land cover that were already taking place, planned or most likely to occur in their areas. Examples of such scenarios included changes in temperature and the expansion or reduction of particular land cover classes.

The tool was initially developed in Microsoft Excel using the historical data analysed per land cover class in each sub-catchment, which was then later integrated into a web-based water use scenario tool constructed by a web-designer. Background data used in the tool included output from the multiple regression equations developed for relationships of ET with rainfall, air temperature and VPD, mean monthly ET, and monthly standard deviations for each land cover class in each sub-catchment derived from the historical data. Figure 3.15 shows the conceptual flow diagram for the water use scenario tool.

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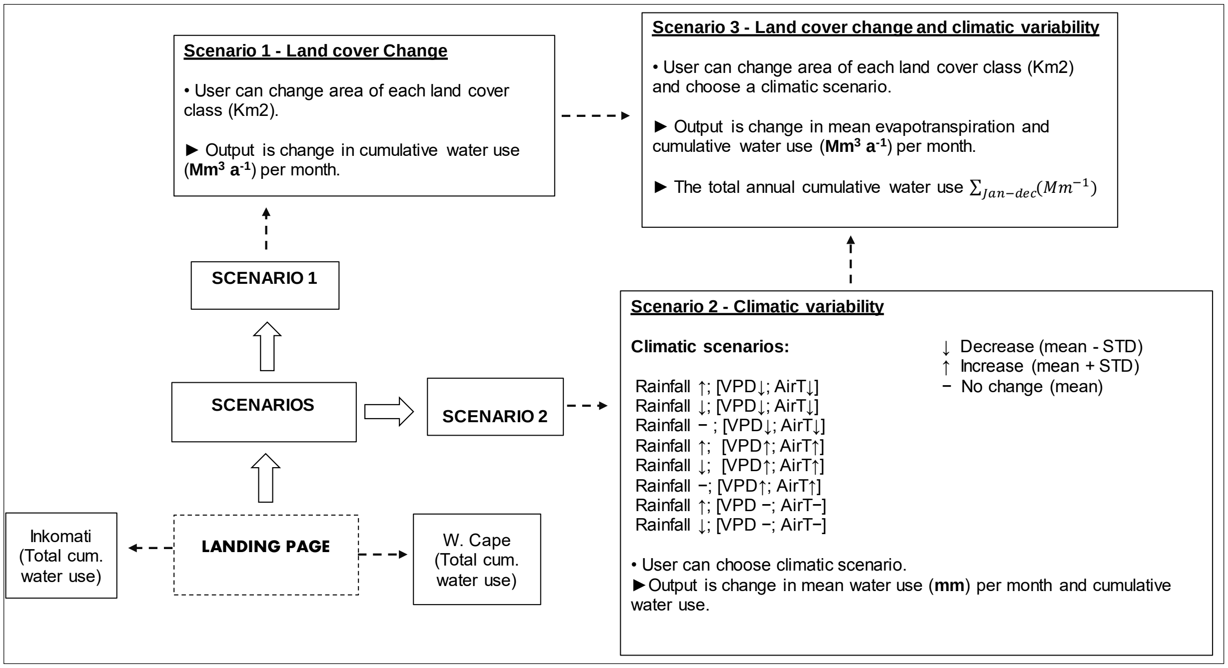

Figure 3.15 Conceptual flow diagram of the water use scenario tool

The tool estimates mean water use (mm) and cumulative water use (Mm^{-3}) for each month of the year based on the historical 13-year monthly data set analysed. Monthly estimates are then totaled to provide an estimate of annual totals (Figure 3.15). For accuracy assessment of the water use estimations, the multiple regression R^2 value and root mean square error (RMSE) were determined for each land cover class per month in each sub-catchment. The RMSE was calculated between the MOD16 satellite product ET and the multiple regression equations derived ET estimates. Land cover impacts on ET can be estimated from changing the area of each land cover class. Impacts of climatic variability on ET can be calculated by applying the linear relationships between ET and the variables. Climatic variability is assumed to refer to increasing or decreasing vapor pressure deficit, air temperature and rainfall. The tool can generate three main scenarios: Scenario One simulates land cover change only. In this scenario the user changes land cover class area(s) to observe changes in water use (Figure 3.15). Scenario Two models climatic change impacts. In this scenario, the user selects one of eight different climatic scenarios (increase/decrease in rainfall, temperature and vapour pressure deficit) built into the tool, to observe changes in water use for all land cover classes. Scenario Three combines land cover and climatic change. In this scenario the user changes both land cover class area(s) and selects climatic scenarios to compute the combined

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effect on water use (Figure 3.15). A full description with screenshots showing the interface of the water use scenario builder tool is shown below.

When the scenario tool is launched, the landing page (Figure 3.16) shows the total area and the current water use status in each sub-catchment.

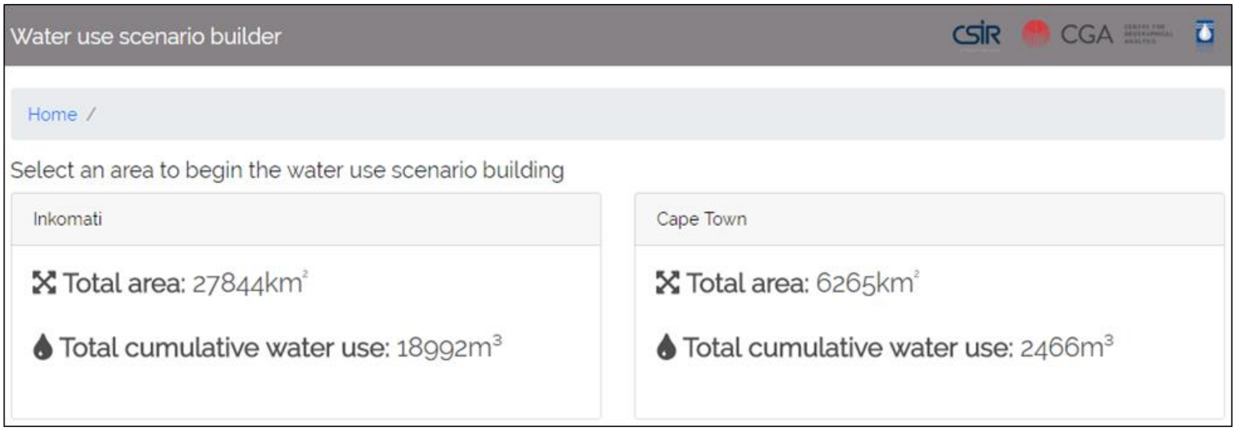

Figure 3.16 Water use scenario tool landing page.

The cumulative water use is calculated as a function of the mean ET and the total area covered. The total area covered by the land cover classes in the Inkomati area is 27 844 km^2 and 6265 km^2 in the Wider Cape (Cape Town area).

Once the specific sub-catchment is selected, detailed information of current water use per land cover class is displayed (Figure 3.17). The web-interface includes tabs for current monthly mean water use and monthly cumulative water use. The final tab provides a land cover map to show the spatial distribution of the various land cover classes.

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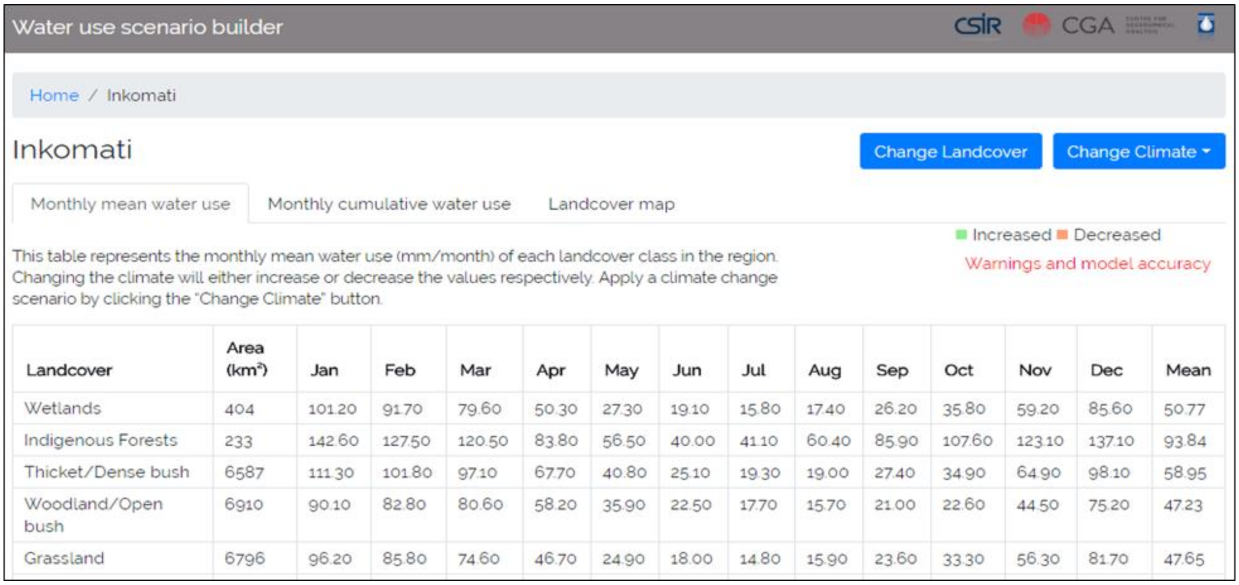

Water use scenario builder

Home / Inkomati

Inkomati

Change Landcover | Change Climate

Monthly mean water use | Monthly cumulative water use | Landcover map

Increased Decreased

Warnings and model accuracy

This table represents the monthly mean water use (mm/month) of each landcover class in the region. Changing the climate will either increase or decrease the values respectively. Apply a climate change scenario by clicking the "Change Climate" button.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Wetlands	404	101.20	91.70	79.60	50.30	27.30	19.10	15.80	17.40	26.20	35.80	59.20	85.60	50.77
Indigenous Forests	233	142.60	127.50	120.50	83.80	56.50	40.00	41.10	60.40	85.90	107.60	123.10	137.10	93.84
Thicket/Dense bush	6587	111.30	101.80	97.10	67.70	40.80	25.10	19.30	19.00	27.40	34.90	64.90	98.10	58.95
Woodland/Open bush	6910	90.10	82.80	80.60	58.20	35.90	22.50	17.70	15.70	21.00	22.60	44.50	75.20	47.23
Grassland	6796	96.20	85.80	74.60	46.70	24.90	18.00	14.80	15.90	23.60	33.30	56.30	81.70	47.65

Figure 3.17 Sub-catchment landing page showing monthly mean water use estimations (mm/month).

The monthly mean water use (mm/month) tab shows the water use of each land cover class with default values on the landing page representing actual mean ET extracted from the satellite data using the zonal statistics method shown earlier (Figure 3.17). The second tab shows the monthly cumulative water use. The monthly cumulative water use (Mm^3) of each land cover class is calculated using the mean water use (mm/month) of each month and the total area of each land cover class (km^2). The total annual cumulative water use is then computed by totalling the water use for all the months. The detail of each of the three water use scenarios prepared for the tool follows.

3.3.3.1 Land cover change scenario

In this scenario the user is able to change the area covered by each land cover class (Figure 3.18) and in changing the area, the result is an overall change in cumulative water use for the area. The *Change Landcover* option is used to either increase or decrease the area of any land cover class.

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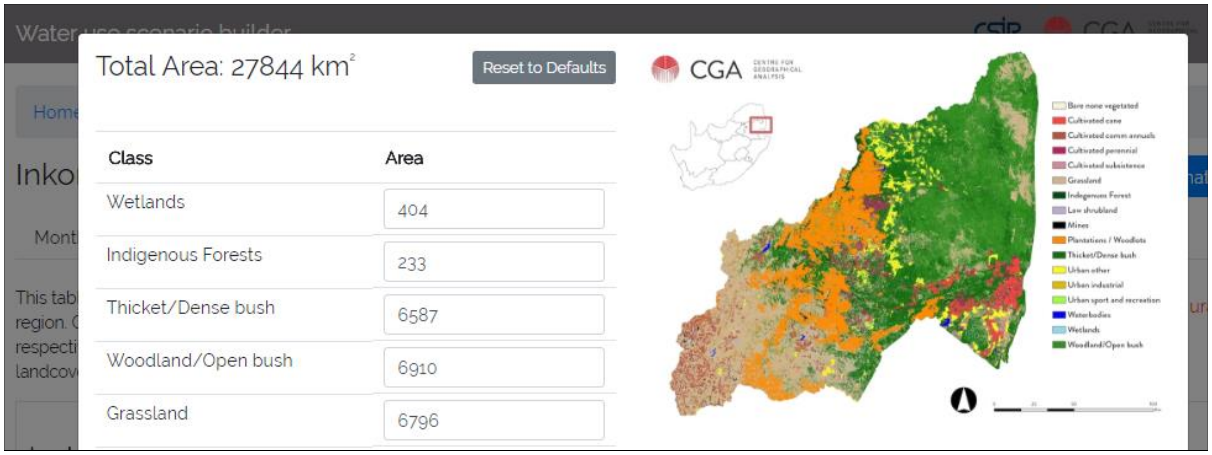

Figure 3.18 Scenario one – changing area of each land cover class.

To ensure the total area of the sub-catchment remains consistent, the user is required to balance the increase/decrease in a particular land cover by altering the area of another one. For example, a 10 km^2 decrease in grassland area should be balanced by adding 10 km^2 to one or more other land cover classes. Once the total sub-catchment area has balanced, the area change can be applied. The tool uses green or red highlights to guide the user and show where there was an increase or decrease respectively in the area and the water use. The annual total water use is then calculated from the cumulative monthly output.

3.3.3.2 Climate scenario change

In this scenario, the user must first select one of two rainfall seasons (wet or dry months) as shown in Figure 3.19.

Figure 3.19 Selection of dry and wet months in climatic scenarios

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The wet/dry months differ between the Inkomati area and the Wider Cape area given that they are in different rainfall regions. Figure 3.19 shows that the dry months in Inkomati are April, May, June, July, August and September. Wet months, characterised by increased rainfall, include January, February, March, October, November and December. We define the changes in climatic drivers as the increasing or decreasing of a particular variable (rainfall, air temperature or vapour pressure deficit). To estimate the increase/decrease in a particular variable the monthly standard deviation of each variable was calculated for each land cover class. In this scenario the user can select one of eight scenarios representing a combination of variables as seen in Figure 3.20.

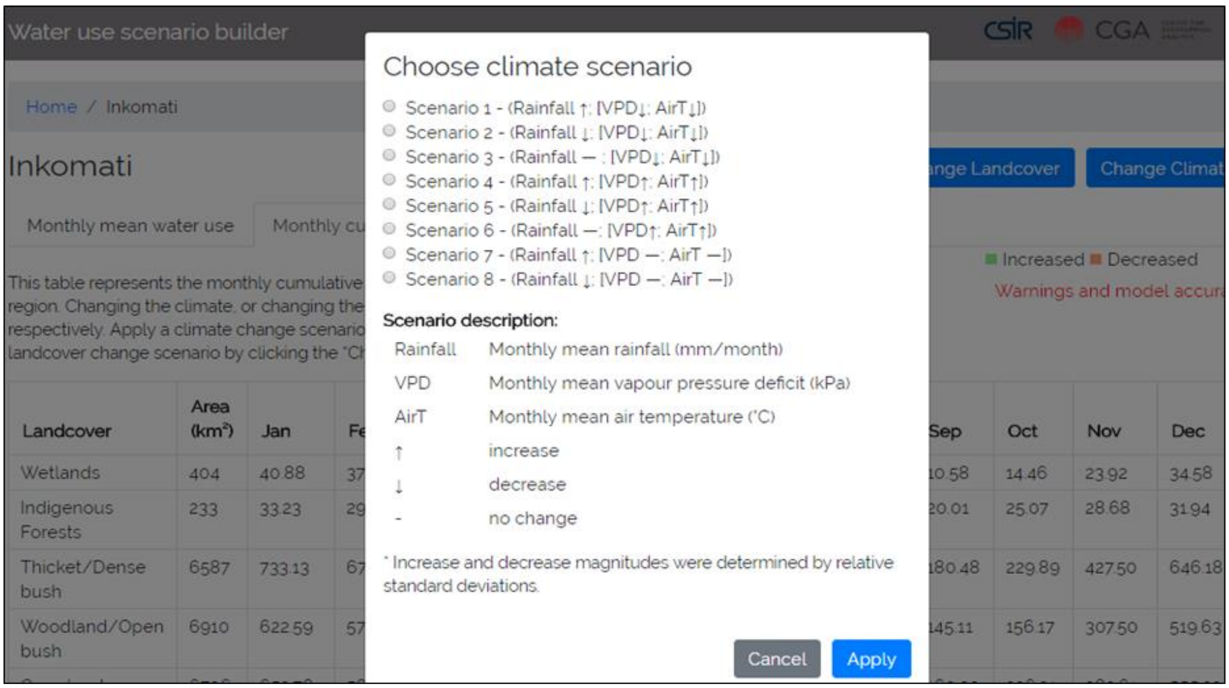

Figure 3.20 Climatic scenario combinations.

Increase/decrease values of climatic drivers are represented as the mean +/- standard deviations. The monthly standard deviations for each land cover class were extracted from the satellite data using the zonal statistics function. No change scenario is considered as the mean of the climatic variable (Figure 3.20). By selecting the climatic scenario and clicking *apply* the climatic scenario changes the mean ET of each land cover class and ultimately the cumulative water use changes per month. The monthly changes are totaled to show the annual total.

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3.3.3.3 Land cover change and climatic variability scenario

The last scenario is a combination of both previous scenarios. In this scenario, the user is able to change the area covered by each land cover class and alter the climatic parameters by selecting one of the provided climatic scenarios in a dry/wet climate. The cumulative net effect is the change in the mean water use and cumulative water use in that particular land cover class. The output from the combined effect of changes in the area of each land cover class and in the selection of different climatic scenarios results in changes in annual total water use. Decreases and increases are shown with red and green highlighting. The aim of this section was to describe the development of the water use scenario tool and highlight the conceptual model. Later in the results section we create few scenarios and report on the results from these scenarios; these results are then later discussed and the scenario tool limitations are outlined.

3.4 CONCLUDING REMARKS

The methods and materials chapter discussed firstly the raw data used in the study, secondly the methods used to analyse the raw data and produce results which are discussed in the following results chapter (Chapter 4). The case study sites used for analysis have also been shown; firstly at the provincial scale and secondly the two sub-catchments: Inkomati and the Wider Cape area. The methods were chosen to answer the outlined questions found in the introduction and therefore to ensure that the aim of the study is achieved. Three main analyses were performed in the study, the first being the analysis of the current water use status by estimating water use from the ET for the year 2012. The second analysis assessed the linkages between ET as a response variable, temperature, vapour pressure deficit and rainfall as independent variables. To do this, multiple regression and correlation statistics were performed. Lastly, the development of the scenario tool for future water use projection was displayed. Also shown are the three main scenarios that are the core functions of the tool and in addition the RSME tables, used to highlight times when the user needs to interpret results with caution, were shown. The next section reports on the results from the first two objectives and in addition reports on results from scenarios as a way of testing the application of the tool.

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CHAPTER 4 RESULTS

The overarching aim of this research was to describe and model the linkages between evapotranspiration, land cover change and climatic variability at different spatial scales. To achieve this, three objectives were set. The presentation of the results follows the same structure as the outline of the objectives for the study: (1) current water use of various land cover classes using MOD16 ET data (Section 4.1); (2) relationships between water use, land cover and climatic variability using a 13-year historical data set (Section 4.2); and (3) future ET changes as a function of land cover and climatic changes using a scenario tool (Section 4.3). Table 4.1 shows the abbreviations used for the land cover classes throughout the results section.

Table 4.1 Abbreviations used for the national land cover classes

Land cover class (NLC 2013/14)	Abbreviation used
Waterbodies	WTB
Wetlands	WTL
Indigenous forests	INF
Thicket/dense bush	TDB
Woodland/open bush	WOB
Grasslands	GRS
Shrubland fynbos	SHF
Low shrubland	LSB
Cultivated commercial annuals	CCA
Cultivated perennial	SPE
Cultivated subsistence	CSU
Cultivated cane	CCN
Plantation/woodlots	PWD
Mines	MNS
Bare-none-vegetated	BNV
Urban commercial	UCM
Urban industrial	UIN
Urban informal	UIF
Urban residential	URS
Urban sports and recreation	USR
Urban others	OUT

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4.1 CURRENT STATUS

Current water use status was analysed at provincial scale for all nine provinces and at sub-catchment scale for the Inkomati and Wider Cape areas. Annual (2012) ET data from the MOD16 global satellite product was used to estimate water consumption from various land cover classes. The latest updated national land cover data (NLC2013/14) was used to extract land cover information. In this section we report on the annual median ET (mm a^{-1}) estimates from the different land cover classes, as well as the cumulative water use (Mm^3 a^{-1}), a function of the mean ET and the area covered by the land cover class.

4.1.1 Current water use (national scale)

Results from four provinces are presented as examples of the analysis. KwaZulu-Natal and Northern Cape were selected because of their large differences in rainfall, the former being the wettest province in the country, and the latter being the driest province according to historical (2000 – 2012) rainfall data. Western Cape and Mpumalanga were selected because they are provinces where the Inkomati and Wider Cape areas are found, therefore they present an opportunity to understand the role of scale in the variability of ET as a function of climatic variability and land cover changes. Full data with summary statistics of the remaining provinces can be found in appendix B.

4.1.1.1 KwaZulu-Natal and Northern Cape

Figure 4.1a shows the highest ET median was estimated in plantation woodlots (PWD) (1 127 mm a^{-1}) in KwaZulu-Natal followed by indigenous forests (INF) and cultivated cane (CCN) land cover classes (refer to Table 4.1 for class abbreviations). The province also recorded the highest water consumption averages compared to the other provinces. Grasslands (GRS) and thicket/dense bush (TDB), although having lower ET medians (667 mm-^{1} and 894 mm^{-1} respectively), had the highest estimates of cumulative water consumption because they cover larger areas.

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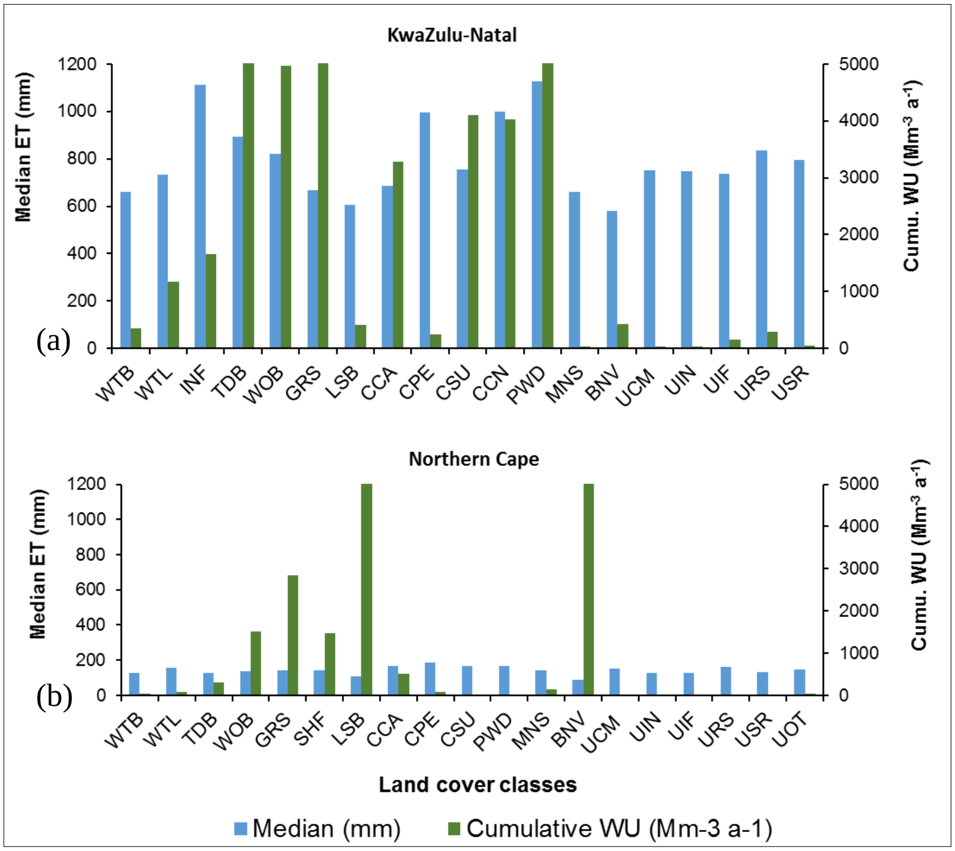

Figure 4.1 Annual median ET (mm a-1) and cumulative WU (Mm3 a-1) in (a) KwaZulu-Natal and (b) Northern Cape (2012).

The Northern Cape (Figure 4.1b) had the lowest estimates of ET across the country; the annual median ET range in the province was estimated to be 88 mm - 184 mm per annum. The Cultivated perennial (CPE) (184 mm a^{-1}) class recorded the highest median ET, followed by cultivated commercial annuals (CCA) and cultivated subsistence (CSU). The highest cumulative water consumption occurred in the low shrubland (LSB) land cover class which covers approximately 60% of the total provincial area.

4.1.1.2 Mpumalanga and Western Cape

Median ET and cumulative water use for Mpumalanga and Western Cape are given in Figure 4.2.

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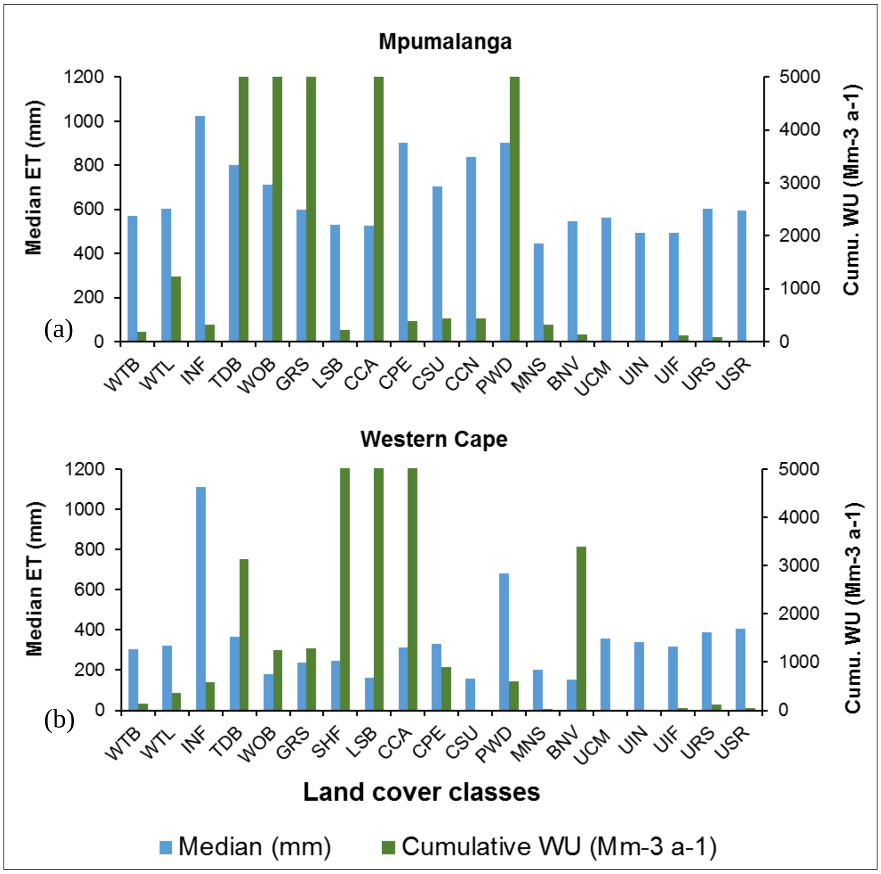

Figure 4.2 Annual median ET (mm a^{-1}) and cumulative WU (Mm^3 a^{-1}) ET in the (a) Mpumalanga and (b) Western Cape (2012).

Indigenous forests recorded the highest ET (1 022 mm a^{-1}) in Mpumalanga, followed by plantation woodlots and cultivated perennials (Figure 4.2a); grassland and woodland/open bush recorded the highest cumulative water consumption. Western Cape indigenous forests recorded the highest median ET (1 111 mm a^{-1}) (Figure 4.2b), and plantation woodlots and urban class recorded the second and third highest respectively. Cumulative consumption was the highest in shrubland fynbos land cover class which covers about 30% of the provincial area.

4.1.1.3 Country-wide averages

Water use (WU) from the nine provinces was combined and averaged to investigate which land cover classes have the highest ET averages and the highest cumulative WU estimates at a country-wide scale (Table 4.2). Also shown in the table is the percentage area covered and the percentage water use. The data was arranged from the highest median ET (cultivated cane) to the lowest (shrubland fynbos).

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Table 4.2 Country-wide estimations of annual (2012) ET (mm) and cumulative water use ($Mm^3\ a^{-1}$).

Land cover classes	Area (km^2)	Average ET (mm)	Cumulative WU ($Mm^3\ a^{-1}$)	Median ET (mm)	Area (%)	Water Use (%)
CCA	31 822	799	25 440	799	2.7	5.4
INF	3 047	754	2 299	759	0.3	0.5
PWD	11 056	645	7 128	647	0.9	1.5
CPE	6 860	535	3 671	525	0.6	0.8
TDB	72 948	505	36 854	528	6.2	7.8
URB	24 685	458	11 303	431	2.0	2.4
WTL	15 307	459	7 023	470	1.3	1.5
WOB	118 765	422	50 087	434	10.0	10.7
CSU	19 779	429	8 495	411	1.7	1.8
GRS	240 940	403	97 164	421	20.4	20.7
CCA	98 630	433	42 716	418	8.3	9.1
WTB	2 713	431	1 168	443	0.2	0.2
MNS	2 363	386	913	366	0.2	0.2
BNV	115 061	352	40 500	336	9.7	8.6
LSB	366 646	339	124 174	329	31.0	26.4
SHB	52 966	214	11 333	267	4.5	2.4
Total	1 183 587		470 267		100	100

* Urban land cover class includes urban residential, urban commercial, urban industrial, urban sports and recreation, urban informal and urban others.

A country-wide estimation of ET from the various land cover classes shows that cultivated cane recorded the highest median ET per annum (799 mm a^{-1}), followed by indigenous forests (759 mm a^{-1}) and plantation woodlots (647 mm a^{-1}). Land cover classes with the highest cumulative WU due to having the largest area percentage cover include: low shrublands which covers 31% area, grasslands and woodland/open bush which cover 20% and 10% respectively.

4.1.2 Current water use (sub-catchment scale)

Current water use was also analysed for Inkomati and the Wider Cape area for the year 2012. Figure 4.3 reports on the annual median ET (mm a^{-1}) and cumulative WU ($Mm^3\ a^{-1}$) of each land cover class in the two sub-catchment areas. Complete tables with other summary statistics (mean, minimum, maximum and standard deviations) of annual ET are provided in appendix B.

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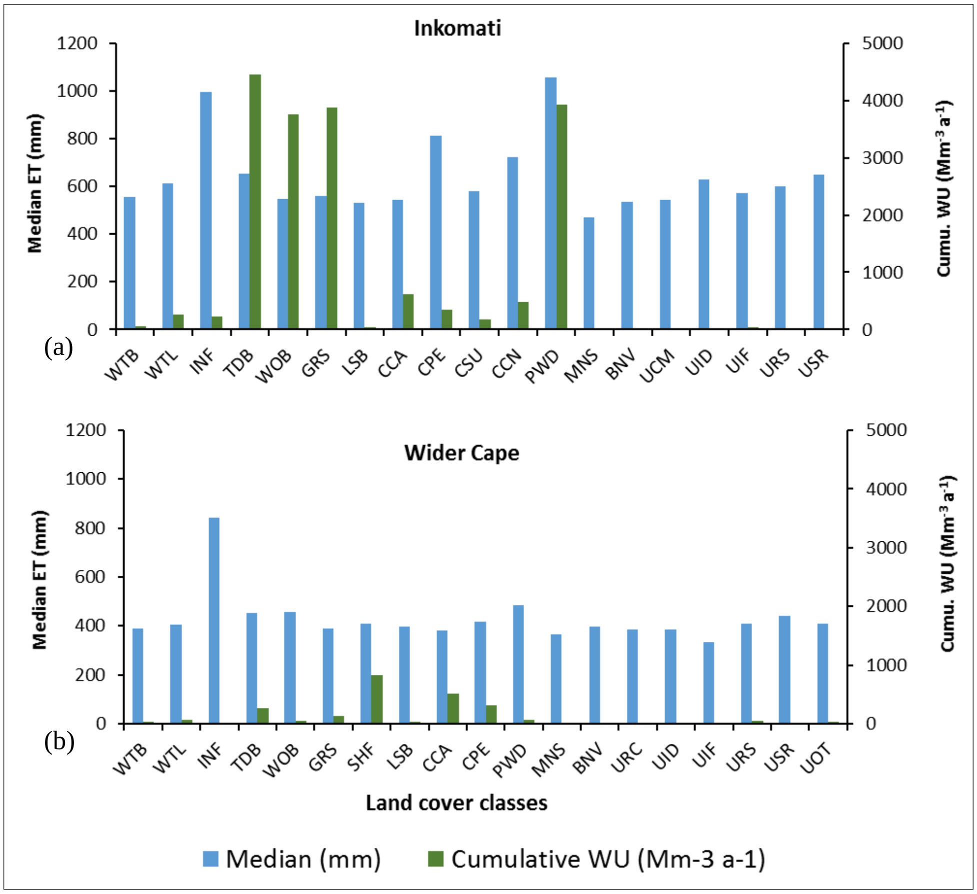

Figure 4.3 Annual median ET (mm) and cumulative water use (2012) in (a) the Inkomati and (b) Wider Cape areas.

Generally land cover classes in the Inkomati recorded higher annual median ET compared to the Wider Cape area (Figure 4.3). Indigenous forests and plantation woodlots had the highest ET medians in both the Wider Cape and Inkomati. In the Inkomati area, ET in plantation woodlots (1 057 mm a-1) was the highest followed by indigenous forests and cultivated perennials (Figure 4.3a). Thicket/dense bush had the highest estimate of cumulative water use in the Inkomati because of the large area it covers. In the Wider Cape area a similar situation is observed as in the Western Cape where indigenous forests recorded the highest annual median ET (842 mm), followed by plantation woodlots and woodland/open bush. Shrubland fynbos land cover class was the largest cumulative water user because of the area it covers in the Wider Cape area (Figure 4.3b).

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4.1.3 Summary of current water use status (2012)

Water use for 21 land cover classes (NLC 2013/14) was calculated for the nine official provinces and demonstrated for KwaZulu-Natal, Northern Cape, Mpumalanga and the Western Cape provinces as examples. At provincial scale, the highest ET was estimated in KwaZulu-Natal. Arranged by land cover class area, the province has the biggest area of the land cover classes with the highest estimated median ET, such as indigenous forests and plantation woodlots. At catchment level, ET in the Inkomati was higher than the Wider Cape area annual ET in the year 2012 with plantation woodlots, indigenous forests and cultivated perennials having the highest estimates when comparing the two study sites. The Inkomati land cover classes similarly had higher cumulative water consumption estimates because of the large extent of the Inkomati area (28 248 km^2) compared to the Wider Cape area (5755 km^2).

4.2 HISTORICAL CLIMATIC VARIABILITY

This section shows results of the analysis of historical (2000 – 2012) linkages between ET, land cover and climatic variability. Historical linkages were analysed on monthly time series data. The results are divided into two parts: the initial part presents analysis which was done at a provincial scale; the second part includes results obtained at sub-catchment level for the two case study areas (Inkomati and Wider Cape). In addition, we investigate how the 2000 – 2012 period compares to the long-term (1950 – 2012) climatic variability using the available long-term rainfall data.

4.2.1 Historical climatic variability (Provincial scale)

The results sequence presented here follows what was done in the previous section; we show, as examples, results from KwaZulu-Natal, Northern Cape, Mpumalanga and Western Cape provinces. The complete results data set for other provinces can be found in appendix C. At provincial level, the initial results compare monthly median ET trends from 2000 to 2012 in different land cover classes (Figure 4.4). Secondly the results compare time series trends of ET and associated climatic variables between the provinces that were used as examples. Finally, multiple regression analysis of ET (response) variable and associated predictor variables (air temperature, vapour pressure deficit and rainfall) results are shown (Table 4.2).

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4.2.1.1 Evapotranspiration variability

Figure 4.4 shows monthly ET (mm) values per land cover class for the selected provinces over a 13-year period (January 2000 – December 2012).

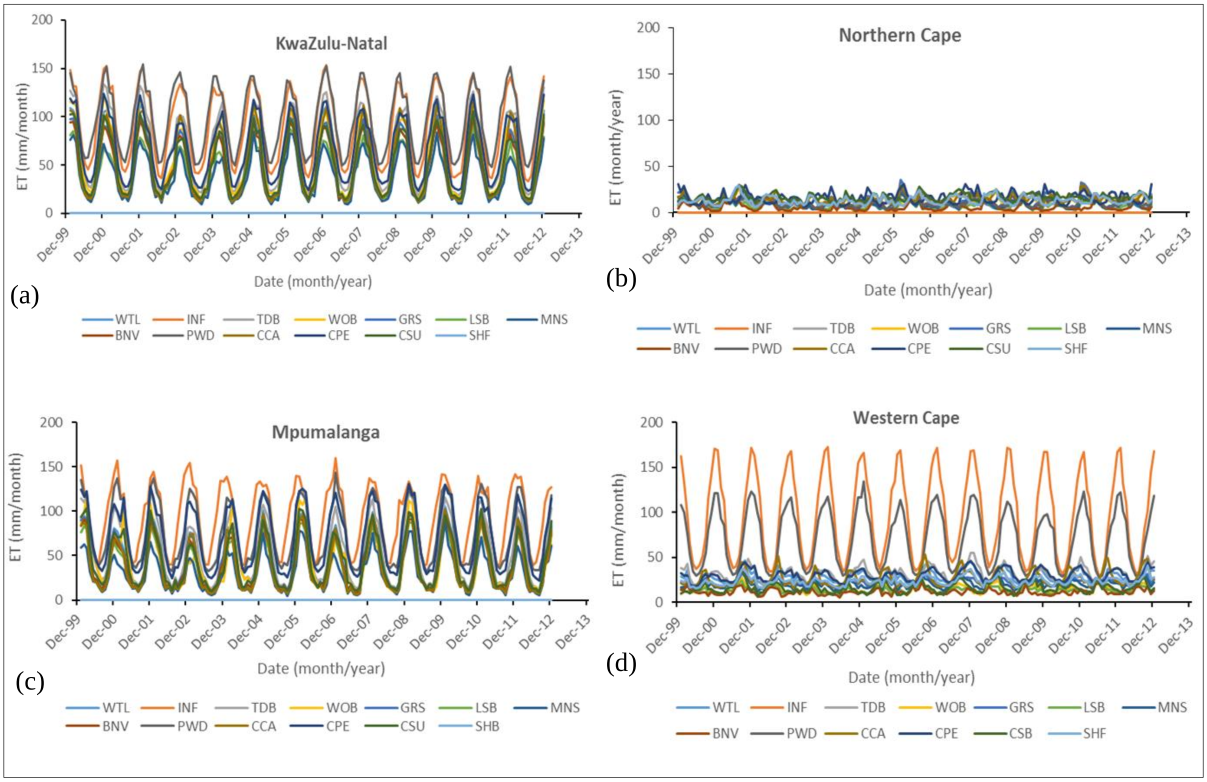

Figure 4.4 Differences in land cover class ET (mm) monthly (2000 – 2012) time series trends in (a) KwaZulu-Natal, (b) Northern Cape, (c) Mpumalanga and (d) Western Cape.

Time series trend analysis results show there is less ET variation between land cover classes in the Mpumalanga and KwaZulu-Natal provinces; results show that ET ranges in the two provinces do not show large differences (Figure 4.4). Larger differences and pronounced ET variability was observed between land cover classes in the Western Cape provinces. In the Northern Cape all land cover classes were estimated to have a median ET range between 0 mm and 50 mm with less seasonality observed in the ET trends. In the Western Cape two land cover classes showed higher ET: indigenous forests and plantation woodlots, while other land cover classes fell within the range similar to the Northern Cape. The time series (2000 – 2012) monthly medians were averaged for each land cover class per province and the results are shown in Figure 4.5.

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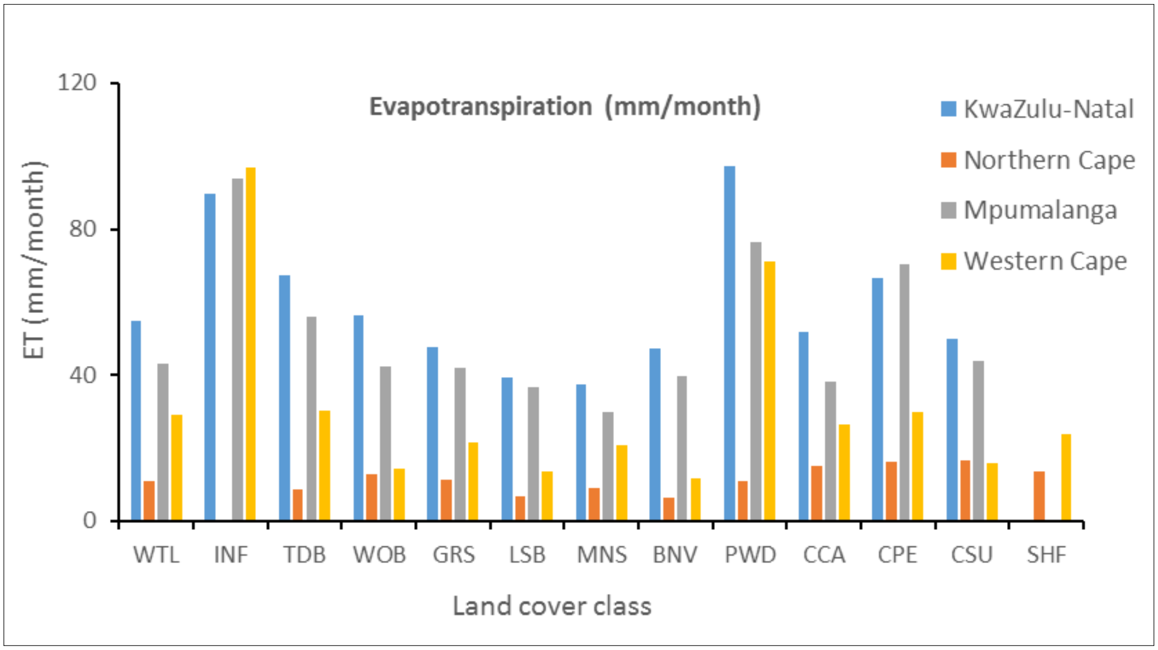

Figure 4.5 Differences in averaged land cover class ET (mm) medians in (a) KwaZulu-Natal, (b) Northern Cape, (c) Mpumalanga and (d) Western Cape.

Figure 4.5 shows that in KwaZulu-Natal, plantation woodlots (97 mm), indigenous forests (90 mm) and thicket/dense bush (67 mm) had the highest estimated monthly average ET. The Northern Cape recorded the least estimates of ET in the country: cultivated subsistence (17 mm), cultivated perennials (16 mm) and cultivated annuals (15 mm), similar to trends in annual (2012) ET. In Mpumalanga and Western Cape, indigenous forests, plantation woodlots and cultivated perennial annual had the highest ET averages. In Inkomati the averages were 94 mm, 76 mm and 70 mm, while in the Western Cape the averages were 98 mm, 71 mm and 30 mm respectively.

4.2.1.2 Provincial climatic variability

Figure 4.6 shows differences in ET and associated climatic variables between the four selected provinces (KwaZulu-Natal, Northern Cape, Mpumalanga and Western Cape.

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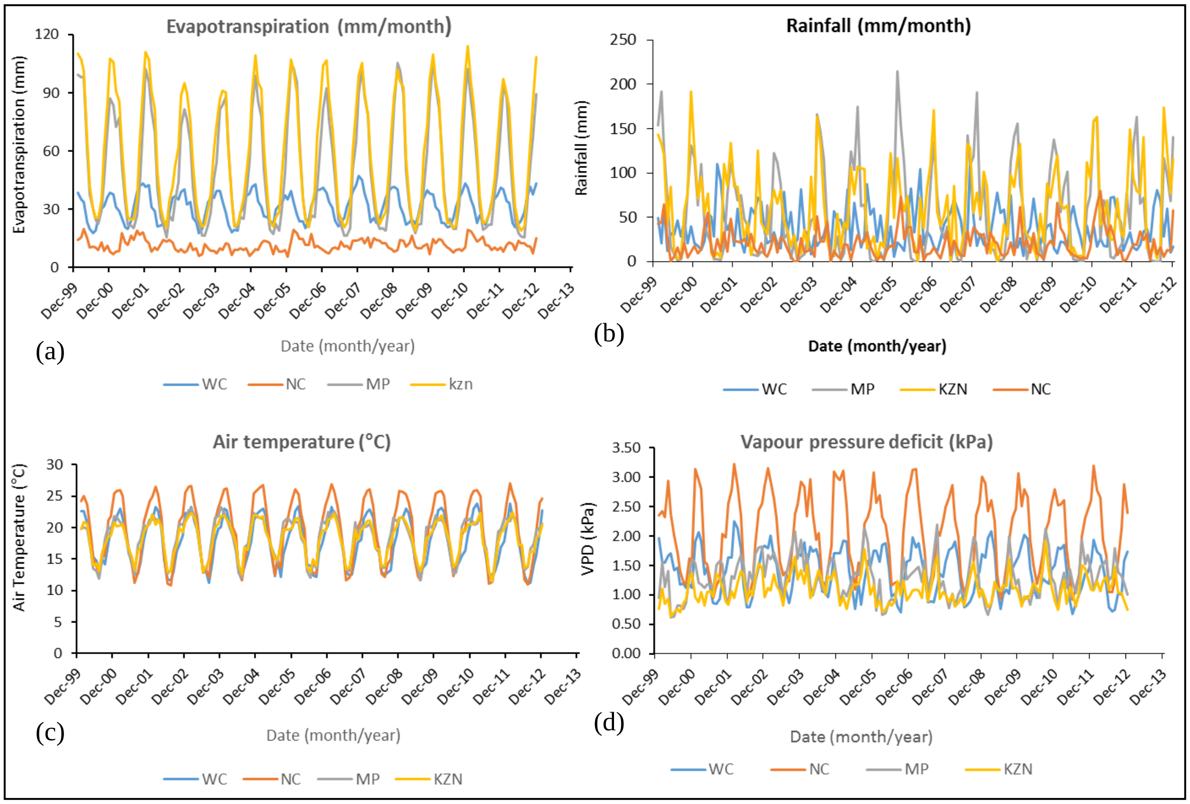

Figure 4.6 Provincial differences in 13-year period ET and associated climatic variables: (a) ET, (b) rainfall, (c) air temperature and (d) vapour pressure deficit.

As previously mentioned the Northern Cape had the lowest ET followed by the Western Cape, Mpumalanga and KwaZulu-Natal. Statistically significant differences ($p<0.05$) were found in ET between the four provinces. In terms of rainfall, Mpumalanga had the highest monthly rainfall peaks followed by KwaZulu-Natal while the Western Cape and Northern Cape had the lowest rainfall according to the 2000 to 2012 monthly rainfall data. Rainfall in Mpumalanga and KwaZulu-Natal were found not be significantly different ($p=0.349$) while rainfall trends in the Western Cape and Northern Cape were significantly different. Temperature and vapour pressure deficit monthly peaks were the highest in the Northern Cape followed by the Western Cape although there were less differences observed in temperature patterns between all four selected provinces.

4.2.1.3 Multiple regression analysis

Table 4.3 (a and b) shows multiple regression results output (intercept, predictor variable coefficients, and adjusted R-squared values) for each land cover class in the selected provinces.

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Table 4.3 Multiple regression analysis coefficients and adjusted R-squared values for each land cover class in the four provinces: Northern Cape, KwaZulu-Natal, Western Cape and Mpumalanga.

(a)

Coeff.	**Area**	**PWD**	**CPE**	**TDB**	**INF**	**WOB**	**CCA**
Air Temp.	N. Cape	-0.07	0.65	-0.21	-	-0.19	0.10
	KZN	9.89	10.09	11.32	13.58	8.47	8.41
	W. Cape	11.23	2.04	3.19	16.18	0.03	0.10
	Mpumal.	8.11	7.80	6.70	10.54	4.39	4.60
VPD	N. Cape	-1.51	-1.16	-0.50	-	-4.43	-2.72
	KZN	-20.52	-43.54	-46.36	-30.31	-47.49	-54.17
	W. Cape	-61.45	-11.93	-24.94	-86.37	-5.72	-17.47
	Mpumal.	-46.48	-44.17	-45.80	-17.93	-40.75	-35.12
Rainfall	N. Cape	0.24	0.17	0.20	-	0.06	0.13
	KZN	0.12	0.15	0.17	0.16	0.14	0.10
	W. Cape	-0.15	0.01	0.03	-0.27	0.04	-0.04
	Mpumal.	0.10	0.16	0.20	0.13	0.22	0.21
Intercept	N. Cape	10.61	1.13	10.22	-	23.60	14.76
	KZN	-63.25	-104.30	-121.16	-189.97	-58.21	-36.63
	W. Cape	-56.86	9.64	6.48	-91.68	22.50	48.15
	Mpumal.	-19.23	-38.87	-35.36	-91.20	-0.31	-5.78
R^2	N. Cape	0.61	0.59	0.57	-	0.65	0.22
	KZN	0.90	0.89	0.88	0.89	0.85	0.88
	W. Cape	0.73	0.27	0.61	0.69	0.70	0.38
	Mpumal.	0.85	0.84	0.81	0.89	0.69	0.80

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(b)

Coeff.	Area	WTL	GRS	LSB	MNS	SHF	BNV	CSU
Air Temp.	N. Cape	0.00	0.19	-0.35	0.08	-0.40	-0.69	-0.30
	KZN	8.84	7.30	4.95	5.34	-	6.50	6.87
	W. Cape	1.84	0.93	0.11	0.22	1.37	0.31	-0.38
	Mpumal.	5.06	4.82	4.09	2.87	-	4.48	4.06
VPD	N. Cape	-2.41	-1.19	-0.14	-1.90	-4.02	-0.60	-7.57
	KZN	-60.66	-48.56	-43.40	-39.44	-	-42.89	-40.42
	W. Cape	-18.56	-9.26	-3.73	-10.29	-13.10	-4.13	6.22
	Mpumal.	-41.24	-39.84	-32.28	-28.50	-	-38.00	-35.75
Rainfall	N. Cape	0.24	0.30	0.16	0.19	0.06	0.12	0.04
	KZN	0.09	0.09	0.09	0.89	-	0.13	0.13
	W. Cape	0.00	0.03	0.07	0.01	0.05	0.08	0.03
	Mpumal.	0.20	0.20	0.20	0.18	-	0.19	0.20
Intercept	N. Cape	10.47	3.16	11.00	7.82	26.67	18.58	32.10
	KZN	-33.85	-27.14	-1.14	-10.48	-	-30.21	-34.56
	W. Cape	20.10	17.56	15.43	29.67	16.03	10.27	31.11
	Mpumal.	-5.02	-2.63	-3.25	7.75	-	-1.29	2.21
R^2	N. Cape	0.61	0.59	0.64	0.61	0.71	0.80	0.51
	KZN	0.87	0.87	0.86	0.84	-	0.88	0.87
	W. Cape	0.20	0.27	0.66	0.50	0.32	0.56	0.65
	Mpumal.	0.85	0.86	0.83	0.85	-	0.85	0.81

The coefficients were used to determine the direction of the relationships. The adjusted R-squared value shows the strength of the relationship between ET and the predictor variables (air temperature, VPD and rainfall) combined or the variability in ET which can be explained by the combined effect of the three predictor variables. Vapour pressure deficit coefficients in the Western Cape were the highest in indigenous forests and plantation woodlots, and these are the land cover classes with the highest ET in the province. According to the results, positive correlation was determined between ET and air temperature in the four provinces except for the Northern Cape where no clear relationship was determined. A general negative relationship was determined between ET and vapour pressure deficit in land cover classes for all the provinces. Rainfall was positively related to ET in the Northern Cape, KwaZulu-Natal and Mpumalanga provinces; there was no clear relationship determined in the Western Cape where some land cover classes showed a positive relationship while others had a contrasting one.

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In the above tables, relationships with R^2 less than 0.5 are highlighted where the regression model explains less than 50% of the variability in the dependent variable. Our regression models show that in these cases the independent variables used were not sufficient to explain the variability in the independent variable. However, it is important to note that even though the overall R^2 of these models was low, the models were still statistically significant.

4.2.2 Historical climatic variability (Inkomati and the Wider Cape areas)

This section shows results of the analysis of historical (2000 – 2012) linkages between ET, land cover and climatic variability in the Inkomati and Wider Cape areas. The first part shows the variability of ET, air temperature, vapour pressure deficit and rainfall from 2000 to 2012 in the two sub-catchment areas; in addition to this, the three predictor variables (VPD, air temperature and rainfall) were then correlated with ET to determine spatial dependency using the Pearson rank correlation. In the second part, comparison of ET and associated climatic variables between different land cover classes in the two sub-catchment sites are shown. Multiple regression analysis results are shown in the final part; in the table the intercept, coefficients and adjusted R-squared values are shown for each land cover class per area (Inkomati and Wider Cape).

4.2.2.1 Climatic variability

Figure 4.7 compares ET and climatic variables monthly time series (2000 – 2012) in the Inkomati and Wider Cape areas.

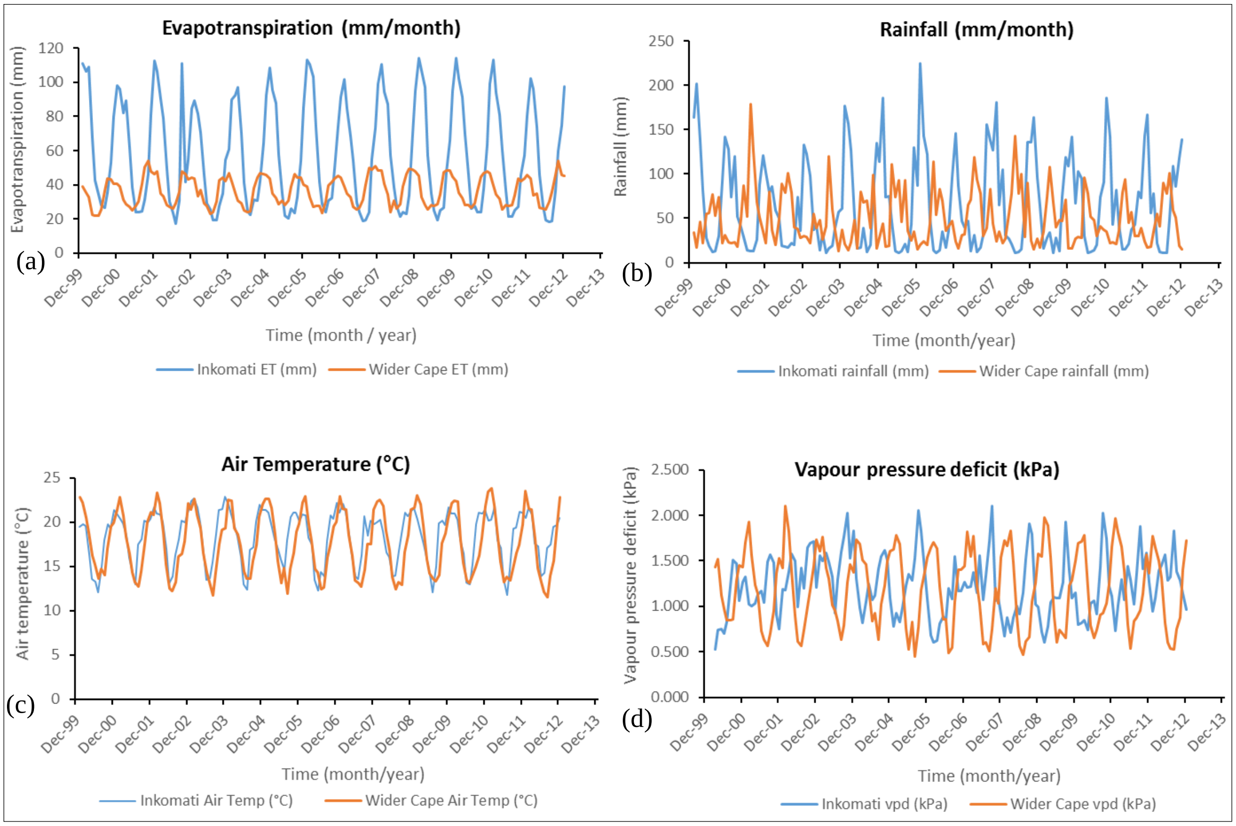

Figure 4.7 Comparison of monthly ET and associated climatic variables in the Inkomati and Wider Cape areas: (a) ET, (b) rainfall, (c) air temperature and (d) vapour pressure deficit.

Evapotranspiration time series results show that ET in the Inkomati area was higher than in the Wider Cape area for the entire period (2000 – 2012) investigated in this study (Figure 4.7). Even though both trends of ET show pronounced seasonal variability, significant differences were found. ET trends in the Inkomati show there was a decline from 2000 to 2012. This is contrary to the Wider Cape area where a slight increase in ET was reported. Rainfall variability followed similar trends observed with ET in terms of seasonal variability; rainfall peaks in the Inkomati area were generally higher than in the Wider Cape area. The wettest month in the Inkomati occurred in 2006 with an average monthly rainfall of 225 mm received in the month of January. In the Wider Cape area, the wettest month was July in the year 2001 with a monthly rainfall total of 178 mm.

Rainfall trends were found to be statistically different. Differences in temperature between the Inkomati and Wider Cape areas were minimal; the monthly temperature range in the Inkomati was 11.8 °C to 22.9 °C while in the Wider Cape area monthly temperature range was 11.5 °C to 23.7 °C. Air temperature differences were found not to be significantly different between the two areas.

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Vapour pressure deficit trends showed pronounced seasonal variations in the Inkomati and Wider Cape areas. In the Inkomati vapour pressure deficit range was 0.49 to 2.10 kPa while Wider Cape vapour pressure deficit range was 0.45 to 2.10 kPa. Trends showed no statistical significant differences.

4.2.2.2 Evapotranspiration and climatic variables correlation

Figure 4.8 shows correlation (Pearson) results to determine the variability of ET which can be explained by the predictor variables (rainfall, temperature and vapour pressure deficit); in other words the results show the dependency of ET on the above mentioned climatic variables (Jovanovic et al. 2015). The medians for each land cover class extracted were averaged to produce a single time series data for each climatic variable per sub-catchment. These were then used to test the dependency of ET on climatic drivers (Figure 4.8).

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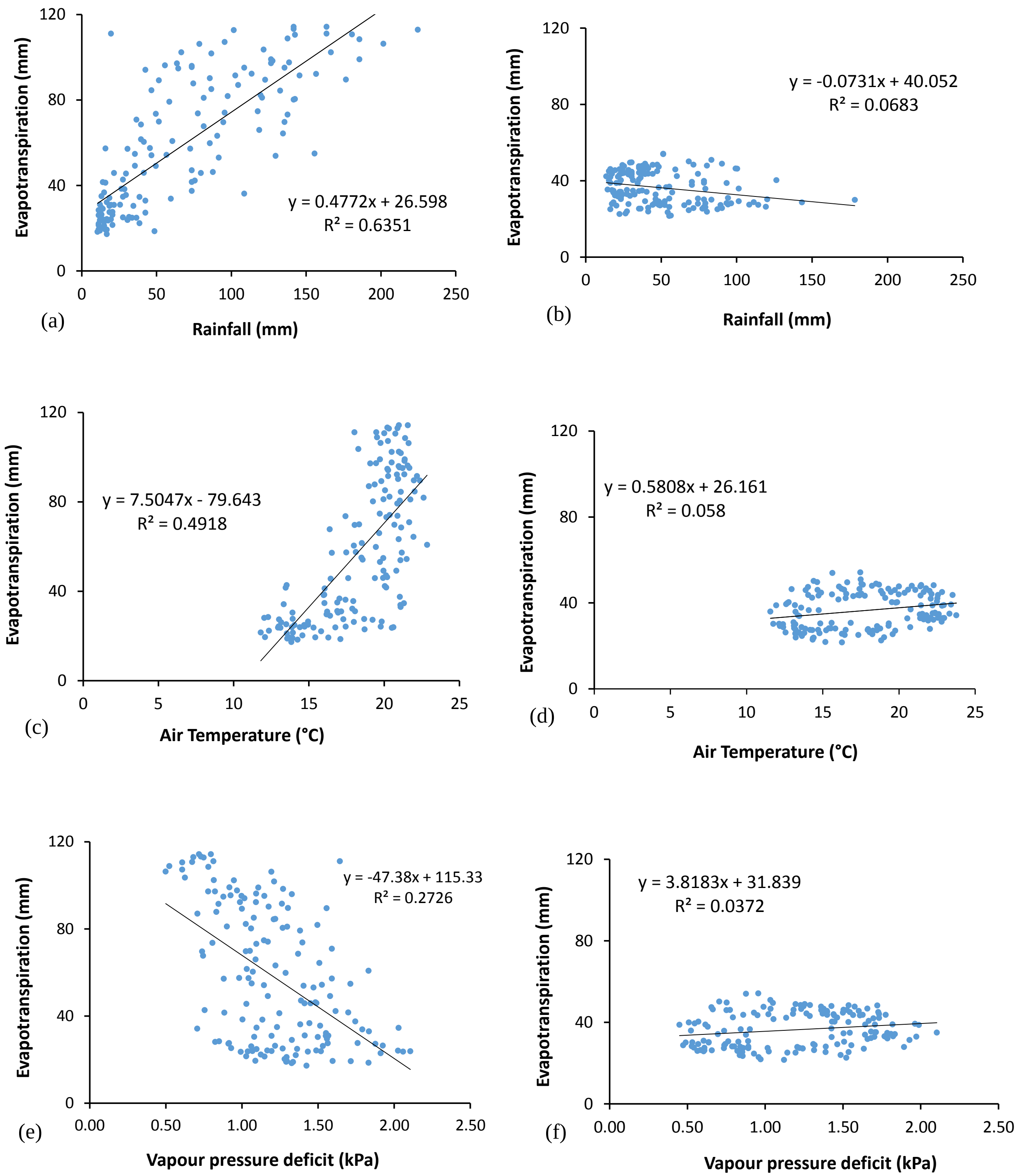

Figure 4.8 Correlation of ET and climatic variables in the Inkomati and Wider Cape areas. Shown in the graphs are correlations of ET with rainfall, air temperature and VPD for the Inkomati (a,c,e) and Wider Cape (b, d, f), respectively.

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Correlation of ET and rainfall in the Inkomati (a) had an adjusted R^2 value of 0.64 while in the Wider Cape (b) R^2 value was 0.068; results were found significant at $p<0.0001$ and $p=0.001$ respectively. Air temperature and ET correlation in the Inkomati reported adjusted R^2 value of 0.49 ($p=0.0001$) while a low $R^2 = 0.058$ squared was reported in the Wider Cape area ($p=0.002$). Vapour pressure deficit correlations were low and significant in both sub-catchment areas: $R^2 = 0.27$ with a significance value of 0.0001 was reported in the Inkomati and $R^2 = 0.037$ ($p=0.016$) in the Wider Cape (Figure 4.8).

4.2.2.3 Climatic variability and land cover

Figure 4.9 shows results from the comparison of ET and associated climatic variables between different land cover classes in the two sub-catchment sites.

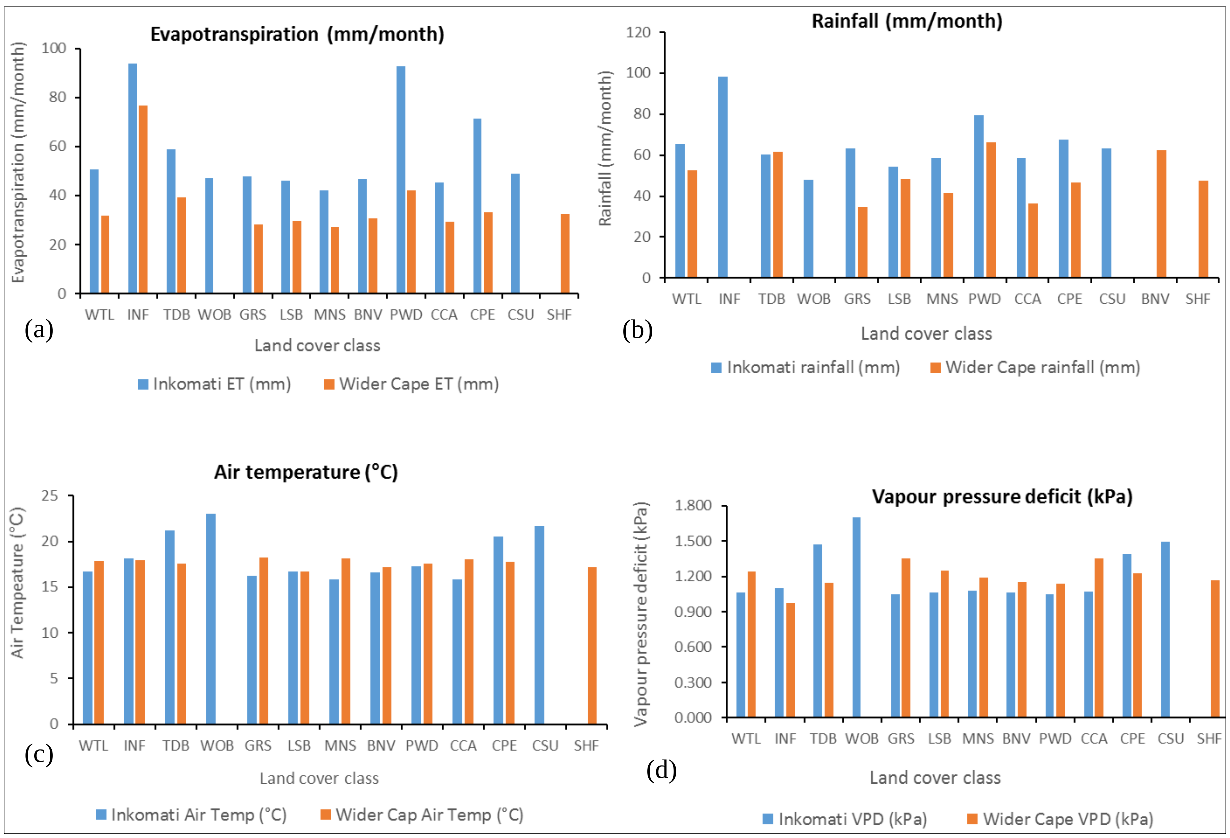

Figure 4.9 Comparison of ET (a) and associated climatic variables (a – evapotranspiration, b – rainfall, c - air temperature and d – vapour pressure deficit) in land cover classes located in the Inkomati and Wider Cape areas.

In Inkomati, indigenous forests (94 mm), plantation woodlots (93 mm) and cultivated perennial (72 mm) land cover classes had the highest monthly median ET. The least ET in the area was

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recorded in the mines (42 mm) land cover class. In the Wider Cape area, indigenous forests (76 mm), plantation woodlots (42 mm) and thicket/dense bush (39 mm) land cover classes recorded the highest median ET; similar to the Inkomati, the mines land cover class (27 mm) recorded the least ET (Figure 4.9). The highest monthly median rainfall was estimated in indigenous forests, plantation woodlots and cultivated perennial classes in the Inkomati area; in the Wider Cape, the highest rainfall estimates were recorded in plantation woodlots, thicket/dense bush and bare-none-vegetated. In terms of air temperature, less difference was observed between the different land cover classes and the two sub-catchment areas; median air temperature range in the Inkomati was 15.8 °C to 23.0 °C; in the Wider Cape area median air temperature range was 16.7 °C to 18.2 °C. Vapour pressure deficit estimates were higher in the Wider Cape area for most land cover classes compared to the Inkomati. General vapour pressure deficit median range for both areas was 0.97 kPa to 1.79 kPa (Figure 4.9).

In the next part, results from the multiple regression analysis are reported. Multiple regressions were performed on monthly median time series (2000 – 2012) data of ET and climatic variables (Table 4.3).

4.2.2.4 Multiple regression analysis

Multiple regression analysis was performed to further analyse the relationship of ET, land cover change and climatic variables for each land cover class. For the analysis, ET variability was analysed as a function of rainfall, temperature and vapour pressure deficit as the predictor variables with the results shown in Table 4.4.

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Table 4.4 Multiple regression analysis coefficients and adjusted R-squared values for each land cover class in the Inkomati and Wider Cape areas.

(a)

Coeffi.	Area	WTL	GRS	LSB	MNS	SHF	BNV	CSU
Air Temp.	Inkomati	7.86	5.98	6.59	5.82	-	-	7.54
	W. Cape	0.8	0.59	2.62	-0.51	2.3	3.61	-
VPD	Inkomati	-59.37	-68.82	-54.89	-52.85	-	-	-56.49
	W. Cape	-16.96	-12.14	-21.78	-9.42	-21.2	-31.34	-
Rainfall	Inkomati	0.06	0.02	0.07	0.078	-	-	0.02
	W. Cape	-0.89	-0.05	-0.04	-0.05	-0.05	-0.04	-
Intercept	Inkomati	-21.37	21.01	-9.47	2.46	-	-	-31.55
	W. Cape	42.96	36.09	115.03	50.1	20.02	7.58	-
R^2	Inkomati	0.89	0.72	0.88	0.86	-	-	0.86
	W. Cape	0.13	0.17	0.13	0.31	-0.05	0.21	-

(b)

Coeffi.	Area	PWD	CPE	TDB	INF	WOB	CCA
Air Temp.	Inkomati	10.02	9.95	9.36	10.94	8.39	8.06
	W. Cape	3.66	2.6	2.64	-	-	-1.59
VPD	Inkomati	-33.89	-55.62	-62.68	-21.44	-64.47	-56.61
	W. Cape	-18.24	-20.94	-14.25	-	-	-14.86
Rainfall	Inkomati	0.023	0.01	0.02	0.08	0.02	0.09
	W. Cape	-0.074	-0.05	-0.06	-	-	-0.15
Intercept	Inkomati	-46.4	-67.78	-48.44	-88.98	-37.07	-64.75
	W. Cape	3.59	15.26	11.22	-	-	83.62
R^2	Inkomati	0.84	0.88	0.85	0.87	0.81	0.84
	W. Cape	0.38	0.12	0.25	-	-	0.47

The above tables (a and b) reports on the intercept, coefficients of predictor variables and adjusted R^2 values from the regression model. Adjusted R^2 of the coefficients in the regression model were generally higher in the Inkomati (0.72 to 0.89) compared to the Wider Cape area (0.12 to 0.47). All regression models in the two areas were found statistically significant ($p<0.05$). In the table, models with R^2 <0.5 have been highlighted.

According to the climatic variable coefficients, a negative relationship was found between ET and vapour pressure deficit; all predictor variable coefficients were negative both in the Inkomati and Wider Cape. Positive coefficients were reported for land cover classes in the Inkomati. Similar

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results were found in the Wider Cape except for cultivated commercial annuals and mines which were found to be statistically non-significant. Contrasting relationships were found between rainfall and ET in the Inkomati and Wider Cape areas: a positive relationship was found between the two variables in the Inkomati while a negative relationship was determined in the Wider Cape. In Table 4.4, in the Inkomati, rainfall data from BNV land cover class reported null values during the extraction. The same occurred for INF during rainfall extraction in the Wider Cape study area. The other two missing land cover classes in the Wider Cape (CSU and WOB) were not present in the AoNC land cover map. For these reasons the above mentioned land cover classes were not included in the multiple regression analysis.

4.2.3 Long-term climatic variability

Figure 4.10 shows the rainfall variability during the study period (2000 – 2012) in relation to the long-term (1950 –2012) rainfall variability. Included in the figure is the standard deviation of the study period rainfall trends.

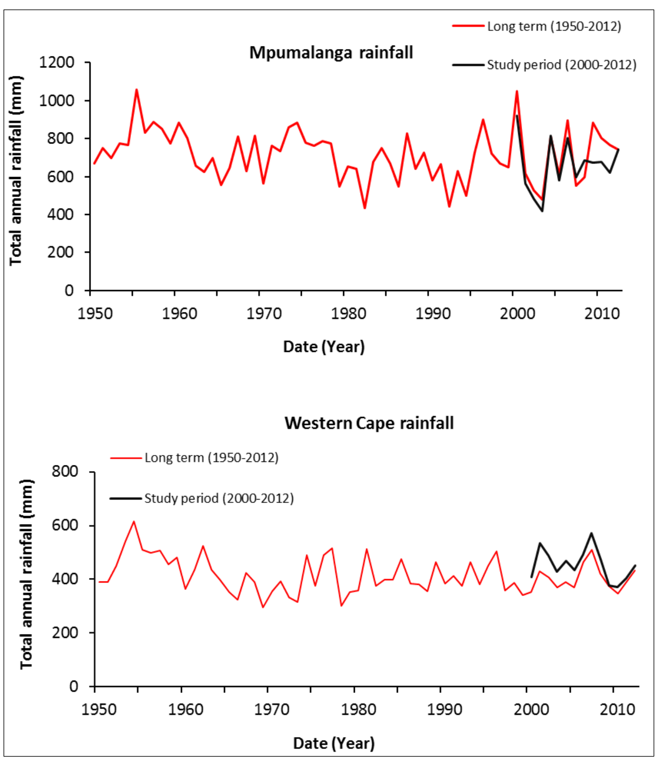

Figure 4.10 Comparison of the study period (2000 2012) rainfall (mm) to the long-term (1950 – 2012) annual rainfall trends in the Mpumalanga and Western Cape provinces.

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The rainfall graphs show the study period (2000 – 2012) rainfall trends did not deviate very much from the long term (1950 – 2012) rainfall trends. This is especially true in Mpumalanga where the area of variability is much lower compared to the Western Cape as shown by the total +/- standard deviation difference. The long-term rainfall variability was analysed to show that the 13-year rainfall variability was representative of the long-term rainfall. Due to the unavailability of such long-term data, similar analysis could not be done with the other climatic variables (air temperature and VPD).

4.2.4 Summary of historical climatic variability and evapotranspiration

The aim of this section was to show results from the analysis of the linkages between ET, climatic variability and land cover changes using a 13-year historical data set. Overall ET estimates were the highest in land cover classes such as plantation woodlots, indigenous forests, cultivated perennials, thicket/dense bush. These land cover classes are also associated with increased rainfall quantities. According to the results, larger variability in ET and associated climatic variables (vapour pressure and rainfall) was found in drier parts of the country (Northern Cape) compared to wet areas such as KwaZulu-Natal. Temperature ranges showed less variability between the study areas as minimal seasonal variation differences were observed with this variable. Variability in these cases refers to trends that do not follow a consistent pattern (e.g. seasonal). ET estimates at provincial scales were higher in KwaZulu–Natal and Mpumalanga, while at sub-catchment scale Inkomati had higher estimates of ET during 2000 to 2012 compared to the Wider Cape. From the regression analysis, negative relationships were found between ET and vapour pressure deficit; temperature was positively related to ET, while rainfall in winter rainfall regions was negatively related to ET but a positive relationship was found in summer rainfall areas (Inkomati). Higher adjusted R-squared values were estimated with multiple regression analysis in the Inkomati area (adjusted $R^2 > 0.7$) compared to the Wider Cape where none of the adjusted R-squared values was above 0.50. The levels from these results showed that all models were statistically significant.

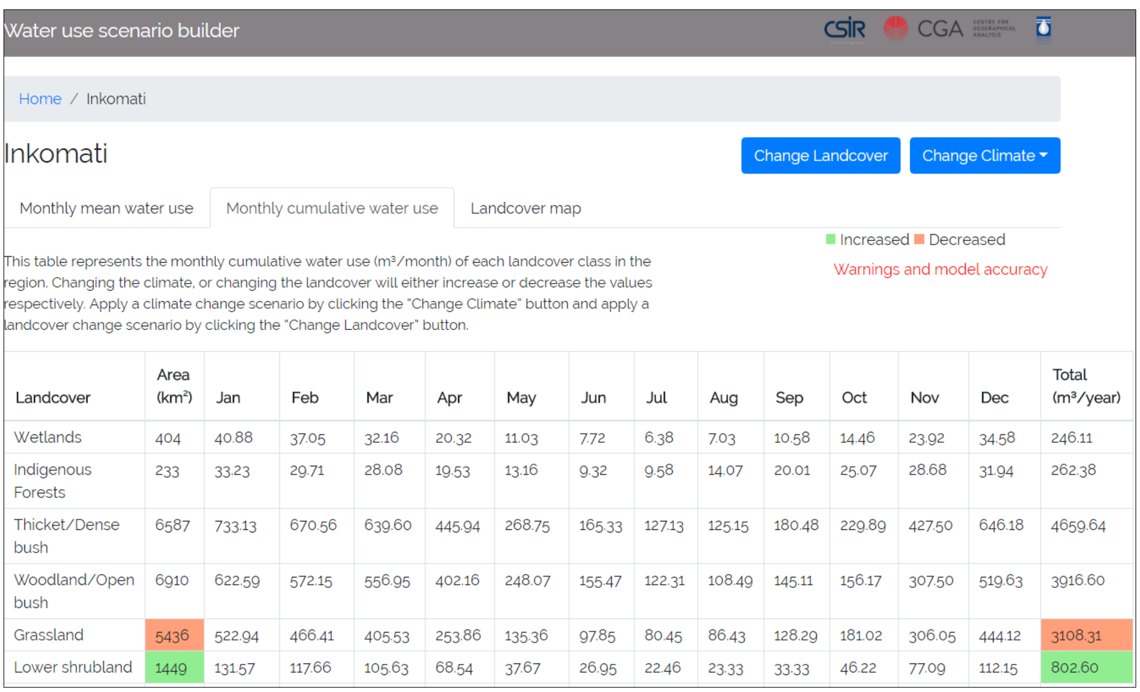
4.3 PROJECTING FUTURE WATER USE CHANGES BY USING DESIGNED LAND COVER AND CLIMATE SCENARIOS

The third objective was to project future ET changes as a function of designed land cover and climatic variability scenarios for the Inkomati and Wider Cape areas using a tool developed for this purpose. Future water use estimations were obtained by applying multiple regression equations developed from regression analysis of ET and three predictor variables: air temperature, rainfall and vapour pressure deficit (VPD). This section shows example results from land cover and climate change scenarios modelled using the scenario tool. The tool was developed in Microsoft Excel using all historical data. A web-design expert subsequently integrated the Excel tool into a web-based scenario builder for use in the overarching WRC project.

Reported initially are land cover change impacts on water use; secondly, climatic change scenarios and lastly the combined effect of these changes. For the purpose of showcasing the tool, only results from the Inkomati area are included in this analysis, however the same functions demontrated here can be applied to the Wider Cape sub-catchment area.

4.3.1 Scenario One – Land cover changes

The impact of reducing the area of four land cover classes (grassland, indigenous forest, plantation and perennial agriculture) by 20% on the annual cumulative water use (Mm^3 a^{-1}) was modelled using the scenario builder. The removed area was hypothetically added to another land cover class. Figure 4.11 below shows how the output of an area change is displayed on the scenerio builder tool.



Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (m³/year)
Wetlands	404	40.88	37.05	32.16	20.32	11.03	7.72	6.38	7.03	10.58	14.46	23.92	34.58	246.11
Indigenous Forests	233	33.23	29.71	28.08	19.53	13.16	9.32	9.58	14.07	20.01	25.07	28.68	31.94	262.38
Thicket/Dense bush	6587	733.13	670.56	639.60	445.94	268.75	165.33	127.13	125.15	180.48	229.89	427.50	646.18	4659.64
Woodland/Open bush	6910	622.59	572.15	556.95	402.16	248.07	155.47	122.31	108.49	145.11	156.17	307.50	519.63	3916.60
Grassland	5436	522.94	466.41	405.53	253.86	135.36	97.85	80.45	86.43	128.29	181.02	306.05	444.12	3108.31
Lower shrubland	1449	131.57	117.66	105.63	68.54	37.67	26.95	22.46	23.33	33.33	46.22	77.09	112.15	802.60

Figure 4.11 Output of the scenario builder when grassland area is reduced and low shrubland is expanded.

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The reduction in the area and cumulative water use of grasslands is shown by the red highlights while the increase in low shrubland area and cumulative water use is shown by the green highlights (Figure 4.11).

Figure 4.12 shows the change in water use in the Inkomati catchment when the particular land cover class (a - grasslands, b – indigenous forests, c – plantation/woodlots and d – cultivated perennial) is reduced by 20% and that removed area is hypothetically added to another land cover class (on the x-axis). The impact of this on cumulative water use ($Mm^3\ a^{-1}$) is shown. On the x-axis, Current represents the annual cumulative water use prior to any land cover changes.

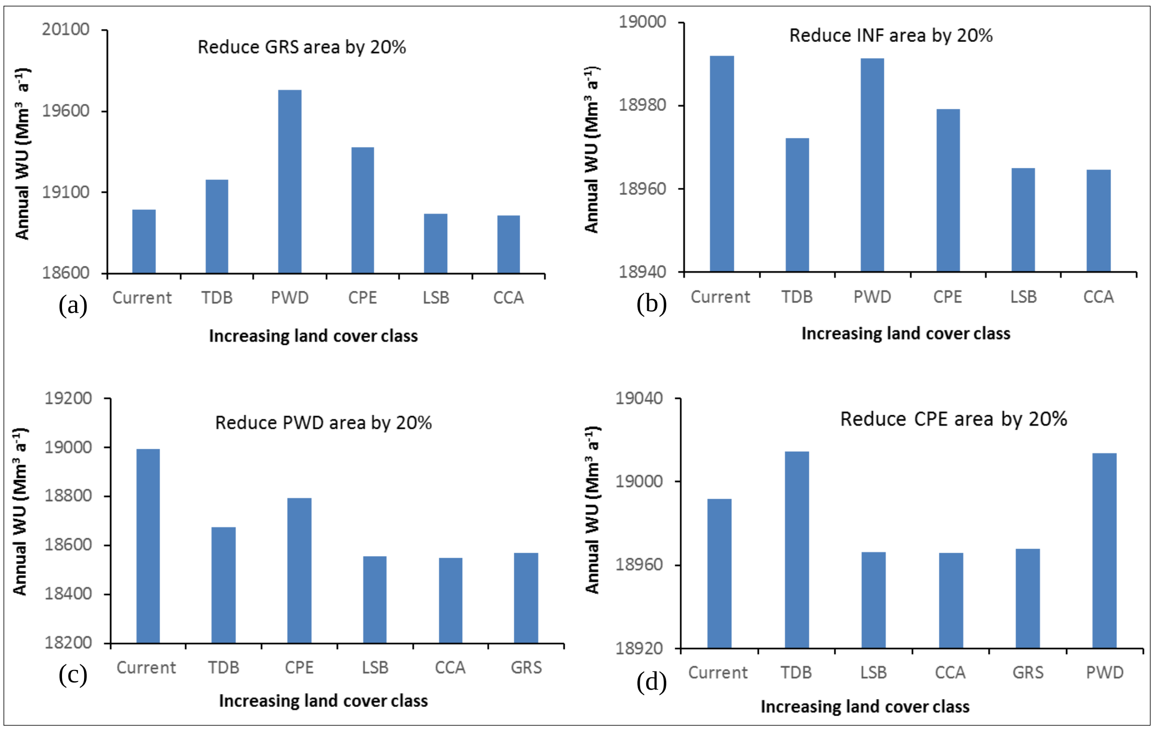

Figure 4.12 Change in annual cumulative water use for the whole sub-catchment (Inkomati) as a result of a 20% reduction in a particular land cover class (a-d). The x-axis shows the current scenario (no change) and the land cover classes that were increased.

Figure 4.12(a) shows that reducing grasslands by 20% (1360 km^2) would have the highest impact on water use if the removed area is added to plantation/woodlots; water use in the Inkomati would increase by 738 Mm^3 per annum. Increasing cultivated perennial land cover class by the same area would increase water use by 388 Mm^3 per annum. Figure 4.12(b) shows that reducing indigenous forests by 20% (47 km^2) and adding the reduced area to any of the land cover classes as shown on the x-axis would slighly reduce the water use. The highest reduction (-27 $Mm^3\ a^{-1}$) would be

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observed if the area was converted into low shrublands and cultivated commercial annuals land cover classes. Figure 4.12(c) shows that a 20% (779 km^2) reduction of plantation/woodlots would have the greatest impact in terms of decreasing annual cumulative water use in the Inkomati area; highest water use reduction occurs when the area is convered to cultivated commercial annuals (-443 Mm^3) per annum. Finally, the impact of the reduction of cultivated perennials and then adding the 20% (84 km^2) reduced area to another land cover class is depicted in Figure 4.12(d). According to the results this would reduce water use in the Inkomati by approximately 25 Mm^3 per annum if the removed area is added to low shrublands, cultivated commercial annuals and grasslands.

4.3.2 Scenario Two – Changes in climatic variability

Water use response was modelled for eight climatic scenarios (increase/decrease in rainfall (R), temperature (airT) and vapour pressure deficit (VPD) using the scenario builder tool. Table 4.5 shows a summary of the different climatic scenarios and the water use response in the Inkomati sub-catchment.

Table 4.5 Summary results of the impacts of climate scenario changes on monthly mean ET (mm).

Scenario	Climate Scenario	Impact on monthly ET (mm)
1	R↑;[VPD↓;airT↓]	Decrease
2	R↓;[VPD↓; airT↓]	Decrease
3	R−;[VPD↓;airT↓]	Decrease
4	R↑;[VPD↑; airT↑]	Increase
5	R↓;[VPD↑;airT↑]	Increase
6	R−;[VPD↑;airT↑]	Increase
7	R↑;[VPD−;airT−]	Increase
8	R↓;[VPD−;airT−]	Decrease

↑ increase; ↓ decrease; − constant

Figure 4.13 (a-d) compares the change in mean monthly ET for four land cover classes (plantation woodlots, cultivated perennials, grasslands and cultivated commercial annuals) as a result of the application of different climatic scenarios. (a) compares Scenario Five (decreased rainfall; VPD and airT increase) and Scenario One (increased rainfall; VPD and airT decrease). (b) compares Scenario Six (rainfall remains constant; VPD and airT increase) and Scenario Seven (increased

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rainfall; VPD and airT remain constant). (c) compares Scenario Eight (decreased rainfall; VPD and airT remain constant) and Scenario Three (rainfall remains constant; VPD and airT decrease). (d) compares Scenario Four (increased rainfall; VPD and airT increases) and Scenario Two (decreased rainfall; VPD and airT decreases).

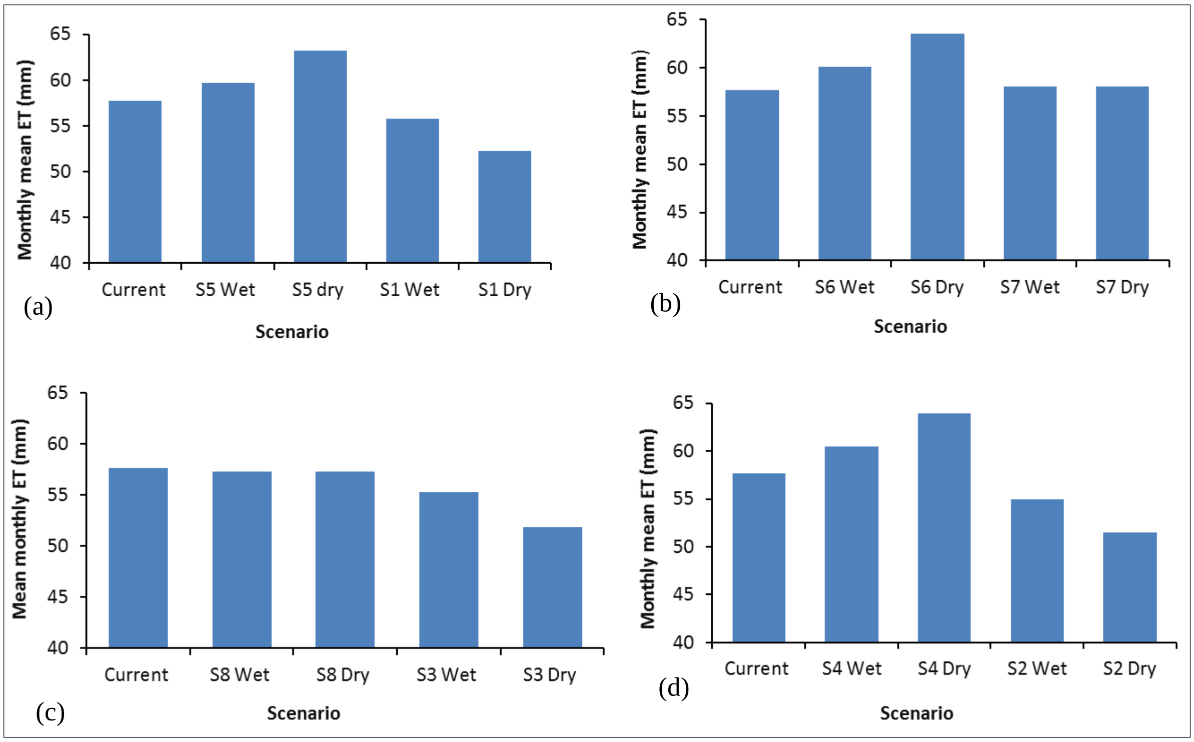

Figure 4.13 Mean monthly ET (mm) changes in the Inkomati area due to the selection of different climatic scenarios.

Default ET (current) in the figure shows the current mean (mm/month) for each land cover class as extracted from the mean MOD16 satellite product. According to Figure 4.13(a), increased rainfall with air temperature and VPD decreasing resulted in a lower mean ET while increasing air temperature and VPD with rainfall decreasing resulted in an increase in mean monthly ET. Figure 4.13(b) compared Scenario Six and Seven; ET mean was found to increase for both scenarios, however the highest increase was observed when air temperature increased while rainfall mean remained constant. Figure 4.13(c) Scenarios Eight and Three comparisons both reported declining ET mean and the greatest decline between these scenarios occurred when air temperature and VPD declined while rainfall remained constant. Lastly, Figure 4.13(d) compared Scenarios Two and Four, Scenario Two reported decreasing mean ET. According to Scenario Four, an increase in all climatic drivers resulted in an increase in mean ET.

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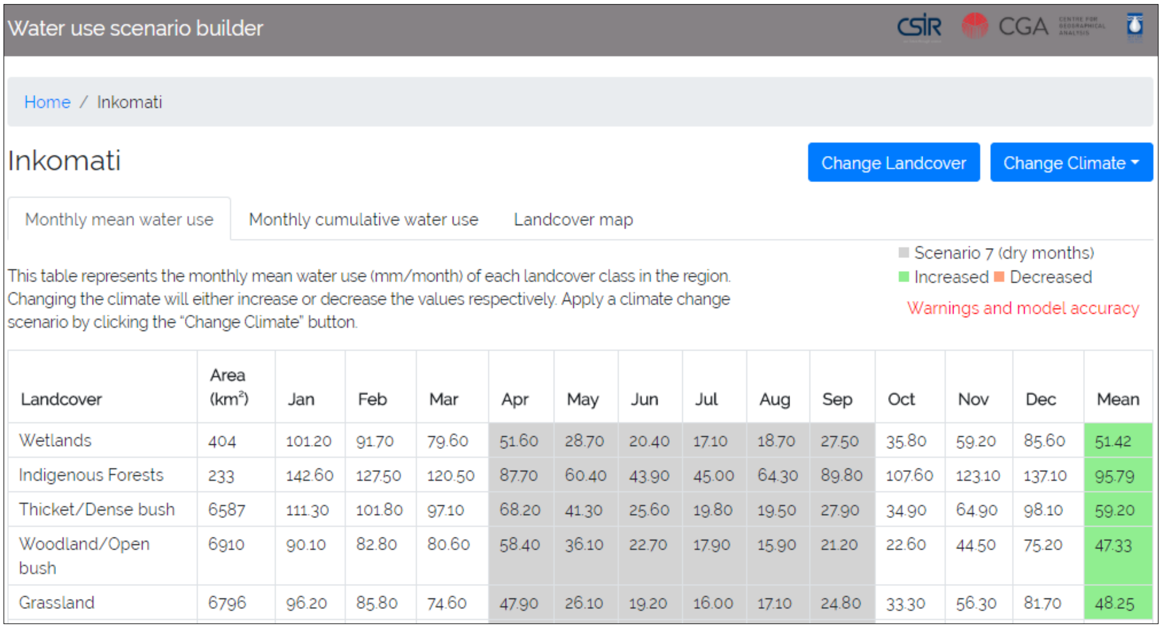
Figure 4.14 below shows the display of the scenario changes output with the scenario builder tool.


Water use scenario builder

Home / Inkomati

Inkomati

Change Landcover
Change Climate

Monthly mean water use
Monthly cumulative water use
Landcover map

Scenario 7 (dry months)
Increased Decreased
Warnings and model accuracy

This table represents the monthly mean water use (mm/month) of each landcover class in the region. Changing the climate will either increase or decrease the values respectively. Apply a climate change scenario by clicking the "Change Climate" button.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Wetlands	404	101.20	91.70	79.60	51.60	28.70	20.40	17.10	18.70	27.50	35.80	59.20	85.60	51.42
Indigenous Forests	233	142.60	127.50	120.50	87.70	60.40	43.90	45.00	64.30	89.80	107.60	123.10	137.10	95.79
Thicket/Dense bush	6587	111.30	101.80	97.10	68.20	41.30	25.60	19.80	19.50	27.90	34.90	64.90	98.10	59.20
Woodland/Open bush	6910	90.10	82.80	80.60	58.40	36.10	22.70	17.90	15.90	21.20	22.60	44.50	75.20	47.33
Grassland	6796	96.20	85.80	74.60	47.90	26.10	19.20	16.00	17.10	24.80	33.30	56.30	81.70	48.25

Figure 4.14 Monthly mean ET output of scenario 7 for dry months in the Inkomati area.

The scenarios were applied and seasonality (dry/wet) is shown in the output. Where there are changes in the mean ET (mm) as previously mentioned, those changes are indicated by the red/green highlights. A summary table of the results of climatic scenario changes have been shown in Table 4.5.

4.3.3 Scenario Three – Land cover and climatic variability changes

Scenario Three combines land cover and climatic variability changes in the scenario builder tool. Figure 4.15(a-d) shows the results of comparing the changes in water use following the application of a land cover change as well as different climatic scenarios. The scenario tool was used to investigate the conversion of a reduction of 20% (779 km^2) of plantation/woodlots and an expansion of grassland land cover class with the same area under different climatic scenarios. The scenarios investigated under this area change include: (a) - Scenario Three (Rainfall remains constant; VPD and airT decline), (b) - Scenario Seven (rainfall increase; VPD and airT stay the same), (c) - Scenario Five (Decline in rainfall; VPD and airT increase) and (d) - Scenario Six (Rainfall remains constant; airT and VPD increase).

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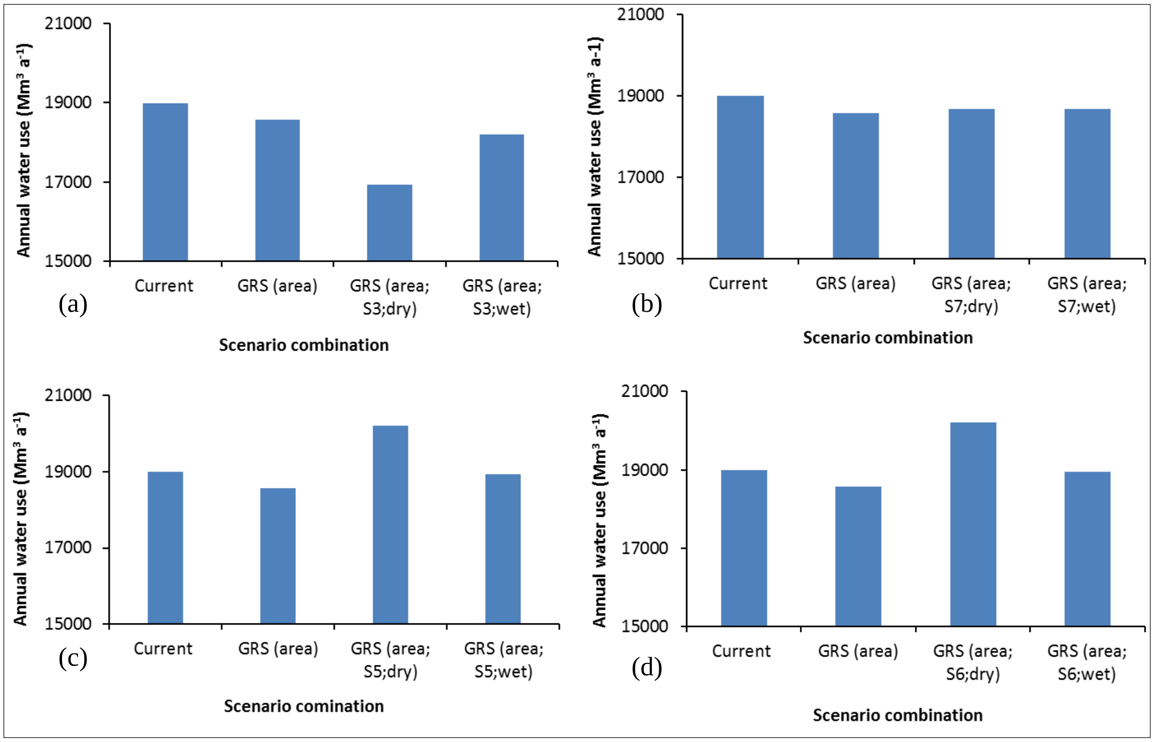

Figure 4.15 Changes in annual cumulative water use following the application of an area change under different climatic scenarios.

Figure 4.15(a-d) shows the default annual cumulative water use (Current on x-axis), the changes due to the increase in grassland area and the reduction by 20% of plantation/woodlots, and lastly the application of the different scenarios under dry and wet climates. The reduction of plantation woodlots and increase in grasslands has a positive impact on water use since overall it is seen to reduce annual water use in the Inkomati area. The application of Scenario Three (Rainfall remains constant; VPD and airT decline) in dry months as shown in Figure 4.15(a) reported the largest decline in annual cumulative water use (-2058 Mm^3). Increases in air temperature and VPD while rainfall declines (c – Scenario Five) or when the mean rainfall remains constant (d - Scenario Six) will result in the increase in the overall cumulative water use even with the conversion of the plantation/woodlot area into grasslands.

4.3.4 Projection accuracy assessment

To help guide the user confidence in making interpretations and decisions using the water use scenario tool a *warning and model accuracy* feature was added to the tool; this feature is for the predicted change in water use for each month per land cover. The multiple linear regression R^2

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value and the root mean square error (RMSE) were the chosen parameters to be used for the model accuracy analysis. The RMSE error was the calculated difference between the satellite ET mean and the multiple regression equation derived mean. Where the model accuracy was considered low and requires being analysed with caution, the cells are shown as highlighted in red. For the RMSE an error within 20% of the monthly mean of satellite derived ET (MOD16) was considered to be an acceptable error while a RMSE above 20% of the mean value of satellite derived ET was flagged red meaning the predicted changes and interpretations thereafter should be made with caution.

Landcover	Multiple linear regression model R^2	Multiple linear regression model RMSE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wetlands	0.886	10.31	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Indigenous Forests	0.875	13.23	<20%	<20%	<20%	<20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%
Thicket/Dense bush	0.858	13.86	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%
Wooland/Opend bush	0.82	14.37	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%
Grassland	0.89	10.43	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Lower shurbland	0.89	10.5	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Mines	0.866	9.96	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%
Bare ground	0.885	9.83	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Plantations/ Woodlots	0.838	13.68	<20%	<20%	<20%	<20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%
Cultivated commercial annuals	0.859	12.21	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%
Cultivated perennial	0.871	11.46	<20%	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Cultivated subsistance	0.862	11.51	<20%	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%

- < 20%: Indicates that the RMSE is smaller than 20% of the monhtly mean water use for the specified landcover
- > 20%: Indicates that the RMSE is greater than 20% of the monhtly mean water use for the specified landcover and should be interpreted with care.

Figure 4.16 Warning and model accuracy feature showing the linear regression model R^2 and root mean square error (RMSE) in the Inkomati area.

The multiple linear regressions (R^2) in the Inkomati area (Figure 4.16) showed higher confidence compared to the Wider Cape area. The R^2 range in the Inkomati was 0.82 to 0.89. According to the RMSE analysis in the Inkomati RMSE was mostly within 20% of the monthly mean water use during the wet months (January, February, March, October, November and December) compared to dry months where RMSE was mostly above 20% of the monthly mean water use for the different land cover classes as seen in Figure 4.16.

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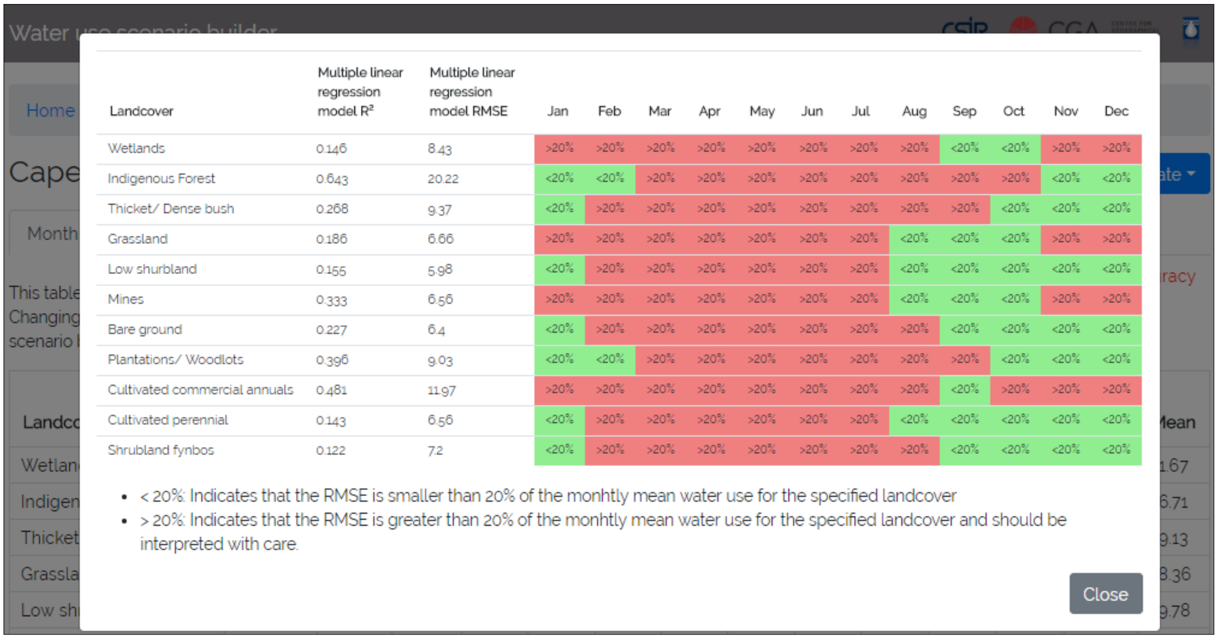

Landcover	Multiple linear regression model R²	Multiple linear regression model RMSE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wetlands	0.146	8.43	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	>20%	>20%
Indigenous Forest	0.643	20.22	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%
Thicket/ Dense bush	0.268	9.37	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%
Grassland	0.186	6.66	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	>20%	>20%
Low shurbland	0.155	5.98	<20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%	<20%
Mines	0.333	6.56	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	>20%	>20%
Bare ground	0.227	6.4	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%
Plantations/ Woodlots	0.396	9.03	<20%	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%
Cultivated commercial annuals	0.481	11.97	>20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	>20%	>20%	>20%
Cultivated perennial	0.143	6.56	<20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%	<20%
Shrubland fynbos	0.122	7.2	<20%	>20%	>20%	>20%	>20%	>20%	>20%	>20%	<20%	<20%	<20%	<20%

- < 20%: Indicates that the RMSE is smaller than 20% of the monhtly mean water use for the specified landcover
- > 20%: Indicates that the RMSE is greater than 20% of the monhtly mean water use for the specified landcover and should be interpreted with care.

Close

Figure 4.17 Warning and model accuracy feature showing the linear regression model R^2 and root mean square error (RMSE) in the Wider Cape area.

The multiple regression R^2 values were very low for most land covers in the Wider Cape area (Figure 4.17) ranging from 0.1 to 0.5, which is very low compared to the Inkomati. According to the RMSE analysis in the Wider Cape most of the months reported RMSE greater than 20% of the monthly mean satellite derived water use. Taking into consideration the low R^2 values in the Wider Cape, this stresses the need to be cautious when interpreting results from the Wider Cape (Figure 4.17).

4.3.5 Summary of projecting future water use changes by using designed land cover and climate scenarios.

The aim of the third objective was to project future changes in water use as a function of changes in land cover and climatic variability. This was done by developing a water use scenario builder tool appropriate for such application. The tool was initially developed as an Excel-based tool and later integrated into a web-platform by a web-developer.

To showcase the first scenario we analysed the changes in water use if a particular land cover class is reduced by 20% and if that area was hypothetically added to another land cover class. These results showed that the replacement of grasslands with plantation/woodlots would result in the highest cumulative water use increase while replacing 20% of plantation/woodlots with cultivated

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commercial annuals or low shrublands would result in the largest decrease in annual cumulative water use. For climatic scenarios we compared the impact of various scenarios on monthly ET (mm) for dry and wet months. According to these results, larger changes (increase or decrease) in the mean ET can be anticipated to occur during dry months compared to wet months in the Inkomati area. Comparison of the scenarios showed that Scenario Six (rainfall remains constant; VPD and airT increase) during dry months will have the highest impact in-terms monthly mean ET. In terms future of decreases in water use, Scenario Two (decreased rainfall; VPD and airT increase) will result in the highest hypothetical reduction of mean ET. Finally combining the two scenarios, we analysed the impact of reducing the plantation/woodlots area by 20% and expanding the grasslands area by this percentage under different climatic scenarios. The highest decline in annual water use was reported when this occurs under Scenario Three (rainfall remains constant; VPD and airT decline).

Chapter 5 discusses the results that have been presented in this current chapter.

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CHAPTER 5 DISCUSSION

This chapter discusses the theoretical and practical implications of the results of the study. The discussion is presented according to the study objectives: the first part discusses current land use and water use analysis, part two discusses linkages of ET, land cover change and climatic variability, while part three discusses the future trends in water use based on examples of the climate and land use scenarios created.

5.1 LAND USE AND WATER USE

There is a significant demand for water research globally, and in South Africa particularly; this relates to research concerning both the quantity and quality of water resources. Knowledge of how much water different land cover classes are using is important for the appropriate allocation and management of this resource. Rising tensions for access to water from different users has also emphasised the need for such water use estimations. These are not only important for understanding current water use status, but also important for future projections of water use as a result of changing patterns of human behaviour which drive land use changes. The first objective of the research was aimed at contributing to this knowledge gap.

The results from this objective (Section 4.1) have shown that the remote sensing approach to monitoring water use can reveal the differences in water use from various land cover classes. This was demonstrated by comparing median ET and cumulative water use from various land cover classes at provincial and sub-catchment scale. Figure 4.1 and Figure 4.2 show water use estimates at a provincial scale by comparing KwaZulu-Natal, Northern Cape, Mpumalanga and the Western Cape. According to these results land cover classes, plantation/woodlots, indigenous forests and cultivated perennial land cover classes were the highest water users. At the sub-catchment scale analysis, a similar pattern was observed when comparing the Inkomati and the Wider Cape areas (Figure 4.3).

Plantation/woodlots land cover class consists of timber trees that are primarily grown for commercial purposes. These mature species have above 70% canopy closures and are known to have deep root systems (Albaugh, Dye & King 2013). Large tree species are able to maintain increased levels of ET because of their ability to obtain water from greater soil depths, which is a significant factor determining vegetation ET differences particularly in dry climates (Zhang,

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Dawes & Walker 2001). Annual ET in forest plantations was the highest in KwaZulu-Natal and Limpopo with a range between 1127 mm and 1274 mm per annum for the year 2012. Similar estimates were reported in a review paper by Dye & Versfeld (2007) with common ET for an established plantation ranging between 1100 mm and 1200 mm per annum. However, in a study comparing water use of alien plant species and native vegetation in the Western Cape and KwaZulu-Natal using remote sensing, annual ET for forestry plantations was found to be 840 mm and 690 mm respectively (Meijninger & Jarmain 2014). These differences could be attributed to the algorithm (SEBAL) and the 250 m pixel resolution at which this investigation was conducted (Meijninger & Jarmain 2014). According to van Eekelen et al. (2015) in the Incomati Basin annual ET was estimated to be 1151 mm per year, similar to ET estimated in plantation/woodlots in this current study from the Inkomati area which was 1057mm per annum.

Cumulative water use results showed that land cover classes that recorded the highest cumulative water use estimations depend on the area in question; land cover classes such as grasslands, shrubland fynbos and low shrublands have lower median ET but have the highest cumulative water use in provinces such as KwaZulu-Natal, the Western Cape and the Northern Cape respectively since they cover larger areas. According to a review by Dye (1996), the estimated ET from shrubland fynbos vegetation pre-afforestation reported in the Western Cape was between 700 mm and 900 mm per year. Using SEBAL, Meijninger & Jarmain (2014) reported 510 mm per year ET median in the Western Cape. The results from this current study, based on the MOD16 product, reported lower estimations of ET from shrubland fynbos vegetation with the estimated annual ET in the Western Cape between 264 mm and 277 mm per year. As previously mentioned, the resolution and satellite product used could be the reason for the observed difference.

A review paper by Dye (1996) also reported that indigenous grassland ET in KwaZulu-Natal pre-afforestation was within the 750 mm – 900 mm range per annum. Our results showed that grassland annual ET was 600 mm – 700 mm in KwaZulu-Natal. This is within the range reported by Meijninger & Jarmain (2014) who estimated a median ET of 630 mm per annum in KwaZulu-Natal. According to Meijninger & Jarmain (2014) the ET spread between natural land vegetation was higher in the Western Cape compared to KwaZulu-Natal; similar results were reported in this current study where median ET range in the Western Cape was between 163 mm and 1111 mm compared to 606 mm – 1112 mm per year in KwaZulu-Natal. This included classes such as

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indigenous forests, thicket/dense bush, woodland/open bush, grasslands, low shrublands and shrubland fynbos.

On a countrywide scale, cultivated sugarcane recorded the highest annual median ET. Using a method which derives a relationship between sugarcane yield and actual ET, Bezuidenhout et al. (2006) estimated that water use of sugarcane at an industrial scale was 598 mm per year. In the same study the average mean annual water use of other mills in South Africa was compared, and the overall range reported was 440 mm – 1016 mm per year (Bezuidenhout et al. 2006) with the highest value of 1016 mm per year recorded in the Komati Mill located in Mpumalanga. Results from a water withdrawals study conducted by van Eekelen et al. (2015) using satellite measurements in the Incomati Basin reported an evaporation estimate of 1044 mm per annum for irrigated sugarcane. Our results with MOD16 showed average annual ET in the Inkomati area was 775 mm and 877 mm per year in the larger Mpumalanga province. Indigenous forests, one of the smallest land cover classes, recorded the second highest median ET on a countrywide scale. At sub-catchment and provincial scale, ET ranging from 871 mm to 1112 mm per year was reported for indigenous forests. By comparison, Meijninger & Jarmain (2014) reported indigenous forests ET of 665 mm and 1015 mm per year in KwaZulu-Natal and Western Cape respectively with SEBAL. Dye et al. (2008) reported that the annual ET of Groenkop forest located in George was 1175 mm per year. Although these land cover classes have the highest water use based on median ET, their small spatial coverage on a countrywide scale makes their impact on water use negligible. At the same time, it highlights the need to monitor their location due to their potential impact on water use.

5.2 EVAPOTRANSPIRATION, LAND COVER CHANGE AND CLIMATIC VARIABILITY

Evapotranspiration as an atmospheric process is driven largely by changes in climate or climatic variability that are natural cycles but can be altered by humans to a certain extent. Land cover changes are known to alter water balance components such as stream flow, groundwater recharge and ET in particular (Zhang, Dawes & Walker 2001). Since land use and land cover changes are largely as a result of human activity, it is thus important to have a thorough understanding of how these activities impact ET. The second objective of the research was aimed at describing these linkages between ET, land cover change and climatic variability.

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Similar trends in monthly ET were reported for the various land cover classes to those observed in the annual (2012) water use results. Based on the monthly results, plantation woodlots, thicket/dense bush and cultivated perennial land cover classes recorded the highest ET averages for 2000 – 2012, while indigenous forests and plantation woodlots had significantly higher ET compared to other land cover classes in the Western Cape. Evapotranspiration differences were found to be closely linked to differences in rainfall both at a provincial and sub-catchment scale. At provincial scale, the highest rainfall estimates were found in KwaZulu-Natal while at sub-catchment scale the Inkomati area recorded higher rainfall compared to the Wider Cape area. According to Oishi et al. (2010), rainfall impacts both components of ET (transpiration and evaporation) by altering the soil moisture and surface wetness. Shoko et al. (2015), using a SEBAL model, reported that ET and rainfall patterns in Matabeleland followed similar patterns of spatial and temporal variability. Similar relationship was observed by Meijninger & Jarmain (2014) who found strong correlations between increased rainfall, ET and high biomass estimates. Strong positive correlation was determined between rainfall and ET from MOD16 in the Inkomati sub-catchment ($r^2 = 0.63$), however weak negative correlation was determined in the Wider Cape ($r^2 = 0.068$) although it was found statistically significant. Similarly, at a provincial scale, the strongest correlation was found in the Mpumalanga province ($r^2 = 0.69$) and lowest in the Western Cape. The low correlation between ET and rainfall in the Wider Cape area, with fynbos as the dominant land cover class, could be a result of the fynbos species in the Cape region exhibiting differing responses to changing rainfall patterns (West et al. 2012). In addition, the negative relationship was found to occur since it is a winter rainfall region. Therefore during periods of high rainfall, low temperatures and cloudy conditions would be experienced resulting in low ET. However, this trend cannot be confirmed with confidence since the correlations between ET and rainfall in winter rainfall areas were found to be low. In addition, we found no other specific local studies in winter rainfall regions to support this assumption. Peterson, Golubev & Groisman (1995) reported a decrease in pan evaporation over the United States and neighbouring regions; according to the results, this was found to be closely correlated with increasing cloud cover in the regions.

Temperature results showed minimal differences between the land cover classes both at provincial and sub-catchment scale. A stronger correlation was found between ET and temperature in the Inkomati ($r^2 = 0.49$) compared to a weak positive correlation reported in the Wider Cape area ($r^2 = 0.058$); however, no statistically significant differences were reported between these two areas.

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Provincially KwaZulu-Natal reported the highest correlation (r^2 = 0.71) and the Northern Cape recorded the lowest. Moratiel, Durán & Snyder (2010) reported similar positive correlation results in a study on the response of reference ET to air temperature and humidity changes. Increases in ET estimated using the FAO-56 Penman-Monteith equation, on which the MOD16 ET is based, were found to be correlated with increasing temperatures and in addition these increases were found to be limited by increasing humidity. Since the current study did not include humidity as a climatic driver, our findings are not able to confirm this. From a long-term study (32 years), Goyal (2004) estimated that a 1% increase in air temperature has the potential to increase ET by 15 mm, highlighting the importance of the anticipated increase in water demand in any catchment due to the increase in temperature. In a study to determine the sensitivity of ET to different climatic variables, Vicente-Serrano et al. (2014) reported that ET showed greater sensitivity to changes in maximum temperatures compared to minimum temperatures. Both these studies estimated ET using the Penman-Monteith equation.

No significant differences in monthly vapour pressure deficit (VPD) trends were identified between the Inkomati and Wider Cape areas, however at provincial scale some provinces reported significant differences in VPD trends. Weak correlation of ET and VPD was determined at sub-catchment scale. A negative relationship between ET and VPD was reported in the multiple regression model that combined all climatic drivers. It was also reported by Jovanovic et al. (2015) using MOD16 satellite data that at high VPD levels, ET decreases. However, results from the individual correlation of ET and VPD showed that in the Inkomati the relationship was negative while in the Wider Cape the relationship between the two variables was slightly positive. Differing relationships were also reported between the provinces. Such results can be expected given the low individual correlation coefficients of ET and VPD below r^2 = 0.30 both at sub-catchment and provincial scale. It can be concluded from our results that vapour pressure deficit alone is not sufficient to explain the variability in ET and that its importance is less than that of air temperature and rainfall. These findings were in contradiction to those reported by Wang, Dickinson & Liang (2012) in a study to determine the factors influencing the variability and trends in pan evaporation from 1973 to 2008. Wang, Dickinson & Liang (2012) found VPD was more responsible for driving variability in pan evaporation compared to other climatic drivers such as wind speed, air temperature and incoming solar radiation. Furthermore VPD is an important atmospheric process driving physiological processes such as the transportation of water between plant parts, and

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ultimately influences transpiration rates (Zhang et al. 2017). Although the study was unable to determine the specific values of VPD which cause pronounced changes in ET, previous studies on VPD stated that high VPD levels encourage optimal transpiration levels in plants (Zhang et al. 2017). However, extremely high VPD can result in increased plant stress. Lower VPD values decrease transpiration rates in plants, resulting in a decreased movement of water between the roots and leaves (Zhang et al. 2017). This highlights the importance of understanding changing patterns of VPD since ultimately it is a driving force of plant transpiration rates (Zhang et al. 2017).

5.3 SCENARIO TOOL FOR PROJECTING FUTURE WATER USE

Projecting future trends relies entirely on our understanding of the historical trends related to the drivers of phenomena under investigation. At a management level, knowledge of how planned development and possible climatic scenarios are likely to impact on critical resources is important for appropriate management of those resources, in this case water resources. Planning for the future requires us to plan for multiple possible scenarios (Star et al. 2016), and this is especially true when attempting to make decisions under increased uncertainty. It is important to recognise that scenario planning is not a method of predicting future changes, but is a useful mode to allow civil society and planners to engage in conversations to discuss ways of preparing potential responses (Star et al. 2016). Therefore, the scenario tool was primarily developed as an attempt to assist water users and managers in answering questions related to water resources under uncertain climatic conditions and land cover changes by designing various possible scenarios.

Paired catchment and water yield studies investigating the impact of vegetation change on water use have played a significant role in generating knowledge about the impacts of changing land cover on the hydrological cycle and its various components (Bosch & Hewlett 1982). Such research in South Africa dates back to the 1930s following the growing concern about the expansion of commercial forestry areas and the associated impacts of these (Dye & Versfeld 2007; Gush 2006). According to our land cover change scenario example, clearing a portion of plantation/woodlots and replacing it with native vegetation such as grasslands was found to significantly decrease water use in the Inkomati area. This concurred with results described by Brown et al. (2005) who reviewed studies reporting on water yield changes on catchments as a result of vegetation changes. The application of a climatic scenario showed that the expected changes in water use are more pronounced in dry months compared to wet months. According to

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Dzikiti et al. (2016) a possible reason for this observation is that in the wet seasons the water use of native vegetation physiologically has the potential to rise to levels that almost match those of introduced (plantations) species. This would result in smaller changes in water use being observed during high rainfall (wet) months as suggested by our results (Figure 4.13). Dye & Versfeld (2007) reported similar findings in a review study.

The effect of seasonality following vegetation changes has been discussed by previous studies. Brown et al. (2005) stated that studies in summer rainfall areas have reported differing results on the impacts of seasonality on observed water yield following changes in vegetation particularly following afforestation. Samra, Sikka & Sharda (2001) reported larger reductions in water yield during high rainfall months following the replacement of 59% grassland with blue gum in India. Scott et al. (2000) reported that dry climates or periods of low water availability have the potential to show greater changes in water yield compared to wet climates. These contrasting findings have led to the conclusion that there is a need for generic methods to be applied for all catchment studies investigating vegetation change impacts on seasonal water yield so that generalised conclusions can be made (Brown et al. 2005). From the climatic scenario example results, increases in ET are less limited by rainfall changes compared to the combined effect of air temperature and VPD. The scenario examples suggest that there is an observed increase in ET when VPD and air temperature increase, even when rainfall decreases. Similarly an overall decrease in ET is reported with a decrease in air temperature and VPD when rainfall increases.

Two assumptions were made in the development of the water use scenario tool. The first assumption was that changes in air temperature and VPD always follow the same trend, in that when temperature decreases then VPD will follow a similar pattern. The reason for this is that increases in air temperature are known to increase the saturation vapour pressure, which results in an increase in the difference or deficit between saturation vapour pressure and actual vapour pressure, which is VPD. However, Szilagyi, Katul & Parlange (2001) reported that this relationship is not always linear as they found increases in ET during a 50 year period that were correlated with rainfall and air temperature increases but with constant VPD levels. The second assumption was that changes (increases/decreases) in the climatic drivers of ET in the future will occur within one standard deviation (plus or minus) of the historical mean obtained. The scenario tool was developed using multiple regression equations, means and standard deviations from each study site per land cover class. Therefore the question of the application of the tool in other studies is

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possible only if the multiple regressions are analysed for data specific to the site and thereafter the equations are applied to the scenario tool.

5.4 CONCLUDING REMARKS

The chapter has discussed the findings obtained in Chapter 4. Possible explanations for the observed differences in land cover ET have been discussed, as have the underlying processes driving the relationships between ET and climatic drivers. Lastly, the climatic and land cover change scenarios generated as examples using the scenario tool in the Inkomati were also discussed in the chapter. In the following chapter (conclusion) the research aims are revisited, the limitations of the study are addressed, main research findings are summarised and lastly, recommendations or possible improvements to the current study are provided for the purpose of contributing to future research.

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CHAPTER 6 CONCLUSION

In this final chapter, the research objectives are revisited, the methodological approach used to achieve these is outlined and the findings are briefly mentioned. Furthermore, the limitations and recommendations are stated that provide insights into how the findings could have been improved, while simultaneously setting the scene for future research. In addition, the conclusion to the study is made and initial research questions are revisited.

6.1 REVISITING OBJECTIVES

Within the overarching aim of understanding the role of climate variability and land cover changes in altering ET at different scales, the first objective was to define the current water use status per land cover class by extracting annual (2012) ET estimates for various land cover classes from remote sensing data (MOD16 data product). The NLC2013/14 land cover map was used to extract land cover information while the 2012 ET data was assumed to represent the current water use. The ET data was extracted for all land cover classes at a 30 m resolution matching the land cover map. To analyse water use from land cover classes, the annual median ET (mm) as well as the cumulated water use (Mm a^{-1}) of each land cover class was compared. The cumulative water use was calculated as a function of the mean ET and area covered by the land cover class assuming that the mean ET of the land cover class is uniform throughout the area covered.

The second objective was to describe the historical linkages between ET, land cover and climatic variability at provincial and sub-catchment scale as done in the first objective. To achieve this objective, monthly historical data (2000 - 2012) of ET and associated climatic variables (air temperature, rainfall and vapour pressure deficit) were extracted for each land cover class in the study sites. For the historical analysis, a land cover data set referred to as 'areas-of-no-change' (AoNC) was generated. The AoNC land cover data set represented classes that have remained consistent or have not changed from 2000 to 2012. This land cover data set was obtained by comparing the NLC1990 and NLC2013/14 and extracting only classes that have remained constant. The variability of ET and climatic variables in each of the study areas was compared per land cover class. Correlation statistics and multiple regression analysis were used to analyse the relationship of ET (dependent) and three independent variables (rainfall, air temperature and

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vapour pressure deficit). The multiple regression equations were used for the projection of future ET based on designed scenarios of land cover change and climatic variability.

The third objective was then to project future ET as a function of changes in land cover and climatic variability. This was done by developing a scenario tool and applying multiple regression equations to estimate future water use changes. The tool provides three main scenarios: the first scenario is for land cover change only, based on the assumption that land cover changes occur in a consistent climate environment. In this scenario, the user is able to alter the area covered by each land cover class, thereby changing the overall water use and cumulative water use in the particular area. The second scenario is a climate change scenario that assumes that climatic variability occurs in environments without land cover changes. In this scenario the user has the ability to choose between eight different climatic scenarios which are defined by increases/decreases in climatic drivers (air temperature, rainfall and VPD). In addition the user chooses whether to apply the scenarios during the dry months of the year or during the wet months of the year. The final scenario is based on the assumption that both the climate and the area of each land cover can change and these have a combined effect on the water use of an area. The outcome of the objective was the development of a tool that can be used by water managers to understand the projected future changes in water use as a consequence of climatic variability and land cover change, and therefore inform decision making.

6.2 STUDY LIMITATIONS

The study has been able to achieve the overarching aim and the outlined objectives, however this was not done without any limitations. The initial limitation to the study is the period (2000 – 2012) used to analyse historical climatic variability. This is a limitation since a 13-year period might be considered insufficient to observe significant changes in climatic variability and a long term data set would have been more advantageous. However, satellite data from the MOD16 satellite product for ET was only available for this period. In an attempt to address this, a long-term (1950 – 2012) ground station rainfall data set was analysed to confirm that the 13-year period falls within the long-term variability. The data set acquired for this exercise was long-term rainfall for the Western Cape and Mpumalanga provinces. The results confirmed that the 2000 – 2012 rainfall trends were within the long-term range of variability (Figure 4.10). The second limitation to the study was that the impact of other climatic drivers of ET, such as solar radiation and wind speed were not included

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as these climatic variables have been considered to be important drivers of ET. Although the direct effect of these was not analysed, it is however important to acknowledge that solar radiation is implicit in the air temperature variable and wind is implicit in the resistance term used in the development of the algorithm. The use of ground station rainfall data as a climatic driver in the provincial analysis instead of spatial rainfall data was another data-linked limitation. Rainfall could therefore not be extracted for each land cover class within the province and the provincial average was applied.

6.3 RECOMMENDATIONS

- Land cover class grouping:

  It is recommended that grouping some of the land cover classes into broader classes could be useful for investigating the objectives of such a study. An example of such a national land cover map is the NLC2009 produced by the South African National Biodiversity Institute (SANBI) which consists of only eight classes including natural, cultivated, degraded, urban-build, waterbodies, plantations, mines and other (SANBI 2009). The grouping can also be based on vegetation characteristics since some land cover classes with similar characteristics do not show large ET differences, for example shrubland fynbos and low shrublands land cover classes.

- ET linkages with climatic variables:

  It is recommended that future remote sensing studies attempting to understand these linkages include in situ data to better understand these relationships. This is because some of these physiological processes governing the relationships observed would be better observed and explained at small scale.

- Inclusion of urban land cover class:

  The urban land cover class was excluded from the areas-of-no-change land cover data set, as the MOD16 satellite product used does not estimate water use from urban areas very well. It is however recognised that the urban land cover class is an important class to include in water use studies. It is recommended therefore that future water use research ensures the inclusion of the urban class in further studies.

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- Satellite product resolution (1 km):

  The course resolution of the MOD16 satellite product (1 km) is considered to be a possible limitation for estimating evapotranspiration for land cover classes which do not cover a larger area per square meter. This includes for example small scale agricultural areas.

- Application of scenario tool in other sites:

  The application of the scenario tool to other site specific problems is possible; for this to be done it is recommended that regression equations for the specific site are generated and these can be applied to project future changes in a variable of interest.

6.4 CONCLUSIONS

In the introduction (Chapter 1) the study set out to address four main research questions:

- Who are the major water users at provincial and sub-catchment scale?
- What is the relationship between ET, climatic variability and land cover changes?
- Are these relationships similar at catchment and provincial scale?
- What are the future changes expected in ET as a result of changes in land cover and climatic variability?

The findings of the thesis showed that vegetation land cover classes associated with characteristics of having deep root systems and large canopies such as thicket/dense bush and plantation/woodlots are the highest water users both at a provincial and sub-catchment scale. Average annual ET reported using MOD16 satellite product data was well within the range of those reported by previous studies. These results are important for the management of such land cover classes especially in already water stressed areas. Furthermore, estimates of ET were found to be higher in areas which were estimated to have increased rainfall both at a provincial and sub-catchment scale, examples of such areas include: KwaZulu-Natal, Mpumalanga and the Inkomati sub-catchment.

The correlation of individual climatic variables with ET showed that air temperature and rainfall were the most important climatic variables responsible for driving observed changes in ET. The least important variable according to the findings was VPD. In terms of the relationship of ET with

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these climatic drivers, the following can be concluded: rainfall in winter rainfall areas showed a negative relationship with ET while in summer rainfall areas the relationship was found to be positive. This was assumed to be a result of the weather conditions during rainfall months in winter rainfall areas which yield low ET estimates. A positive relationship was found between ET and air temperature. Contrasting relationships were found between ET and VPD; no clear reasons were determined for this observation. Combining these variables in the multiple regression analysis yielded high R^2 values, but mostly in the Inkomati area since in the Wider Cape area the R^2 values from the multiple regression analysis were still found to be low. These results further show that interpretation of output from the scenario tool in the Wider Cape should be done with caution due to the low confidence shown in the R^2 values as well as the high RMSE found to be outside 20% of the monthly mean satellite-derived ET reported. The reason for this is assumed to be due to the low rainfall which resulted in increased ET variability in the Wider Cape during the 2000 to 2012 period in comparison to Inkomati. In addition to this, the general large spatial variability in topography and other microclimatic variables in the Wider Cape area are assumed to be contributing factors to the observed low R^2 values. According to the scenario tool the highest impacts on water use as a result of changing land cover and climate variability can be expected to take place during dry months compared to the wet months in the Inkomati area. Furthermore, the scenario tool examples showed that any changes in climatic variability associated with the combined increase in air temperature and VPD will result in the increase of monthly mean ET regardless of the direction of change in rainfall. For the purpose of showcasing the conceptual model of the water use scenario tool, examples made were all focused on the Inkomati sub-catchment; however similar estimations of future water use changes can be made for the Wider Cape area using the scenario tool. In addition to this, it is envisaged that the tool will later be upscaled to include provincial scale analysis of future water use once testing and improvements have been done using the sub-catchment data currently available. The tool can be accessed using the link: https://csirwateruse.firebaseapp.com/inkomati (2018).

Based on the findings, it is practical to say that the quantification of water use from various land cover classes or vegetation types is an important task for water management. This is particularly true for an already water stressed country like South Africa. As an example, our understanding of the water use of natural vegetation is critical because this offers the opportunity to be able to compare the impact of introduced vegetation such as alien plantations on water resources. In the

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same way we can determine water use changes as a result of the expansion of urban residential areas. It is only through this understanding that response measures to possible impacts on water availability as a result of changing land use/land cover can be made. Climatic variability is expected to have inevitable impacts on water use and water availability, and this is largely due to the changes in climatic drivers of ET. Varying responses to changes in rainfall, air temperature and VPD from natural land cover classes are likely to inform decisions made on land use changes in the future, increasing the importance of understanding the historical relationships between these variables. The development of a prototype water use scenario tool presented in this research provides an example of the most practical application of this nature of research; the impact of this in the future will be measured by the uptake of such a tool by water resource managers.

In conclusion to the study, differences in water use from the various land cover classes were shown using the MOD16 satellite data product. The linkages of ET with the selected climatic drivers were also described using the selected methods. In addition, although future projections of ET or water use changes are only just estimates, they are still important for water resource planning and management under uncertain climatic conditions and changing human behaviour, which ultimately both affect land cover patterns. It is important to highlight that the scenario tool does not attempt to predict or forecast future ET; however, it contributes in enabling decision makers to engage in discussions about the future possible scenarios.

31 741 words

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APPENDIX A

Table A.1 Reclassification used to aggregate the 72 land cover classes in the NLC2013/14 product (on the left column) and new land cover classes (21) used for the current status analysis (right column).

Original NLC (2013-2014)	Version 2 of land cover groups (used in the current Deliverable 2)
Water seasonal	Waterbodies
Water permanent	Waterbodies
Wetlands	Wetlands
Indigenous Forest	Indigenous Forest
Thicket /Dense bush	Thicket /Dense bush
Woodland/Open bush	Woodland/Open bush
Grassland	Grassland
Shrubland fynbos	Shrubland fynbos
Low shrubland	Low shrubland
Cultivated comm fields (high)	Cultivated comm annuals
Cultivated comm fields (med)	Cultivated comm annuals
Cultivated comm fields (low)	Cultivated comm annuals
Cultivated comm pivots (high)	Cultivated comm annuals
Cultivated comm pivots (med)	Cultivated comm annuals
Cultivated comm pivots (low)	Cultivated comm annuals
Cultivated orchards (high)	Cultivated perennial
Cultivated orchards (med)	Cultivated perennial
Cultivated orchards (low)	Cultivated perennial
Cultivated vines (high)	Cultivated perennial
Cultivated vines (med)	Cultivated perennial
Cultivated vines (low)	Cultivated perennial
Cultivated permanent pineapple	Cultivated perennial
Cultivated subsistence (high)	Cultivated subsistence
Cultivated subsistence (med)	Cultivated subsistence
Cultivated subsistence (low)	Cultivated subsistence
Cultivated cane pivot - crop	Cultivated cane
Cultivated cane pivot - fallow	Cultivated cane
Cultivated cane commercial - crop	Cultivated cane
Cultivated cane commercial - fallow	Cultivated cane
Cultivated cane emerging - crop	Cultivated cane
Cultivated cane emerging - fallow	Cultivated cane
Plantations / Woodlots mature	Plantations / Woodlots
Plantation / Woodlots young	Plantations / Woodlots
Plantation / Woodlots clear-felled	Plantations / Woodlots

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Original NLC (2013-2014)	Version 2 of land cover groups (used in the current Deliverable 2)
Mines 1 bare	Mines
Mines 2 semi-bare	Mines
Mines water seasonal	Mines
Mines water permanent	Mines
Mine buildings	Mines
Erosion (donga)	Bare none vegetated
Bare none vegetated	Bare none vegetated
Urban commercial	Urban commercial
Urban industrial	Urban industrial
Urban informal (dense trees / bush)	Urban informal
Urban informal (open trees / bush)	Urban informal
Urban informal (low veg / grass)	Urban informal
Urban informal (bare)	Urban informal
Urban residential (dense trees / bush)	Urban residential
Urban residential (open trees / bush)	Urban residential
Urban residential (low veg / grass)	Urban residential
Urban residential (bare)	Urban residential
Urban school and sports ground	Urban sport and recreation
Urban smallholding (dense trees / bush)	Urban others
Urban smallholding (open trees / bush)	Urban others
Urban smallholding (low veg / grass)	Urban others
Urban smallholding (bare)	Urban others
Urban sports and golf (dense tree / bush)	Urban sport and recreation
Urban sports and golf (open tree / bush)	Urban sport and recreation
Urban sports and golf (low veg / grass)	Urban sport and recreation
Urban sports and golf (bare)	Urban sport and recreation
Urban township (dense trees / bush)	Urban informal
Urban township (open trees / bush)	Urban informal
Urban township (low veg / grass)	Urban informal
Urban township (bare)	Urban informal
Urban village (dense trees / bush)	Urban others
Urban village (open trees / bush)	Urban others
Urban village (low veg / grass)	Urban others
Urban village (bare)	Urban others
Urban built-up (dense trees / bush)	Urban others
Urban built-up (open trees / bush)	Urban others
Urban built-up (low veg / grass)	Urban others
Urban built-up (bare)	Urban others

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Table A.2 List of weather stations used for rainfall data and their respective geographic locations. The data for rainfall was obtained by the South African Weather Service (SAWS).

Province	**Station name**	**Coordinates**	
Gauteng	Irene wo	-25.91	28.21
	Jhb bot tuine	-26.16	28.00
	Johannesburg int wo	-26.14	28.23
	Pretoria Unisa	-25.77	28.20
	Vereeniging	-26.57	27.96
KwaZulu-Natal	Babanango	-28.36	31.21
	Charters Creek	-28.20	32.41
	Ladysmith	-28.58	29.75
	Makatini Research Centre	-27.39	32.18
	Mandini	-29.16	31.40
	Mooi River	-29.22	30.00
	Mtunzini	-28.95	31.71
	Pietermaritzburg	-29.63	30.40
	Pongola	-27.41	31.59
	Riverview	-28.44	32.18
	Ulundi	-28.31	31.42
	Virginia	-29.77	31.06
	Vryheid	-27.78	30.80
Free State	Bethlehem wo	-28.25	28.33
	Bloemfontein wo	-29.10	26.30
	Fauresmith	-29.75	25.32
	Frankfort - tnk	-27.27	28.49
	Gariep dam	-30.56	25.53
	Kroonstad	-27.67	27.31
	Vrede	-27.42	29.17
	Welkom	-27.99	26.67
Mpumalanga	Bethal	-26.46	29.46
	Ermelo wo	-26.50	29.98
	Komatidraai	-25.51	31.91

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Province	**Station name**	**Coordinates**	
	Nelspruit	-25.50	30.91
	Secunda	-26.50	29.19
	Skukuza	-24.99	31.59
	Witbank	-25.83	29.19
North-West	Klerksdorp	-26.90	26.62
	Lichtenburg	-26.13	26.16
	Mafikeng wo	-25.80	25.54
	Ottosdal	-26.81	26.01
	Pilanesberg	-25.26	27.22
	Potchefstroom	-26.74	27.08
	Taung	-27.55	24.77
	Ventersdorp	-26.31	26.81
	Vryburg	-26.95	24.65
Northern Cape	Alexanderbaai	-28.57	16.53
	Calvinia wo	-31.48	19.76
	De Aar wo	-30.67	23.99
	Kimberley wo	-28.81	24.77
	Port Nolloth	-29.25	16.87
	Postmasburg	-28.35	23.08
	Prieska	-29.67	22.74
	Springbok wo	-29.67	17.88
	Sutherland	-32.40	20.66
	Twee Rivieren	-26.47	20.61
	Upington wo	-28.41	21.26
Eastern Cape	Barkly-Oos (Caerleon)	-30.93	27.61
	Bisho	-32.89	27.29
	Cradock-mun	-32.17	25.63
	East London wo	-33.04	27.82
	Elliot	-31.34	27.84
	Grahamstown	-33.29	26.50
	Port Alfred - airport	-33.56	26.88

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Province	Station name	Coordinates	
	Port Elizabeth awos	-33.99	25.62
	Queenstown	-31.92	26.88
	Somerset East	-33.05	25.72
	Umthatha wo	-31.55	28.67
Western Cape	Beaufort-West	-32.35	22.57
	Cape Agulhas	-34.83	20.01
	Cape Town wo	-33.96	18.60
	George wo	-34.00	22.38
	Hermanus	-34.43	19.22
	Knysna	-34.05	23.08
	Langebaanweg aws	-32.97	18.16
	Malmesbury	-33.47	18.72
	Oudtshoorn	-33.60	22.19
	Paarl	-33.72	18.97
	Porterville	-33.01	18.98
	Stilbaai	-34.37	21.39
	Tygerhoek	-34.15	19.90
	Willowmore	-33.30	23.48
	Worcester-aws	-33.66	19.42
Limpopo	Mara	-23.14	29.56
	Marken	-23.59	28.39
	Oudestad	-25.18	29.34
	Polokwane wo	-23.86	29.45
	Thabazimbi	-24.58	27.41
	Thohoyandou wo	-23.08	30.38
	Warmbad Towoomba	-24.90	28.32

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APPENDIX B

Table B.1 Summary statistic of annual (2012) ET in the Limpopo province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	180	536	202	1390	200	523	0.14	97	0.15
WTL	446	514	214	1541	173	476	0.36	229	0.35
INF	461	1036	330	1577	240	1048	0.37	477	0.73
TDB	17 394	673	186	1599	190	668	13.94	11 706	17.83
WOB	62 195	499	186	1599	126	466	49.85	31 020	47.26
GRS	19 768	522	186	1599	122	491	15.84	10 316	15.72
LSB	5903	396	186	1426	77	379	4.73	2339	3.56
CCA	7287	442	226	1518	120	415	5.84	3222	4.91
CPE	1083	766	250	1541	257	738	0.87	830	1.26
CSU	4017	463	232	1599	137	414	3.22	1860	2.83
PWD	779	1156	250	1599	242	1274	0.62	900	1.37
MNS	233	425	186	1341	109	423	0.19	99	0.15
BNV	706	448	186	1426	102	419	0.57	316	0.48
UCM	12	529	318	1307	142	499	0.01	6	0.01
UIN	11	484	273	1318	175	421	0.01	5	0.01
UIF	84	493	245	1370	148	454	0.07	41	0.06
URS	56	546	266	1370	172	485	0.04	30	0.05
USR	47	471	274	1423	154	425	0.04	22	0.03
UOT	4110	516	224	1466	163	486	3.29	2122	3.23
	124 772						100	65 639	100

Table B.2 Summary statistic of annual (2012) ET in the Eastern Cape Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	343	471	127	1507	236	434	0.20	162	0.20
WTL	1504	451	140	1495	198	421	0.90	678	0.84
INF	1299	1006	262	1619	214	1046	0.78	1307	1.63
TDB	21 376	703	130	1755	266	675	12.76	15 022	18.72
WOB	5573	520	127	1650	245	483	3.33	2899	3.61
GRS	69 956	490	127	1755	185	461	41.74	34 269	42.71
SHF	6435	431	188	1369	134	411	3.84	2776	3.46
LSB	34 671	239	127	1432	60	226	20.69	8303	10.35
CCA	5373	534	143	1540	229	514	3.21	2870	3.58
CPE	476	686	172	1755	207	672	0.28	326	0.41
CSU	7642	653	181	1650	162	658	4.56	4991	6.22
PWD	1541	835	142	1755	235	777	0.92	1287	1.60
MNS	34	437	149	1311	208	439	0.02	15	0.02
BNV	5547	244	127	1562	114	213	3.31	1354	1.69
UCM	19	579	197	1298	171	566	0.01	11	0.01
UIN	24	623	203	1306	227	589	0.01	15	0.02
UIF	172	558	174	1279	197	542	0.10	96	0.12
URS	147	560	180	1296	207	536	0.09	82	0.10
USR	64	591	174	1316	226	568	0.04	38	0.05
UOT	5388	692	156	1650	191	699	3.22	3729	4.65
	167 585						100	80 229	100

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Table B.3 Summary statistic of annual (2012) ET in the Free State Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	438	265	78	939	114	242	0.34	116	0.31
WTL	2170	334	78	939	133	354	1.70	725	1.97
INF	68	355	160	980	85	333	0.05	24	0.07
TDB	1437	312	80	980	104	298	1.12	449	1.22
WOB	1100	260	81	980	121	216	0.86	286	0.78
GRS	49 802	339	80	980	123	317	38.92	16 904	45.86
LSB	33 014	191	78	939	46	186	25.80	6306	17.11
CCA	37 423	304	82	764	100	286	29.25	11 362	30.82
CPE	34	325	124	732	110	317	0.03	11	0.03
CSU	293	245	176	596	42	239	0.23	72	0.19
PWD	487	365	82	980	120	359	0.38	178	0.48
MNS	173	234	81	722	102	214	0.14	40	0.11
BNV	813	219	78	939	130	165	0.64	178	0.48
UCM	13	326	123	613	109	310	0.01	4	0.01
UIN	15	296	120	661	101	282	0.01	4	0.01
UIF	260	330	103	613	126	306	0.20	86	0.23
URS	98	328	116	661	108	317	0.08	32	0.09
USR	36	327	103	589	115	328	0.03	12	0.03
UOT	272	261	93	646	87	228	0.21	71	0.19
	127 945						100	36 861	100

Table B.4 Summary statistic of annual (2012) ET in the Gauteng Province.

Landcover class (NLC 2013/14)	Area (km2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	45	405	231	829	81	405	0.36	18	0.33
WTL	379	466	231	918	69	464	2.98	177	3.13
INF	0	416	353	470	56	470	0.00	0	0.00
TDB	710	463	231	934	71	460	5.59	329	5.82
WOB	1731	436	222	934	62	429	13.62	755	13.37
GRS	4616	442	224	934	59	440	36.33	2043	36.16
LSB	90	404	222	918	58	399	0.71	36	0.64
CCA	3351	454	232	934	61	452	26.36	1523	26.96
CPE	15	456	311	746	55	449	0.12	7	0.12
CSU	10	442	232	639	83	437	0.08	5	0.08
PWD	168	467	231	918	64	463	1.32	78	1.39
MNS	91	376	253	761	66	377	0.72	34	0.61
BNV	16	426	244	829	64	427	0.13	7	0.12
UCM	17	386	224	662	80	377	0.13	7	0.12
UIN	19	415	234	761	77	416	0.15	8	0.14
UIF	278	357	222	686	68	344	2.19	99	1.76
URS	142	437	245	746	66	436	1.12	62	1.10
USR	55	430	222	918	87	435	0.43	24	0.42
UOT	974	448	222	934	64	447	7.66	436	7.73
	12 709						100	5648	100

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Table B.5 Summary statistic of annual (2012) ET in the North West Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	148	284	79	942	97	272	0.14	42	0.14
WTL	344	399	79	942	96	401	0.33	137	0.46
INF	10	407	313	794	55	404	0.01	4	0.01
TDB	2259	421	81	942	84	428	2.15	951	3.18
WOB	17 377	353	81	942	102	376	16.51	6138	20.55
GRS	25 692	311	81	942	94	323	24.41	7986	26.74
LSB	34 137	215	81	942	78	190	32.43	7335	24.56
CCA	19 899	284	107	942	84	268	18.91	5645	18.90
CPE	53	421	138	709	89	436	0.05	23	0.08
CSU	2313	284	97	624	70	269	2.20	657	2.20
PWD	158	379	106	777	82	383	0.15	60	0.20
MNS	546	275	103	700	85	263	0.52	150	0.50
BNV	437	359	84	942	69	364	0.42	157	0.53
UCM	18	344	129	599	94	353	0.02	6	0.02
UIN	24	359	129	771	90	355	0.02	8	0.03
UIF	188	293	106	607	80	285	0.18	55	0.18
URS	68	360	140	607	89	366	0.06	24	0.08
USR	29	357	129	699	112	359	0.03	10	0.04
UOT	1555	308	83	677	92	322	1.48	480	1.61
	105 254						100	29 869	100

Table B.6 Summary statistic of annual (2012) ET in the Mpumalanga Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
INF	311	1018	456	1474	217	1022	0.41	317	0.63
PWD	7494	957	238	1712	254	902	9.94	7175	14.15
CPE	425	925	377	1481	201	902	0.56	393	0.77
CCN	504	877	537	1637	194	835	0.67	442	0.87
TDB	8550	804	210	1637	171	799	11.34	6874	13.56
WOB	12 807	692	210	1712	147	714	16.99	8867	17.49
CSU	659	652	278	1396	160	704	0.87	430	0.85
UOT	1402	630	261	1529	174	665	1.86	884	1.74
WTL	1991	621	214	1558	156	604	2.64	1237	2.44
URS	135	618	275	1254	152	603	0.18	83	0.16
GRS	27 768	604	210	1712	126	600	36.83	16 781	33.10
USR	25	620	290	1368	183	593	0.03	16	0.03
WTB	321	574	210	1507	192	570	0.43	184	0.36
UCM	14	588	312	1341	159	563	0.02	8	0.02
BNV	238	569	210	1406	148	548	0.32	135	0.27
LSB	403	547	210	1421	164	528	0.53	220	0.43
CCA	11 381	543	259	1637	112	526	15.10	6178	12.19
UIN	39	550	286	1357	171	495	0.05	22	0.04
UIF	226	541	290	1349	192	492	0.30	122	0.24
MNS	702	463	261	1382	103	447	0.93	325	0.64
	75 396						100	50 694	100

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Table B.7 Summary statistic of annual (2012) ET in the Western Cape Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	445	325	93	1294	135	306	0.35	145	0.44
WTL	1058	343	93	1298	140	323	0.82	363	1.12
INF	555	1059	315	1301	184	1111	0.43	588	1.81
TDB	7780	403	93	1301	216	365	6.05	3138	9.64
WOB	5327	235	93	1298	121	180	4.14	1252	3.84
GRS	5154	251	93	1298	104	237	4.01	1292	3.97
SHF	36 594	277	93	1299	119	246	28.44	10 140	31.14
LSB	29 150	175	93	1239	45	163	22.65	5091	15.63
CCA	17 043	315	94	1299	110	312	13.24	5360	16.46
CPE	2588	347	103	1290	145	329	2.01	898	2.76
CSU	7	171	128	339	41	159	0.01	1	0.00
PWD	804	743	131	1299	308	680	0.62	598	1.84
MNS	91	230	95	1294	82	204	0.07	21	0.06
BNV	21 413	159	93	1301	43	151	16.64	3396	10.43
UCM	31	381	131	1290	113	359	0.02	12	0.04
UIN	40	373	134	1277	139	341	0.03	15	0.05
UIF	138	350	119	1277	138	317	0.11	48	0.15
URS	276	427	131	1290	163	387	0.21	118	0.36
USR	83	469	131	1272	221	405	0.06	39	0.12
UOT	117	429	130	1266	209	372	0.09	50	0.15
	128 694						100	32 564	100

Table B.8 Summary statistic of annual (2012) ET in the Northern Cape Province.

Landcover class (NLC 2013/14)	Area (km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	301	143	47	939	78	126	0.08	43	0.10
WTL	449	161	65	939	54	155	0.12	72	0.18
TDB	2217	140	46	1082	70	128	0.61	310	0.75
WOB	10 935	139	45	1082	53	135	3.02	1516	3.67
GRS	19 991	143	45	1082	41	143	5.53	2849	6.91
SHF	9936	147	56	644	36	143	2.75	1464	3.55
LSB	228 406	114	43	1082	37	107	63.16	26 145	63.39
CCA	2232	225	55	1082	134	168	0.62	501	1.22
CPE	371	201	55	624	108	184	0.10	75	0.18
CSU	39	217	108	419	83	167	0.01	8	0.02
PWD	9	175	61	650	74	164	0.00	2	0.00
MNS	825	161	49	630	76	144	0.23	133	0.32
BNV	85 447	94	43	1082	26	88	23.63	8061	19.54
UCM	14	160	56	895	61	152	0.00	2	0.01
UIN	14	136	58	501	74	126	0.00	2	0.00
UIF	95	131	54	520	49	127	0.03	12	0.03
URS	51	167	56	500	69	163	0.01	9	0.02
USR	29	145	55	502	68	131	0.01	4	0.01
UOT	256	147	54	895	39	147	0.07	38	0.09
	361 617						100	41 245	100

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Table B.9 Summary statistic of annual (2012) ET in the KwaZulu-Natal Province.

Landcover class (NLC 2013/14)	Area (km2)	Mean (mm)	Minimum (mm)	Maximum (mm)	STD (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	501	715	338	1731	213	661	0.55	358	0.48
WTL	1462	802	338	1903	230	733	1.59	1173	1.56
INF	1529	1083	412	2033	269	1112	1.66	1655	2.20
TDB	19 271	921	341	1846	216	894	20.97	17 742	23.59
WOB	5977	832	338	1903	190	821	6.50	4974	6.61
GRS	33 153	700	338	1903	167	667	36.08	23 213	30.86
LSB	616	660	341	1786	183	606	0.67	407	0.54
CCA	4621	710	338	1724	146	685	5.03	3282	4.36
CPE	248	994	417	1664	227	994	0.27	246	0.33
CSU	5323	771	350	1799	187	757	5.79	4103	5.45
CCN	4054	995	561	1786	213	997	4.41	4032	5.36
PWD	7085	1062	376	1903	245	1127	7.71	7522	10.00
MNS	49	766	367	1730	309	659	0.05	37	0.05
BNV	668	631	338	1903	177	580	0.73	421	0.56
UCM	45	785	367	1489	188	752	0.05	35	0.05
UIN	48	774	368	1664	171	746	0.05	37	0.05
UIF	217	750	367	1534	150	736	0.24	163	0.22
URS	335	873	372	1654	220	837	0.36	293	0.39
USR	63	849	373	1577	209	796	0.07	54	0.07
UOT	6636	825	346	1799	200	797	7	5473	7.28
	91 901						100	75 220	100

Table B.10 Summary statistic of annual (2012) ET in the Inkomati area.

Landcover classs (NLC 2013/14)	Area (Km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	Standard D (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	83	611	291	1453	231	555	0.29	50	0.27
WTL	400	652	291	1412	183	611	1.41	260	1.39
INF	232	999	430	1423	240	997	0.82	231	1.23
TDB	6516	683	243	1600	172	652	23.07	4447	23.69
WOB	6848	550	243	1645	123	546	24.24	3765	20.05
GRS	6753	575	243	1600	131	560	23.90	3883	20.68
LSB	88	550	247	1600	154	532	0.31	48	0.26
CCA	1091	567	364	1369	113	542	3.86	619	3.30
CPE	414	830	349	1431	217	813	1.47	344	1.83
CSU	317	577	331	1227	92	580	1.12	183	0.97
CCN	614	775	331	1469	230	722	2.17	476	2.54
PWD	3887	1009	302	1645	273	1057	13.76	3924	20.90
MNS	43	509	325	1369	137	469	0.15	22	0.12
BNV	44	580	284	1431	160	534	0.16	26	0.14
UCM	6	574	338	1134	165	544	0.02	3	0.02
UIN	9	649	397	1355	155	627	0.03	6	0.03
UIF	79	563	338	1342	95	570	0.28	44	0.24
URS	51	609	307	1189	112	601	0.18	31	0.17
USR	10	647	338	1366	146	650	0.04	7	0.04
UOT	765	531	294	1436	123	507	2.71	406	2.16
	28 249						100	18 776	100

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Table B.11. Summary statistic of annual (2012) ET in the Wider Cape area.

Landcover classs (NLC 2013/14)	Area (Km^2)	Mean (mm)	Minimum (mm)	Maximum (mm)	Standard D (mm)	Median (mm)	Area (%)	Total (Mm^3a^{-1})	Total (%)
WTB	78	416	241	1271	108	388	1.35	32	1.31
WTL	167	424	241	1249	102	405	2.90	71	2.87
INF	5	828	471	1271	195	842	0.08	4	0.16
TDB	533	487	241	1271	144	452	9.26	260	10.54
WOB	97	484	241	1242	119	458	1.69	47	1.90
GRS	343	407	241	1271	106	390	5.96	140	5.67
SHF	1921	430	241	1271	108	408	33.38	826	33.51
LSB	84	402	241	1242	96	398	1.46	34	1.37
CCA	1351	386	241	1143	62	380	23.47	522	21.16
CPE	694	446	260	1242	127	417	12.07	310	12.57
PWD	127	530	258	1249	191	484	2.21	67	2.73
MNS	10	379	260	763	69	366	0.18	4	0.16
BNV	28	410	241	1271	104	396	0.48	11	0.46
UCM	18	411	261	1271	111	384	0.32	8	0.31
UIN	19	409	241	1232	119	385	0.34	8	0.32
UIF	59	358	241	1143	91	336	1.03	21	0.86
URS	122	464	245	1271	174	411	2.12	57	2.30
USR	31	483	245	1271	168	440	0.53	15	0.60
UOT	67	434	241	1186	123	408	1.17	29	1.18
	5755						100	2464	100

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APPENDIX C

This appendix shows monthly ET (mm) trends per land cover class for provinces not included in the results section.

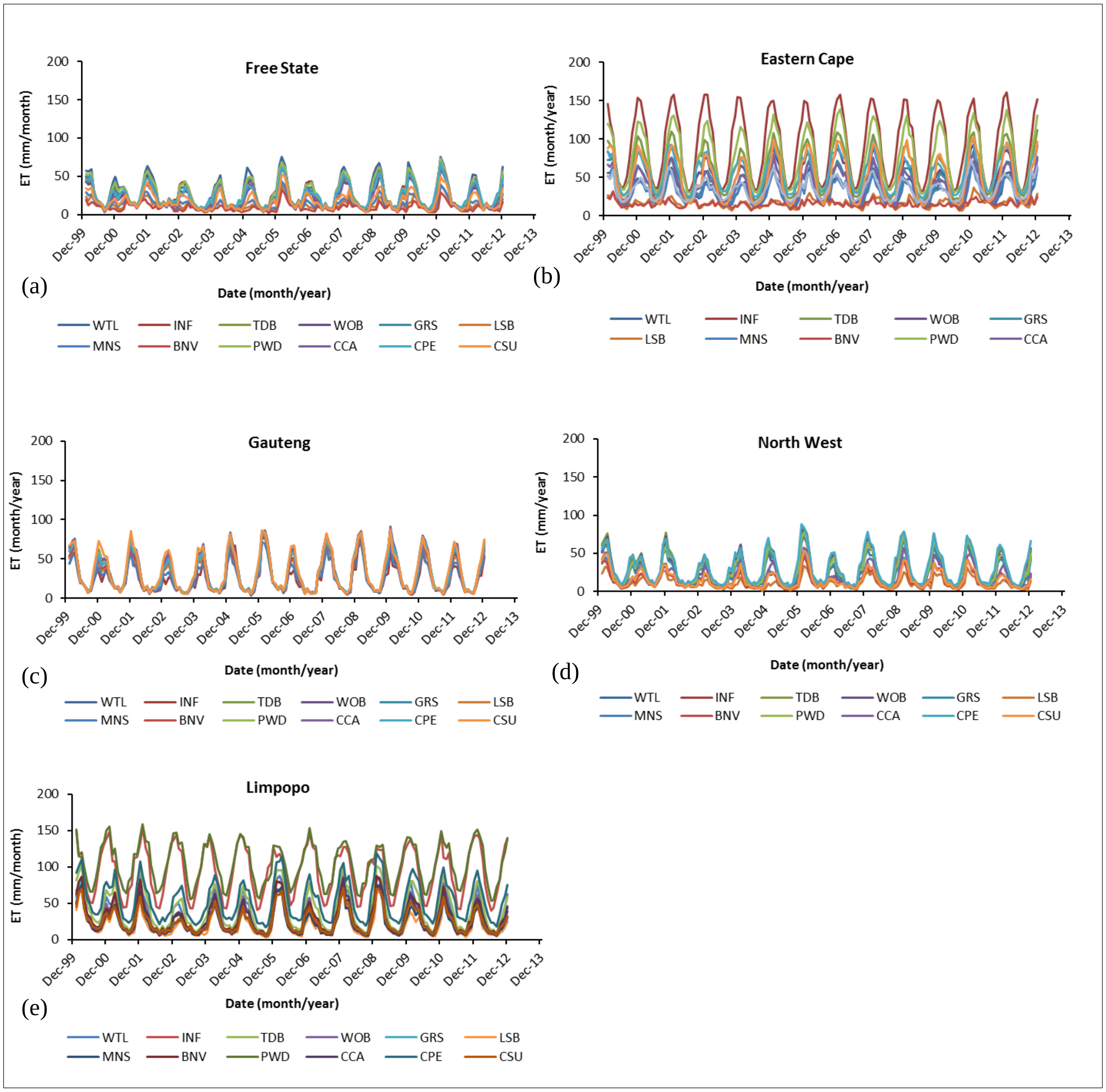

Figure C.1 Differences in land cover evapotranspiration (mm/month) in (a) - Free State, (b) - Eastern Cape, (c) - Gauteng, (d) - North West and (e) - Limpopo from 2000 – 2012.

Figure C.2 shows provincial differences in ET, rainfall, air temperature and vapour pressure deficit. Provinces shown include: Eastern Cape, Free State, Gauteng, North West and Limpopo.

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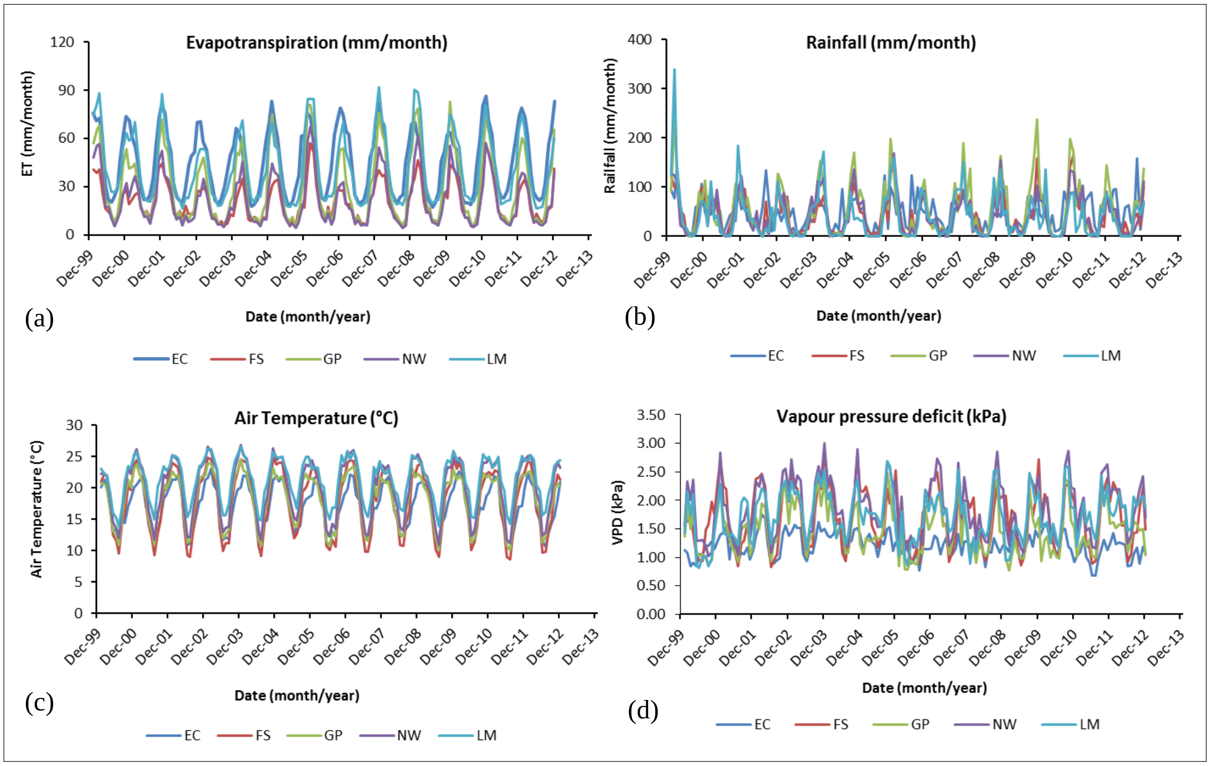

Figure C.2 Evapotranspiration (a) and associated climatic variables (a - rainfall, b - air temperature and c - vapour pressure deficit) monthly trends from 2000 – 2012.

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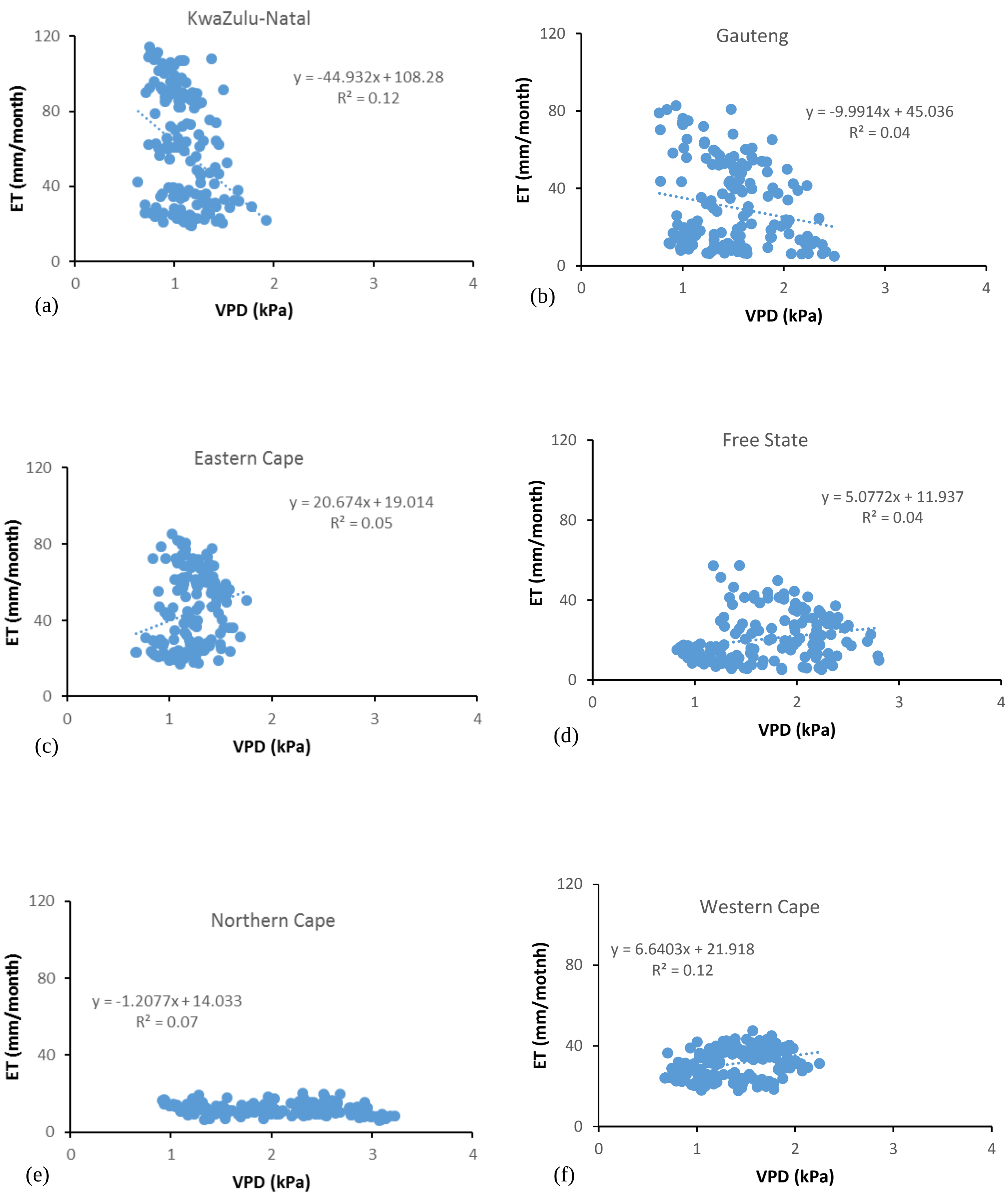
Figure C.3 shows the correlation of ET (mm/month) and vapour pressure deficit (kPa) in all nine provinces.



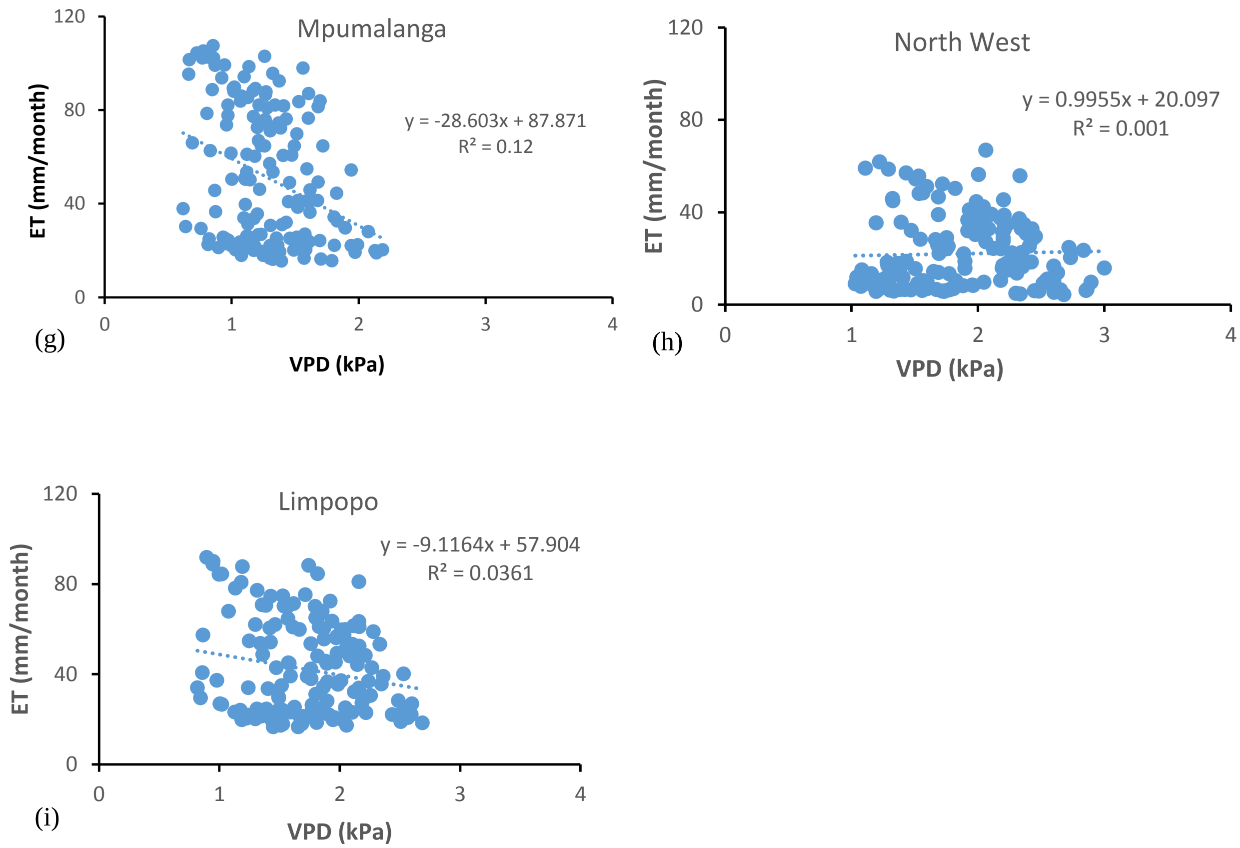


Figure C.3 Correlation of ET and vapour pressure deficit in all nine provinces. (a) - KwaZulu-Natal, (b) - Gauteng, (c) - Eastern Cape, (d) - Free State, (e) - Northern Cape, (f) - Western Cape, (g) - Mpumalanga, (h) - North West and (i) - Limpopo.

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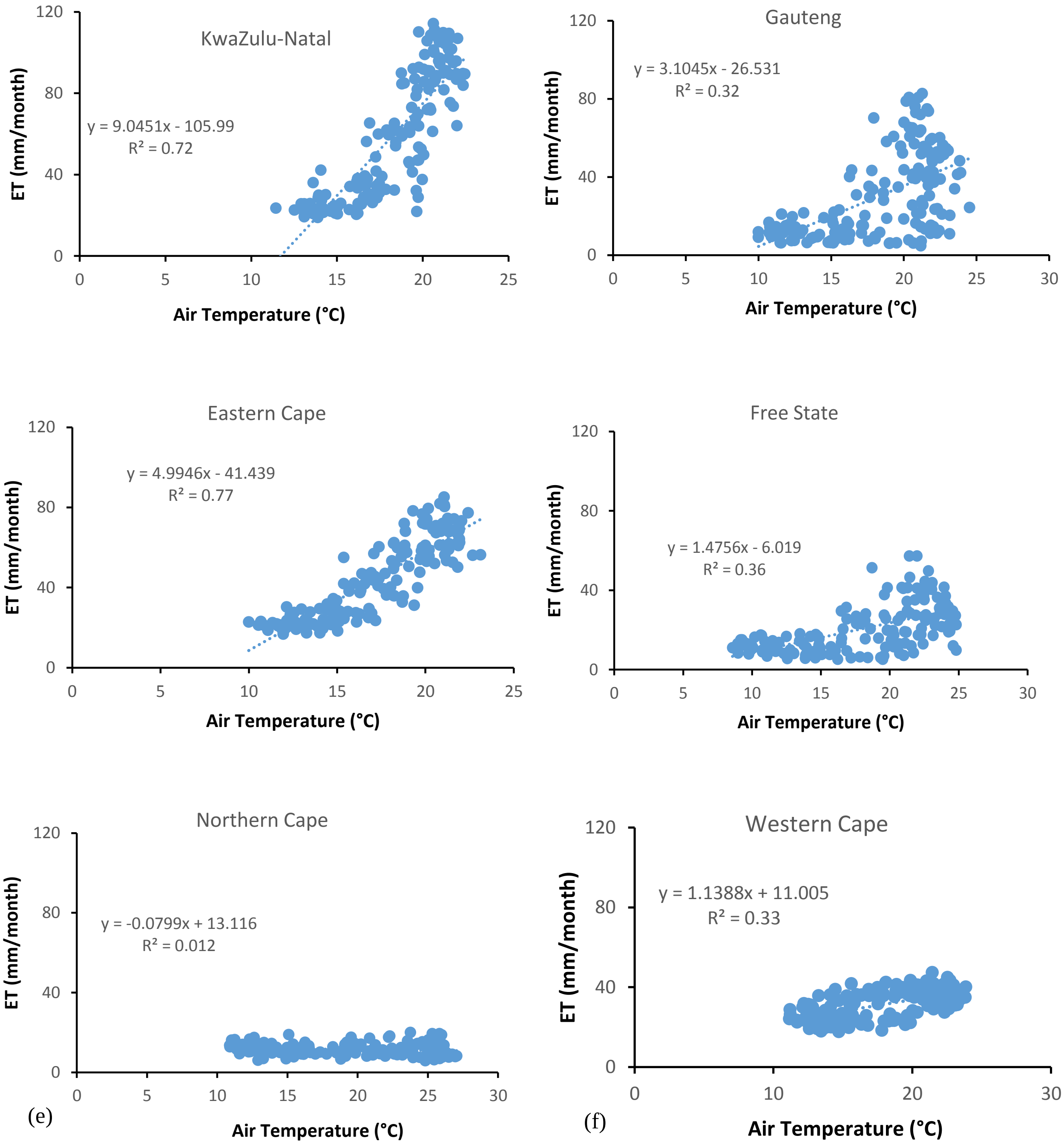
Figure C.4 shows the correlation of ET (mm/month) and air temperature (°C) in all nine provinces.



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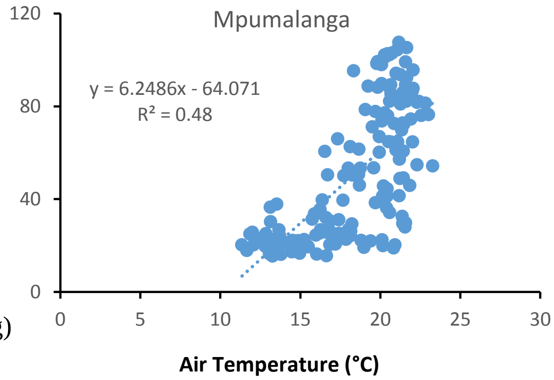
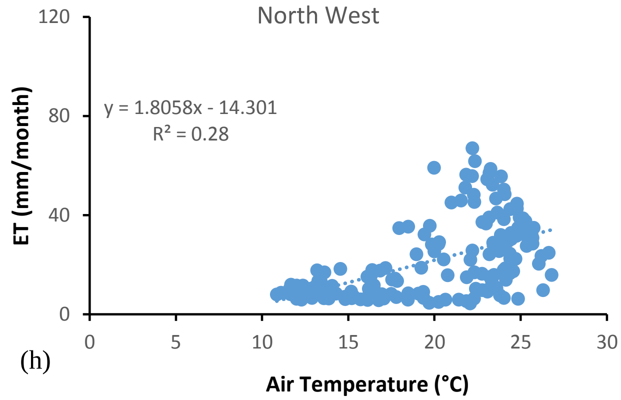
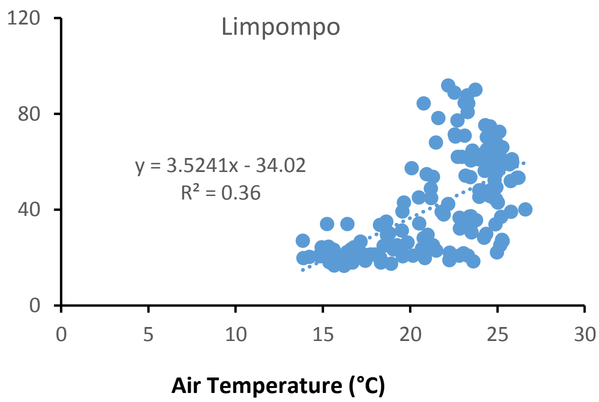


(g)



(h)



(i)

Figure C.4. Correlation of ET (mm/month) and air temperature (°C) in all nine provinces. (a) - KwaZulu-Natal, (b) - Gauteng, (c) - Eastern Cape, (d) - Free State, (e) - Northern Cape, (f) - Western Cape, (g) - Mpumalanga, (h) – North West and (i) - Limpopo.

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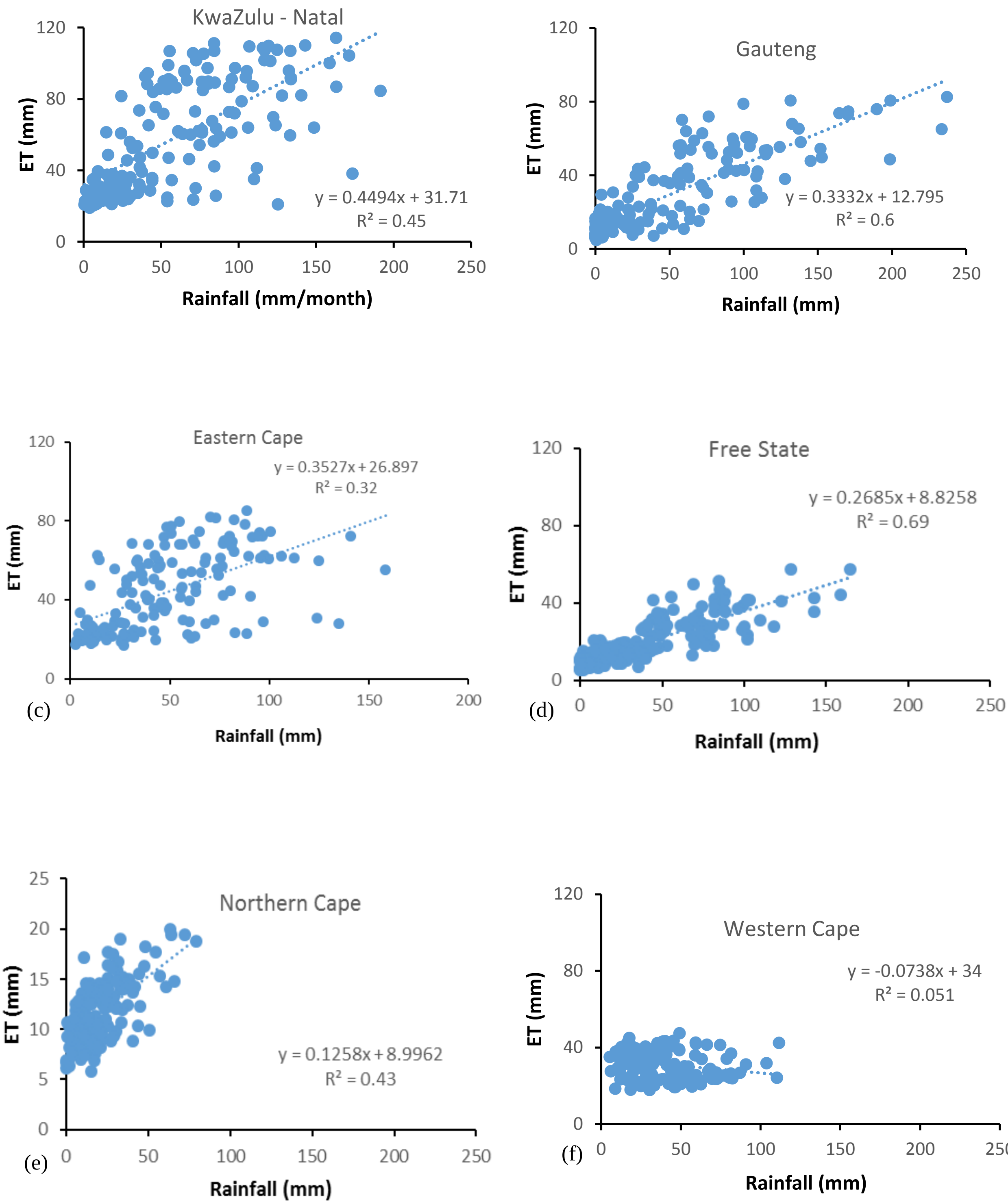
Figure C.5. Correlation of monthly ET (mm) and rainfall (mm) in all nine provinces.



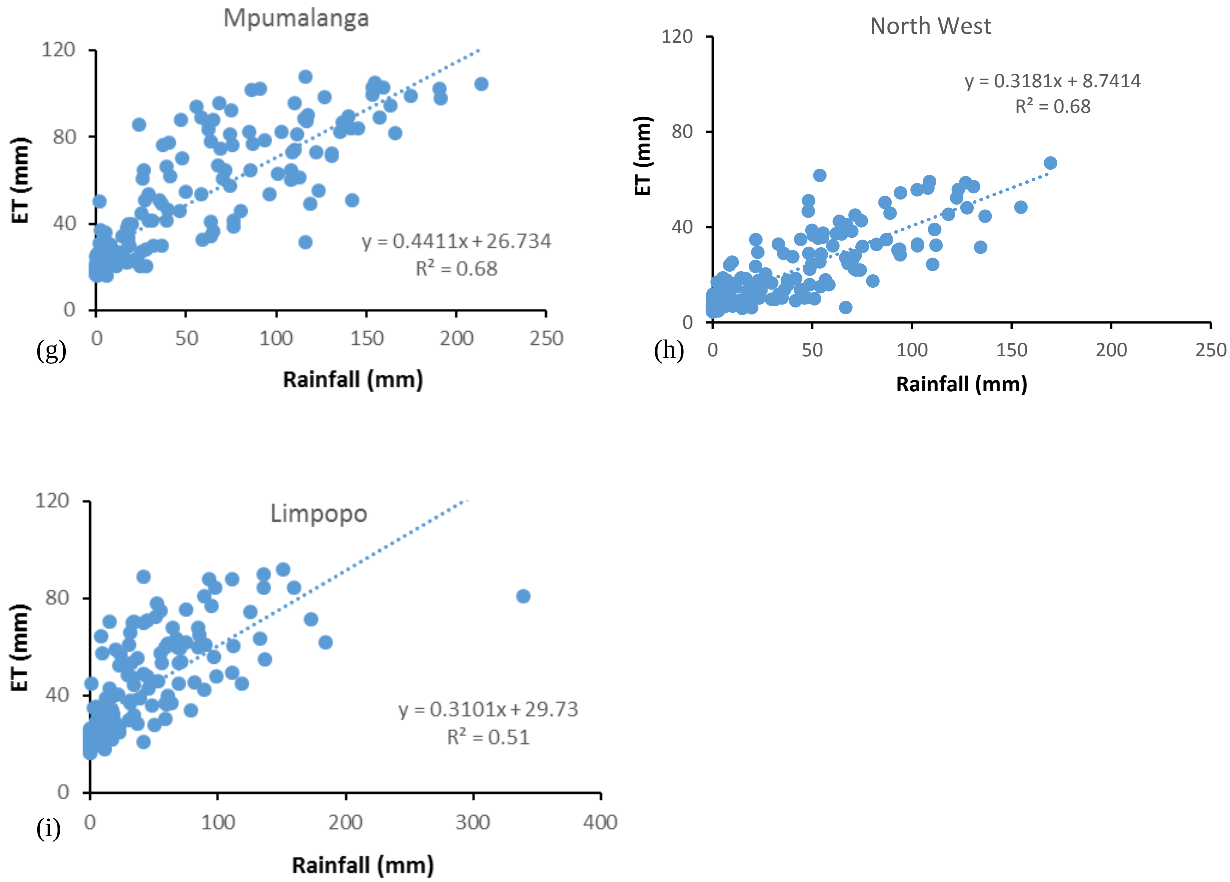


Figure C.5. Correlation of monthly evapotranspiration (mm) and rainfall (mm) in all nine provinces. (a) - KwaZulu-Natal, (b) - Gauteng, (c) - Eastern Cape, (d) - Free State, (e) - Northern Cape, (f) - Western Cape, (g) - Mpumalanga, (h) –North West and (i) - Limpopo.